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TERRAIN INVENTORY
for the
CLAYOQUOT SOUND AREA

YEAR THREE

for:

British Columbia Ministry of Forests
South Island Forest District

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by:

MADRONE CONSULTANTS LTD.
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Stuart Fraser and Kate Miller were responsible for overall project management and coordination. Kate Miller and Bryan Tasaka shared mapping coordinator responsibilities for this project, and they were assisted by Diana Weld and Julie Williams. Sandra Bird performed the data entry. Bryan Tasaka created study area location maps. Monorestitution and data capture were performed in-house at Madrone by Ernie Pacholuk and Kathy Tait. Hugh Hamilton Ltd. provided GIS support performing the final edits and creating the legends and final maps. Christine Haubrick formatted the text and made this report a presentable document.

SUMMARY

This report accompanies and describes terrain and terrain stability mapping for parts of the Clayoquot Sound area. The work was completed by Madrone Consultants Ltd. in partnership with EBA Engineering Consultants Ltd. and Hugh Hamilton Ltd.; all under contract to the British Columbia Ministry of Forests with funding from Forest Renewal British Columbia (FRBC).

To date, three years have been spent working on the inventory, and approximately 161,000 hectares have been mapped. In Year One, nine areas were mapped totaling 89,400 hectares, and the work was completed and delivered to the client in 1997. The areas mapped in Year One include Bedwell, Bulson Creek, Catface, Flores Island, Fortune, Hesquiat Peninsula, Sydney River, Tofino Creek, and Tranquil Creek. In Year Two, five areas were mapped totaling 47,400 hectares, and the work was completed and delivered to the client in 1998. The areas mapped in Year Two include Atleo, Hesquiat, Marble, Pretty Girl, and Ursus. The results of these two years of mapping are presented in separate reports.

This report accompanies the maps produced for the Year Three portion of the multi-year project. In Year Three, two areas were mapped–Kennedy River and Muriel Ridge–totaling 24,100 hectares. This report includes a description of mapping procedures, physical environment, terrain types, terrain hazard classification systems, and management concerns.

The main objective of the mapping project was to identify areas prone to geologic hazards, in particular, landslides, surface erosion, and sedimentation. The maps and this report will be used to assist in development planning by identifying potentially unstable terrain before roads are built in new areas and before cutblocks are laid out.

We employed a five-class Terrain Stability Classification in which Class V terrain is the most unstable and Class I the least unstable. Unlike most other terrain mapping projects conducted in British Columbia, we utilized formal stability criteria based on the results of an extensive study of terrain attributes and past landsliding on logged terrain (Rollerson et al., 1998).

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PROJECT INTRODUCTION

1.0 INTRODUCTION

Clayoquot Sound is an area of 2,546 km^2 (254,600 ha) located on the west coast of Vancouver Island. It is a landscape consisting of steep walled inlets, mountains, hills, lakes, and streams forming a highly rugged and spectacular area. Clayoquot Sound is famed for its scenery, recreational opportunities, wildlife viewing, and for its important place in native culture and history.

It is also famous as the site of conflicts between resource industries and those opposed to them. Clayoquot Sound has been the site of logging for decades, but in the early and mid 1990s, environmental and other groups have vociferously demanded the cessation or dramatic reduction in the rate of logging. World attention was focused on this conflict.

One outcome was the establishment of the Clayoquot Sound Scientific Panel for Sustainable Management in Clayoquot Sound (Scientific Panel for Sustainable Forest Practices in Clayoquot Sound, 1995). Its report (CSSPR, 1995) recommended the best use of Clayoquot Sound's resources. That report has been touted as representing world class standards for resource management.

One of those standards was the recommendation that the area be mapped for terrain and terrain stability to enable resource management planners to identify and thereby avoid or specially manage potentially hazardous slopes. The past legacy of logging and landslides has contributed greatly to the conflict and left permanent scars on the landscape, as well as, the trust the public has toward the resource industry. This damage and tahe resulting scars cannot be allowed to happen again. We hope that accurate terrain and terrain stability mapping will assist resource managers in achieving their objectives in a way that will minimize the probability of future landslides, sedimentation, or soil erosion.

This report accompanies terrain and terrain stability maps produced in a portion of the Clayoquot Sound area. This submission represents the third part of a multi-year project to complete the terrain mapping for the entire Clayoquot Sound area. The terrain mapping forms one part of a larger endeavor to conduct resource mapping in the Clayoquot Sound area, which embraces the mapping of terrestrial ecosystems and hydroriparian corridors. In Year One, a landslide inventory was carried out over the entire Clayoquot Sound area, and a terrain attribute study was conducted on a selected sample of landslides on logged terrain. Madrone Consultants Ltd. is the prime contractor awarded the task of completing these surveys. We sub-contracted to EBA Engineering Consultants Ltd. (EBA) to perform one-half of the terrain mapping and all of the landslide inventory and terrain attribute study. EBA also assisted in the hydroriparian component.

The objective of the terrain component of this project was to identify and map hazardous areas with respect to slope failures and erosion prior to forest harvesting. Terrain is considered hazardous if it is prone to landsliding or if it is likely to deliver sediment to streams following logging.

The results of the project are presented as maps showing terrain, terrain stability and surface erosion potential at a scale of 1:20,000. The maps are based on air photo interpretation with field checking, primarily by foot traverse, supplemented with limited helicopter reconnaissance (Terrain Survey Intensity Level B; B. C. Ministry of Forests, 1995a). These maps can be used to plan road and cutblock locations and to identify areas where increased intensity of watershed management is necessary. The maps should not be used for making site-specific decisions concerning logging activities.

2.0 METHODS

Terrain mapping and the assessment of terrain stability and surface erosion potential involves three steps:

1. Pre-fieldwork: interpretation of air photos and delineation of terrain unit polygons
2. Confirmation of these data with field checks
3. Correction of data and mono-restitution of the air photos

2.1 Pre-fieldwork

The first phase of mapping involved "pre-typing" or interpretation of color air photos taken in 1996 at a scale of approximately 1:17,000. Full stereo coverage was obtained for the Year Three study areas (see Clayoquot Sound Study Areas map on following page). The first step was to prepare all air photos so that interpretation could begin. Air photo preparation includes labeling and ordering flight lines, marking air photos with north arrows and study area boundaries, identifying coordination points, and "boxing" the edges to allow matching between adjacent photos and flight lines. Only every second photo was used for typing.

Terrain polygons were delineated on the air photos with ink pens. Each polygon was labeled initially with the terrain classification (see *Terrain Classification Systems for British Columbia,* Howes and Kenk, 1997). Interpreting the terrain from air photos is an acquired skill, which relies on the interpreter's experience with the area and knowledge of glacial geomorphology. We rely on a three-dimensional view of the ground to interpret slope gradient, shape, position relative to the landscape, cover textures, and evidence of slope processes such as landslides, avalanche tracks, fan deposition, or avulsing channels. Lines are drawn around areas (polygons) of relatively homogeneous terrain, representing visible slope facets, distinct landforms or areas exhibiting certain processes such as gullying or snow avalanching. The minimum size of our polygons was 1 cm^2 or about 4 ha on a 1:20,000 scale map.

Although we attempt to distinguish "pure" map units containing only one terrain unit, in some cases, polygons include a mixture of terrain types, for example, colluvial veneers (Cv) and steep rock outcrops (Rs). Because it is impossible at this scale to map individual outcrops, this was mapped as a complex of the two terrain units (e.g., Cv/Rs). In some cases, complexes of three units may appear. Where polygons contain complexes, we have rated the terrain stability of the most unstable or potentially unstable component.

A portion of the Clayoquot Sound study area has been mapped at various times in the past (refer to Historical Terrain Stability Mapping in Clayoquot Sound following Study Areas map). As mapping standards have changed over the years, some of this mapping is now clearly below standards, while other mapping was close to 1996 standards. According to contract specifications, we attempted to upgrade those areas where the mapping was close to current standards. However, for various reasons, we later abandoned this attempt and re-mapped most areas on clean 1996 photos.

Insert Clayoquot Sound Study Areas map

Insert Historical Map

2.2 Field Checks

The second phase involved checking a sample of the terrain polygons in the field for accuracy and gathering more information about any given terrain polygon (e.g., texture). Our contract specified that the field assessment would be carried out at a Terrain Survey Intensity Level B (B. C. Ministry of Forests, 1995a), which dictated that we would field check at least 50% of pre-typed terrain polygons.

To achieve this objective, we identified areas of access including non-deactivated roads, coastlines for boat access, and helicopter landing areas. The ruggedness and extensive forested cover in the Clayoquot Sound area restricts the number of appropriate landing spots. Nevertheless, by using a combination of helicopters and trucks, we were able to meet these sampling requirements.

Once in the field, we dug soil pits or described soil in exposures created by windthrow, road cuts, gully sidewalls, and landslide scars. The location of each of the observation points was recorded on the air photo and later transferred to the terrain map along with polygon information. We used standard data collection forms, a copy of which is included in Appendix IV. Those forms were archived, and their information was used in the construction of a terrain database.

At each observation point along a traverse, notes were made on the nature of the material such as its texture and deposit thickness, shape and gradient of the slope, presence and form of bedrock outcrops, active geomorphic processes, and drainage characteristics. Seepage, an important factor in terrain stability, was assessed by the presence of hydrophytic vegetation such as devil's club (*Oplopanax horridus*) and lady fern (*Athyrium felix-femina*).

In addition to basic soil and terrain data, we paid attention to the evidence of slope processes, particularly those resulting from active or historical landsliding. This evidence may consist of fresh or ancient landslide or slump scars, leaning or 'jackstrawed' trees, or tension cracks. Soil creep was assessed by the degree of tree-stem deformation (that was caused by creeping soil but not snow or other external factors) and the presence of fresh colluvium on the ground surface.

Fieldwork was completed in September 1998, and the mappers used Tofino as a base camp. The Madrone mapping team consisted of Marian Oden, Jason Hindson, Brad Harrold, and Pamela Williams. The EBA team was comprised of Polly Uunila and Bruce Maxwell.

2.3 Air Photo Correction and Mono-restitution

During and after field checking mapped polygons, we were in a position to edit the pre-typing. Lines were modified and labels were changed to reflect our findings. We also added labels for soil drainage (six classes; Table 1), landslide-induced stream sedimentation or LISS (Table 7, page 28), surface erosion potential (Table 6, page 27), and terrain stability table (Table 3, pages 23-24). The edited photos were internally checked by in-house quality control and then sent to the FRBC correlator (Steve Chatwin, *P.Geo.*) for external quality checking.

Upon approval of our mapping from the correlator, our edited photos were given to Madrone's digital mapping department for "mono-restitution". This is a computerized process in which distortion and tilt in the photos are digitally corrected and linework is transferred (by digitization) from the photos to a digital terrain map (in this case - TRIM). The final product is a planimetrically correct map showing the locations of the polygon lines. To ensure maximum accuracy, the control points were cascaded from our photos to the original 1:60,000 photos used to generate the TRIM files. The cascade control was done under contract to Hugh Hamilton Ltd. of Vancouver. At the same time, terrain attributes and interpretations (i.e., the labels) were entered into a standardized terrain database, which would later be attached to the map file for presentation.

During this phase, there are frequent iterations between the digital mapping department and the mappers to correct mistakes, fill in missing information, confirm labels, etc. The draft maps require careful checking to ensure that the thousands of polygons are complete and accurately labeled. We produced terrain maps showing all terrain units in the study areas along with numbered polygons. We produced a stability/erosion hazard map with these interpretations labeled.

Table 1. Soil Drainage Classification

Six Classes for Soil Drainage	
r	Rapidly drained
w	Well drained
m	Moderately well drained
i	Imperfectly drained
p	Poorly drained
v	Very poorly drained

Soil drainage class refers to the speed and extent which water is removed from a soil in relation to additions.

3.0 PHYSICAL ENVIRONMENT

3.1 Physiography

Clayoquot Sound is a complex region of inlets and bays set in a rugged area of western Vancouver Island. In his physiographic classification of British Columbia, Holland (1976) places the area in the Insular Mountains unit. The lowlands forming the western extremities of the area, including the Hesquiat Plateau, Vargas Island, and the Tofino - Ucluelet Lowlands, lie within the Estevan Coastal Plain. The more mountainous interior portions of the Sound are part of the Vancouver Island Ranges - a sub-unit of the Vancouver Island Mountains. Yorath and Nasmith (1995) recognize this area as the West Vancouver Island Fiordland physiographic subdivision - an apt term for this area of interspersed mountains and sinuous fiords.

The Estevan Coastal Plain is a narrow strip of subdued terrain mostly less than 50 m in elevation stretching discontinuously along the west coast of Vancouver Island. For most of its length, it is less than 5 km wide, but at the Hesquiat Peninsula, it reaches 12 km in width. In places, it contains steep sided hills, which protrude above the surrounding plain; Radar Hill south of Tofino is one such example (Yorath and Nasmith, 1995). The plain is covered with glaciomarine/glaciofluvial sediments deposited during a time of raised sea levels in the form of shallow sea sediments or deltaic sequences of silts, sands, and coarser material. In places, ice advances have deposited tills above or in place of marine sediments. The coastline is mainly rocky with some intermittent crescent beaches formed between rocky headlands. The portion of the plain between Tofino and Ucluelet in particular contains some of the finest beaches in Canada. Holland regards this unit to be a remnant of a late Tertiary erosion plain.

The Vancouver Island Ranges physiographic unit of Holland (1976) forms the northwesterly trending backbone of the island. Although not the tallest mountains on Vancouver Island, peaks typically reach over 1,500 m elevation. This unit contains numerous inlets or fiords that form deep cuts into the mountain range. They appear to be true fiords representing ancient river valleys that have been deepened and widened by glaciation during the Pleistocene Epoch. Characteristically, they have steep valley walls, which tend to drop directly into the inlet waters. Most follow bedrock structural features and trend north to northeast except for Sydney, the straightest of the inlets, which trends northwest by north. Several of the larger rivers have a distinct east-west trend in some reaches; good examples are the Megin, Bedwell, and Ursus Rivers.

3.2 Climate

Established climate stations that represent Clayoquot Sound are at Ucluelet Kennedy Camp, Tofino Airport, and Estevan Point. All are located at elevations under 50 m and represent the climate of the Estevan Coastal Plain but not the Vancouver Island Ranges that form the main part of The Clayoquot Sound area. There are intermittent records from areas covering shorter time intervals (e. g., Henderson Lake, Clayoquot Lake), but long-term climatic data from the mountains are lacking.

The data we do have suggest strong orographic effects resulting in higher average and more intense rainfall in the mountains compared to the coastal plain - an effect that appears to disappear eastward of the main axis of the Vancouver Island Ranges.

Thus, the short record of Henderson Lake (about 25 km east of Kennedy Lake and near the axis of the Vancouver Island Ranges) set rainfall records for Canada (if not North America) both for yearly precipitation (8123 mm in 1931) and for wettest **month** (2019 mm in December 1923); whereas, only about 35 km further east, Port Alberni shows a moderate 1886 mm **yearly** average.

The trend in rainfall intensity is apparently similar. The maximum 24-hour precipitation values at Tofino, Ucluelet, and Estevan are 184.2, 185.1, and 218.9 mm (AES 1993a). In contrast, at the Brynmor Mines in the mountains behind Ucluelet, intensity records for B. C. were set for 2 hours (70.9 mm), 6 hours (139.4 mm), and 24 hours (489 mm) (Phillips, 1990). The effect of orographic influence on precipitation is also noted in the "Landslide Inventory" (EBA, 1997), which discovered that there was an increase in the landslide frequency with increasing distance from the sea in The Clayoquot Sound area.

Annual precipitation totals at Tofino, Ucluelet, and Estevan are 3285, 3356, and 3180 mm. Of this, about 10% to 15% falls as snow - a proportion that increases with elevation and distance from the coast (AES, 1993a). Above 300 m elevation, rain-on-snow events occur between October and April and may generate the highest instantaneous stream discharges of the year.

If the trends in monthly rainfall over the year at Tofino, Ucluelet, and Estevan are representative of the Sound, then there is a marked seasonality. About three-quarters of the total rainfall occurs in the six month period between October and March, inclusive. The ratio of highest monthly rainfall to the lowest is about 5.5. The wettest months are November, December, and January. The relatively low rainfall period in the summer months come to an end in late September or early October. By the end of October, the area is buffeted by an unrelenting series of large low-pressure cyclonic systems moving on-shore from the Pacific. Each of these storms brings heavy precipitation and, commonly, strong winds.

We believe that embedded within these large storms are cells of highly intense rainfall that may dump large volumes of water in short time periods. One or more of these cells may be responsible for the astonishing records at Brynmor Mines. These cells may have a short life span as they travel across the landscape but could be highly influential in triggering clusters of landslides under certain circumstances. Furthermore, their localized distribution makes them difficult to detect in the sparse rainfall gauge network.

At Tofino Airport and Estevan Point, the annual average temperature is 9.0°C and 9.2°C - among the mildest in Canada. Winters are relatively mild, and climate stations in the lowland areas of The Clayoquot Sound area are frequently the warmest places in the country during January and February. Summers are correspondingly cool compared to more interior locations on Vancouver Island (for example, in Port Alberni, July daytime temperatures can be 15°C warmer than at Tofino). The lowlands and inlets are cooled by maritime winds, but more importantly, during July and August are commonly blanketed by morning advective fog, which may not disperse until mid-day. For example, at Tofino Airport, the months of July through October are the foggiest with an average of about 12 days per month (AES, 1993b).

The main effect of the mild temperatures is to minimize the depth and duration of snowpacks at lower elevations where the ground is essentially snow-free all year. On average, Tofino and Estevan have only 12 and 13 days with measurable snowfall, and the corresponding figure for Ucluelet is 9 days (AES, 1993a). These values are also among the lowest in Canada. Both snowpack depth and duration increase with increasing elevation to the extent that in places along the eastern boundary of the study area, there is evidence of localized snow avalanches.

3.3 Hydrology

The Clayoquot Sound area contains several large rivers draining the Vancouver Island Ranges (Table 2). These drainages flow into the sea at or near the head of sheltered inlets, which deeply penetrate into the fiordland region. Moyeha, Megin, Bedwell (including Ursus), and Kennedy are the largest rivers draining large, highly mountainous catchment areas that extend well beyond the Clayoquot Sound study area. Sydney, Clayoquot, Tranquil, Cypre, and Bulson watersheds are smaller in size comprising areas mainly within Clayoquot Sound. These watersheds drain areas of intermediate relief with lower average elevations than the larger rivers. Tofino, Cotter, Watta, and Pretty Girl form smaller watercourses less than 5,000 ha.

There are no well established stream gauging stations in the study area. The nearest and most representative are Sarita River, Carnation Creek, and the Ucona River (Laird in Madrone, 1991). All three are located on the west coast of the Island; Sarita and Carnation to the south and Ucona, which drains into Gold River, is just to the north. Sarita and Carnation drain mainly forested, low elevation catchments. Sarita, with a catchment of 16,200 ha on moderate-relief terrain up to 950 m elevation, is probably representative of intermediate drainages in the study area such as the Megin and Bulson and, to a lesser extent, Clayoquot River, Ursus, Tranquil, and Sydney (although Ursus lacks lakes). The Ucona River drains 18,500 ha in mountainous terrain up to 1,800 m elevation. It therefore has a much higher snowpack contribution to streamflow. It is probably representative of the Moyeha and, to a lesser extent, the smaller Bedwell River and more subdued Kennedy River. Carnation is a well studied watershed of 10,100 ha of low elevation terrain (less than 700 m). It will be representative of creeks such as the Cypre River. Table 1 lists the major drainages in the Sound and their similarity to gauged rivers.

Table 2. Major Drainages in the Clayoquot Area

Drainage	Approx. Area (km^2)	Max. Elevation	Lake(s)	Floodplain	Similarities To
Kennedy River	229	1515	Small (new)	Yes	Ucona
Clayoquot River	50	1300	Yes	Lower	Sarita
Tofino Creek	42	1360	No	Mid-valley	Sarita
Tranquil Creek	65	1200	Yes	Lower	Sarita
Bulson Creek	81	1400	Yes	No	Sarita
Bedwell River	212	1850	No	Lower	Ucona
Cypre River	58	1150	No	Lower	Sarita
Moyeha River	181	1800	No	Lower	Ucona
Cotter Creek	31	1500	No	Lower	Carnation
Megin River	254	1750	Yes	Lower	Ucona
Watta Creek	38	1450	Yes	Short	Carnation/
Sydney River	65	1200	Yes	Short	Sarita
Pretty Girl	45	1100	Yes	Lower	Sarita/

All drainages show the highest mean monthly discharges (and instantaneous flows) during the winter months, namely, between October and February. The Ucona River also shows high monthly discharges during the months of May and June reflecting the influence of snow melt from higher elevations. Because of its size, presence of late-lying and persistent snowpack, and heterogeneity of terrain, the Ucona shows less variation between the highest monthly discharge and the lowest monthly discharge. The Moyeha River can be expected to have a similar pattern.

The Sarita contains relatively little high elevation ground in its watershed, and, consequently, the main contribution to streamflow is rainfall rather than snow melt. Hence, the highest discharges are in the winter months with pronounced low flows in the summer and early fall period. The system is buffered to some extent by lakes and a relatively large area. The response of streamflow to storm precipitation is somewhat muted; although, protracted rainfall in a succession of winter storms may still produce large discharges. However, very low summer flows are characteristic and can be expected to occur in most of the medium sized and smaller drainages in The Clayoquot Sound area.

Carnation Creek contains lower elevations, and its hydrology is almost completely dominated by rainfall rather than snow melt. Lacking storage elements (e.g., lakes, extensive floodplains, and wetlands), its streamflow has a relatively fast response to storm precipitation (Hartman and Scrivener, 1990). We can expect streams such as Cypre, Watta, and Cotter to have similar responses.

With its rugged relief, steep slopes, and high precipitation, The Clayoquot Sound area is geologically active. Despite extensive forested cover, there is a high rate of sediment transfer from hillslopes to streams and rivers. Based on data from Carnation, Laird (Madrone, 1991) has estimated that natural sediment yields in The Clayoquot Sound area watersheds will equal or exceed 0.5 tonnes/per ha/per year. Most of this sediment will be generated during the late fall and winter months associated with peak discharges. Although in the larger systems much of the suspended sediment yield will be contributed from bank and channel bed erosion, landslides reaching stream channels form an important local contribution. The landslide inventory (EBA, 1997) confirmed that logging activity increases the rate of landslides over natural rates by a factor of nine. This will undoubtedly have a dramatic effect on sediment supply rates.

3.4 Glacial History and Surficial Materials

Much of the present appearance of the landscape is due to the glaciations during the Pleistocene Epoch of which the latest major glaciation, the Fraser (or Late Wisconsin), has left the most extensive and readily identifiable evidence. The Fraser Glaciation commenced about 29,000 years ago reaching its maximum extent about 15,000 years ago (Yorath and Nasmith, 1995). Initially, the glacial advance on Vancouver Island consisted of alpine glaciers that in places expanded and coalesced into some of the larger valleys such as the Cowichan. By about 19,000 years ago, glacial ice of the Cordilleran Ice Sheet on the mainland began to cross the Georgia Trough and extended across Vancouver Island. In the study region, the main direction of ice movement was southwesterly (Alley and Chatwin, 1979).

According to Holland (1976), the terrain below about 1,200 m was affected by ice of the Cordilleran Sheet. Mountain peaks above this elevation were sculpted by local origin, alpine glaciers. In general, peaks above this elevation tend to be more rugged than lower peaks. In any case, it appears that the total thickness of ice was considerably lower here than in the interior of the Island and on its eastern side.

The thickness of the ice sheet was probably at least 1,555 m in the Beaufort Range (Fyles, 1963) but was thinner on the west coast, probably dropping to 800 to 1,000 m. Clague *et al*. (1981) set the 500 m surface contour for ice thickness at the Fraser Maximum (14,500 to 15,000 years ago) just off-shore beyond the Estevan Coast Plain. Presumably, the ice extended as a shelf into the Pacific. The weight of the ice in the study area depressed the land by approximately 50 m relative to the sea level at the time compared to up to 120 m along the Georgia Straight shoreline (Yorath and Nasmith, 1995). Clague *et al*. (1981) report maximum late Pleistocene marine transgression to about 32 to 34 m at Hesquiat Harbour. The ice began to wane about 13,000 yearsa ago and despite several small readvances was essentially gone by about 10,000 years ago.

Evidence of glaciation lies in the shape of the valleys and fjords, striations and grooves in exposed bedrock, and in the nature of the surficial deposits throughout the study area. Down wasting glacial ice deposited extensive sediments on the landscape in the form of morainal (or till), glaciofluvial, and, to a lesser extent, glaciolacustrine deposits.

Throughout the study region, the dominant surficial materials are morainal deposits. These materials cover the hillsides, valley bottoms, and coastline but in places may be buried by colluvium, fluvial, or other sediments. Secondary surficial materials include fluvial, glaciofluvial, marine, and glaciomarine sediments and organic deposits, which typically occur along valley floors and the coastline. Morainal deposits are most commonly present as a blanket on mid-slopes where the surface of the deposits more or less conforms to the shape of the underlying bedrock. These landforms are mapped as Mb but are complexed with shallower deposits (morainal veneer or Mv), exposed rock, or colluvial deposits (on steeper slopes).

On lower valley positions, it is not uncommon to find thicker morainal deposits in which the surface does not reflect the underlying rock surface. These deep deposits are prone to post-glacial gullying or incision by down-cutting creeks or rivers. The erosional scarps along gully sidewalls or alongside creeks or rivers tend to be subject to debris slides and slumps.

3.4.1 Till

Tills are also common on upper slopes where they tend to be thin in the form of veneers (Mv) and where they are usually complexed with colluvial veneers (Cv) or steep, exposed rock (Rs).

Morainal material (till) is generally poorly sorted consisting of a wide range of particle sizes including gravel and boulders usually set within a matrix of finer-textured material (most often silty sand or sandy silt). The coarse fragment content varies from about 30% up to 70% and in most cases the dominant clast is the local bedrock. In other parts of Vancouver Island (Alley and Chatwin, 1979), clasts imported from the Jurassic Coast Intrusives can be found indicating that Cordilleran Ice overrode the Island at some point in the last glaciation, but we cannot confirm that such rocks are found in The Clayoquot Sound area.

Till in the study area exhibits reddish-brown to pale yellow colours within 1.0 m of the surface. This colour is due to the soil-forming process of podzolization that has taken place in the Holocene (recent) epoch. At the base of this upper horizon, there is commonly a sharp discontinuity above a greyish coloured, relatively consolidated material. Many people know this as “hardpan”. This represents either an unweathered counterpart to the overlying material or a basal till deposited under the ice during its expansion phase. In the majority of cases, there is no difference in clast or fines content between the upper and lower deposits suggesting that post-glacial weathering is responsible for the difference and that the discontinuity is due to the present extent of a weathering front. In some cases, a difference exists suggesting that they are different materials and that the lower unit is a basal till. In either case, the lower unit represents a relatively impermeable material such that most groundwater flow is perched on its surface and most flow is confined to the weathered zone. Numerous landslide scars expose the surface of the unweathered tills suggesting that they commonly function as failure planes in the development of debris slides. The maximum rooting depth corresponds to the depth of the weathered soil in most places, which, in general, is less deep in till-derived soils than in soils derived from colluvium.

Most tills have been consolidated to some degree even though weathering in the upper 1 m may have reduced this effect. In general, erosional slopes in till stand at steeper gradients than in unconsolidated materials such as fluvial or glaciofluvial sediments. The same is true for road-cuts.

3.4.2 Colluvium

Colluvium is defined as material in which gravity is the dominant process in deposition. Colluvial landforms can be landslide deposits or talus, or they can be mantles deposited over morainal blankets that in turn overlie rock.

Colluvium occurs on some of the steeper slopes throughout the region and at the base of bedrock outcrops where slow or rapid downslope movements are dominant processes. It is present as blankets or veneers (Cb, Cv). On slopes between 50% and 80% colluvium may be complexed with morainal deposits (Cw/Mw or Mw/Cw). The texture of the colluvial matrix is commonly subangular to angular rubble or blocks loosely set in a matrix of silty sand. This material is generally moderately well to well drained depending on the texture of the matrix. Coarse textured colluvium or talus may be rapidly drained. Active colluvial slopes are often subject to soil creep or continued rockfall or rock slide deposition, which in places could represent a hazard to forest workers.

3.4.3 Glaciofluvial

Glaciofluvial (FGj, FGp) sediments are found along the valley floor of many of the rivers in the study region. These deposits consist of moderately well sorted and stratified gravels and sands laid down by meltwater from ice during deglaciation. They can be massive (no structure) or bedded, and contain lenses of silt in places. These sediments are moderately well to well drained, but when exposed in steep, natural erosional scarps, they are subject to rapid failure and constant ravelling.

3.4.4 Fluvial

Fluvial deposits (Fp, FAp, Ff) are post-glacial (Holocene) deposits associated with active rivers and streams. Extensive floodplain deposits are present in the Clayoquot Sound area alongside major rivers such as the Sydney, Bedwell, and Moyeha especially in their lower reaches. In general, these are well-sorted sediments but vary in their specific texture. In some places, floodplains contain well-sorted gravels with intercalated sands. In others, floodplains contain finer sediments with decreasing grain size towards the surface (representing flood-deposited silts). Fluvial sediments can be active or inactive depending on their position relative to the modern stream or river. The distinction between active and inactive is not defined in quantitative terms (Howes and Kenk, 1997). We have mapped floodplains with vegetative evidence of recurrent floods (e.g., sparsely vegetated gravel bars) as active; otherwise we have assumed an inactive status.

Fans are common features forming at slope breaks along stream channels. By definition, fans have slope gradients up to 15° (26%) above which they are “cones”. Fans vary in their stability; stable fans have entrenched stream channels with no evidence of recent avulsion. Geomorphically active fans show evidence of recent and recurrent stream avulsion with poorly incised channels. Both active and inactive fans are present in the study area.

Most fluvial sediments are prone to erosion as they are water-laid and contain highly detachable particles. Because they are generally located on gentle slopes, erosion under natural conditions is mainly confined to channel banks; however, as in every surficial material, accelerated erosion is possible with poor road construction practices.

3.4.5 Marine

Marine (Wv, Wp) deposits are present in numerous places along the coastline in the study region. These recent deposits are composed of sands, silts, and clays and include active beaches, as well as, relict beach deposits. The most extensive areas of marine deposits can be found on the Hesquiat Peninsula where air photos reveal a succession of beach ridges formed as the land surface gradually rises above sea level. Both archaeological and geological evidence point to emergence of the land relative to the sea of about 2 to 4 m in the last 4,000 years (Clague et al., 1981).

3.4.6 Glaciomarine

Glaciomarine (WGp) sediments were deposited during the last deglaciation when sea level was higher and when fine silts and clays were released from the melting of floating ice and ice shelves. Because they were deposited in near-shore marine environments under conditions of decaying ice shelves, these sediments are commonly compact deposits containing coarser fragments originating as drop-stones or ice-rafted rocks. Glaciomarine deposits are confined to those parts of the study area below 50 m in elevation. They are uncommon in the Clayoquot Sound area and have been sparingly mapped; however, they may be more extensive but buried under more recent deposits. Further north in the Escalante River, there are extensive glaciomarine deposits buried by more recent marine deltaic sands and silts. These are difficult to detect except where they are exposed in terrace scarps. Glaciomarine deposits are also known to occur along the eastern shore of Fortune Channel where they are visible in gully sidewalls and road cuts.

Certain glaciomarine deposits in northern British Columbia are “sensitive” in that their particle structure is highly prone to sudden collapse and subsequent liquefaction. In 1994 near Terrace, a mudslide occurred in glaciomarine sediments on a very gentle slope (Geertsema, and Schwab, 1995). Although there is no evidence that sensitive sediments occur in the Clayoquot Sound area, there is the possibility that they are present but so far undiscovered and warrants very careful treatment of glaciomarine sediments. Where they are encountered, road construction must be done with extreme care.

3.4.7 Organics

Organic (Ov, Op) materials are found mainly associated with wetlands throughout the study area. Most are located in bogs where centuries of waterlogging in acid soil conditions have created anaerobic environments and slowed decomposition. This in turn has resulted in the accumulation of peaty materials (Sphagnum moss species). Bogs are also common along the margins of lakes, most of which are in the very gradual process of becoming bogs entirely as the peat accumulation encroach on the open water. Bogs occur where precipitation is the most important form of water input. Where groundwater is predominant, a different kind of wetland – a “fen” – tends to form. The organics accumulating in these environments are formed from forb vegetation (sedges and rushes) and non-sphagnum mosses. This results in organic material less raw and acid than bog organics. Fens can be transitional to bogs where both precipitation and groundwater are significant contributors or where groundwater is low in dissolved salts. Some wetlands in the Clayoquot Sound area form on moderate slopes that are subject to copious seepage. Here, the organics form a blanket (Ob) over other deposits - commonly till.

Organic soils have extremely poor bearing strengths and therefore are generally avoided in road construction. In addition, many wetlands have disproportionately high biodiversity values in the predominantly forested Sound that further reduces the desirability of development activity.

3.5 Bedrock Geology

Clayoquot Sound is a complex assemblage of formations created by the accretion of terranes, a number of intrusions, and, lastly, accumulations of sedimentary rocks. Much of our information comes from Muller, 1977 and Massey, et al., 1994.

The main structural feature in the Sound is the West Coast Fault, which runs northwest-southeast parallel with the west coast of the Island. This is a deep fault thought to be a continuation of the San Juan Fault to the south and separates the older rocks of the Wrangellia Terrane (the main structural unit of the Island) from the younger sedimentary and volcanic rocks of the Pacific Rim Terrane (Yorath and Nasmith, 1995).

The oldest rocks in the Sound are members of the Paleozoic Sicker Group, which in the Clayoquot Sound area consist mainly of metamorphosed sedimentary rocks such as greywackes and argillites. They occur both east and west of Bedwell Sound at its southern limit, between Bedwell and Herbert Sounds, and at the head of Herbert. Volcanic rocks of the Sicker Group also occur in the Sound but appear to be rare. Rocks of the Sicker Group underlie about 9,400 ha or 4% of the total land area in the Sound. According to the Landslide Inventory (EBA, 1997), ground underlain by Sicker Group has experienced a disproportionate number of landslides, almost twice the average landslide frequency. The reason for this is not clear, but EBA suspects that the reason may be due to factors other than the bedrock geology *per se*.

The most common rocks in the Sound are members of the West Coast Complex, a group of mainly crystalline intrusive rocks of unclear age. Muller regards them as Jurassic. According to Muller, they are genetically related to the Jurassic Island Intrusives, which are also termed Island Plutonic Suite according to the B. C. Ministry of Energy, Mines and Petroleum Resources Open File1994-6. These two groups together account for about 46% of the land area in the Sound or about 100,000 ha. The rocks in general are hard and competent and weather to a gravelly, silty sand or sand. The Island Intrusives also had higher than average landslide frequencies although not quite to the same extent as the Sicker Group.

Triassic volcanics of the Karmutsen Formation are the second most common rocks in the Sound underlying about 72,000 ha or 33% of the land area. These are basaltic lavas generally forming moderately hard, competent rocks. Karmutsen rocks are also the most common rocks on Vancouver Island forming the core of the Wrangellia Terrane, which is the underpinning of Vancouver Island as well as the Queen Charlottes.

The most recent rocks are those of the Cenozoic Carmanah Group. These are sandstones, siltstones, and conglomerates and mainly underlie much of the flat or undulating terrain in the Estevan Coastal Plain. These rocks are thought to be members of the Pacific Rim Terrane, which collided with the west coast of Vancouver Island in the Tertiary period.

4.0 GEOMORPHOLOGICAL PROCESSES

4.1 Debris Slides and Debris Flows

Debris slides and flows are rapid downslope movements of soil and organic materials. These are shallow, translational landslides in which failure occurs in weathered soil overlying a relatively impermeable plane - usually parallel to the ground surface. The failure plane is most commonly either a rock surface or the top of an unweathered till horizon.

Debris slides are distinguished from flows by the mechanism of movement after failure. Debris slides, although usually initiating in saturated soil, move as a non-coherent mass of mixed clastic and organic material. Flows, as their name implies, move in a slurry with rheologic properties. Debris flows can be confined where a sidewall or headwall slide delivers debris into a channel in which conditions are conducive to the initiation and maintenance of flow. Unconfined debris flows may also occur in The Clayoquot Sound area where sufficient moisture is available to sustain the mobilized debris as a flow. In general, flows travel considerably farther than slides although the differences are not consistent. EBA (1997) found it difficult to distinguish debris flows from slides on air photos and thus lumped the two processes together in their analysis. In our mapping, we also had difficulty distinguishing open-slope debris flows from debris slides. Debris slides are denoted -R”s, and debris flows are denoted -R”d.

Debris flows may entrain soil and organic material as they travel. Consequently, their final mass at deposition may be substantially larger than at initiation. Because of their greater travel distances (especially in confined environments), they often have greater impacts on down stream resources.

Debris slides and flows occur on moderately steep or steep hillslopes where the forces acting downward on a slab of soil (e. g., the slope component of gravity) exceeds the forces maintaining the slab in place (e. g., the shear strength of the soil and the resistance to sliding along the failure plane). The ratio of these forces is called the Factor of Safety (FS)[1]. Where the FS drops to 1.0, failure of the slab in question occurs.

Most or possibly all landslides occur in conditions of high soil moisture associated with storms with prolonged and/or intense precipitation. In some cases, high soil moisture develops after rain-on-snow. Saturation of the soil decreases the shear strength of the soil and, through buoyancy, reduces the frictional resistance of the slab to sliding. Rainfall onto the ground surface under a forest is rapidly converted to subsurface flow (surface flow is less common). The water flowing underground is mainly concentrated in the upper 1 m of the soil perched above either a rock surface or an unweathered till horizon. The flow paths appear to be highly irregular following root pores, cracks, or other structural openings in the soil matrix. Much of the groundwater flows along or just above the interface between the mineral soil and the forest floor (e. g., Chamberlin, 1972). Evidence of this anisotropic character of water flow can be observed in a road cutslope during a winter storm.

Hillslopes are highly variable, and within even a relatively uniform terrain polygon there will be a wide range of terrain microsites with different slope gradients, micro-catchment basins, groundwater flow regimes, soil depths, and soil shear strength. This spatial variability combined with the variability in soil moisture due to precipitation and flow paths makes it highly difficult to model and predict slope failures. Within any steep terrain polygon, the FS diminishes with

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[1] FS is the ratio of Forces Resisting Failure divided by the Forces Promoting Failure.

increasing soil moisture, and failure will occur if and where the FS of the most sensitive microsite reaches 1.0.

Logging probably increases the landslide frequency. EBA found in its landslide inventory that logged terrain was approximately nine times more prone to sliding than unlogged terrain. Part of the increase is associated with road construction due to oversteepened fillslopes, localized saturation of soils due to drainage concentration, and undermined cutslopes. EBA found that about 50% of the open-slope landslides in logged terrain were initiated in roads (most of this from road fills) and the remainder initiated on open slopes in clearcuts. The increased failure frequency in logged open-slope terrain units is believed to be due to the gradual elimination of root-strength contribution to shear strength (e. g., Zeimer and Swanston, 1977) and possibly to the alteration of near-surface groundwater movement.

Given the difficulty of predicting landslides on this basis, a geographic approach has been developed relating the failure frequencies to the attributes of terrain polygons. Preliminary results from the terrain attribute study (Rollerson et al., 1998) are available and have been used to develop our terrain stability criteria for terrain polygons. This procedure is more fully discussed in Section 5.1.

4.2 Rock Slides

Natural failures in rock landforms can take the form of slides, topples, falls, lateral spreads and flows (Varnes, 1978). In The Clayoquot Sound area, slides and falls are the most common with some topple failures. Failures in rock usually occur along a structural weakness as in a joint or fault. Rock slides occur when a rock mass fails along a plane of weakness parallel or sub-parallel to the ground surface. Rockfall involves a “free-fall” from a steep rock escarpment. Both involve the rapid downslope movement of rock debris forming colluvial cones (talus), blankets or veneers (overlying the previous ground surface), or irregular slide deposits (e. g., Ch). Rockfalls or rock slides are most likely to occur on weathered rocks with pronounced and/or steeply dipping joints, faults, or bedding planes. High rainfall and seismic activity are two phenomena that contribute to the incidence of landslides (Howes, 1981). Locally, frost action may promote slab failure along near-surface openings in rock.

EBA (1997) found only three rock slides (which they called rock avalanches) in the Clayoquot Sound area. The largest of these occurred in the upper Kennedy River where the deposit dammed the river forming a new lake. The EBA study also identified 55 rockfalls as shown by the presence of a fresh detachment surface and rubbly or blocky deposits downslope.

We believe that logging has little or no effect on rock slide frequency except possibly for the effect of blasting during road construction. It is conceivable that diverted drainage can increase the water loading on a particular joint or set of joints such that failure occurs. Although we have observed localized slab failure above a blasted road cut, there is no evidence that significant rock slides have resulted from road construction in the Clayoquot Sound area.

4.3 Gully Erosion

Gullies are erosional landforms created by the incision of streams into hillsides. They are produced by the progressive erosion of channels (degradation), sidewall erosion (including mass failures), and headwall retrogression. Many gullies have been formed by landslides or have been modified by landslides (mainly debris flows) that initiate on their sidewalls and/or headwalls.

By definition, gullies contain streams, but the relationship between the erosive power of those streams and the size and morphology of gullies is complex. Some gullies are relict having been formed under conditions that differ from those of today. Such relict gullies may be relatively large with small streams or streams with low erosive power. Other gullies may also contain unusually small streams, but their morphology is more closely related to landslide history rather than stream erosion.

Certain gullies in The Clayoquot Sound area have developed along large joints or faults in the bedrock. These are usually straight-line features many of which do not directly follow the fall line downslope. Joint-controlled gullies are typically in rock, and their size may not reflect the erosive power of their streams. These gullies are geologically older than gullies formed in glacial deposits.

Post-glacial gullies are the most common. These have formed in glacial deposits, mainly till, within the past 13,000 years. We suspect that much of the gully erosion occurred in early post-glacial time when vegetative cover was less dense than at present.

Gullies have an important influence on terrain stability. Terrain polygons containing gullies have a higher failure frequency than non-gullied polygons (Rollerson et al., 1998). In that study (including Clayoquot Sound), dissected terrain showed a mean landslide frequency of 0.17 landslides per ha compared to only 0.08 on uniform slopes.

Gullies contain sidewalls and headwalls, which are typically much steeper than adjacent open slopes. Most gullies also have stream flow and confined profiles; both conditions promote the development of debris flows. As noted earlier, debris flows travel further and are more likely to deliver debris to larger streams in the valley bottom than debris slides on open slopes. In general, the larger and steeper the sidewalls/headwalls (except those in rock), the greater the probability for failure. The Gully Assessment Procedure (B. C. Ministry of Forests, 1995b) recognizes four factors in its assessment of debris flow hazard: gully sidewall gradient, steepness, material, and channel gradient.

Logging on gullied terrain can have a substantial impact on both soil erosion and landslide incidence. Falling and yarding across gullies frequently damages vegetative and forest floor cover and causes disturbance of mineral soils on the sidewalls. This increases surface soil erosion and accelerates the natural delivery of sediment to the channel. If logging slash is not cleaned out, the added organic material may induce sediment wedges that may be prone to sudden downstream movement in floods. Tripp (1994) identified poor treatment of gullies as a major source of fisheries impacts in logged terrain in coastal British Columbia.

4.4 Other Processes

Other geomorphological processes include: slumps and slump/earthflows, surface erosion, piping, stream channel and bank erosion, soil creep, and windthrow.

4.4.1 Slumps and slump/earthflows

Slumps are rotational failures contrasting with shallow translational slides that are common in The Clayoquot Sound area on steep upper slopes. Many debris slides or flows may actually initiate as slumps, but due to the presence of a shallow failure plane, they rapidly convert to a translational form.

Slumps may be simple landslides with a single soil mass failing over a curved plane, or they may be complex with numerous discrete masses. Sliding may take the form of pure backward rotation around a horizontal axis, or it may be complex with a translational component over a planar surface. Slumps, in contrast to slides and debris flows, usually occur on deep, cohesive soils such as those derived from deep, silty tills or fine-textured glaciomarine or glaciolacustrine deposits.

In certain soils, the action of the slump disturbs the soil structure and causes the mass to liquefy. The resultant mass is then subject to earthflow, which together with the initiating slumping is called a slump/earthflow. These processes may involve the rapid delivery of liquefied soil downslope not commonly to a stream or river.

Most slumps are caused by the removal of toe-support in a deep cohesive soil. In nature, the most common example is the undercutting of banks by streams or rivers. Complex slumps have been a common event in post-glacial history along the major drainages although the scars remaining may be difficult to discern because of revegetation. Slumps and slump/earthflows are much less common in the Clayoquot Sound area than their translational counterparts mainly due to the relative paucity of deep cohesive soils and widespread presence of failure planes close to the surface. The EBA report did not classify slumps separately in their inventory due mainly to the difficulty in distinguishing them from debris slides and flows on air photos.

In logging, road construction may accelerate the incidence of slumping due to the removal of toe support in cutslopes. Small scale slumping of cutslopes is a common occurrence; this may lead to larger problems with drainage concentration if ditches are blocked. In some circumstances, road-induced slumping may cause large failures with significant environmental impacts; however, such events have not, to our knowledge, occurred in The Clayoquot Sound area. Clearcut logging alone probably has little effect on the process of slumping. The curved failure plane in slumps generally occurs beneath the rooting zone.

4.4.2 Surface Erosion

The erosion of soils by water or wind can play a major role in geomorphology, but in The Clayoquot Sound area, it is relegated a secondary significance after mass erosion. Many (but not all) gullies are features created by soil erosion caused by hillside channels. Surface erosion may have been highly active on the landscape in early post-glacial times, but more recently, the dense vegetation and, more importantly, the extensive forest floors have minimized soil erosion on open slopes.

The extensive forest floors in the Clayoquot Sound area are highly effective in preventing soil erosion. The porous layer of decomposing litter from the forest canopy readily allows infiltration of even the most prodigious rainfall intensities. Thus overland flow is generally uncommon – but not non-existent – under coniferous forests. Under certain circumstances, a limited amount of overland flow may occur where near-surface flow is concentrated or where the forest floor has been compacted. On certain steep forested slopes in The Clayoquot Sound area, it is not uncommon to find roots exposed above the ground surface. This reflects a lowering of the ground surface due to a combination of surface erosion and accelerated decomposition of the surface organics.

Only where the forest floor is removed does surface erosion become significant. This occurs in nature on landslide scars and windthrow pits and mounds. The former are more important in sediment movement as they are linear along the fall line and more commonly allow delivery of sediment to streams or rivers. Pits and mounds expose mineral soil to raindrop splash and overland flow but less commonly move sediment due to their discontinuous spatial distribution. Windthrow can assist in moving soil downslope over time, but rates and magnitudes have not been measured in research.

Logging increases erosion and sedimentation by exposing mineral soils. This is done by increasing the landslide rate above the natural one by road and trail construction and by soil disturbance created by yarding, skidding, or forwarding. Roads are probably the most common culprit in increasing sedimentation rates in watersheds, and researchers have found, for example, that such rates are related to the road density (Reid and Dunne, 1984).

Erosion or landslide scars, both from clearcut open slopes and from roads, also increase sedimentation rates. Most of the increase will occur in the first few months after the event then the rate of sediment transfer decreases if the scar remains inactive. Exposure of mineral soils occurs to some extent in most clearcut blocks although the overall extent is usually limited. Gully sidewalls are particularly prone to exposure.

Soils most prone to surface erosion are those in which particles are easily detached from the matrix by the impact of raindrop splash and flowing water. These soils tend to be fine to medium sands with low clay contents. Typically, poorly consolidated soils derived from glaciofluvial, coarse-textured glaciomarine and ablation tills have the highest susceptibility. Any fluvial deposit is subject to erosion and entrainment as well.

Long, steep, uniform slopes are most at risk because surface runoff will gain high velocities and with it high entraining powers. Broken slopes with plentiful surface irregularities are less prone to erosion as runoff is interrupted.

4.4.3 Piping

Piping refers to concentrated sub-surface flow through preferential pathways in the soil. Piping is perhaps the most important flow mechanism for groundwater in forested environment (e. g., Cheng, 1975). Piping in till soils may play a role in landslide initiation where it contributes to localized saturation. Piping may also contribute to the retrogression of landslide headwalls on steep slopes in the Clayoquot Sound area. This process, in expanding gully systems, has been observed in other areas (e. g., Selby, 1993).

In unconsolidated, coarse-textured sediments, piping can have different consequences. Under conditions of high groundwater flow, pipes can enlarge as particles along the walls of the pipe are entrained. The resulting expansion can trigger a massive collapse of material that, if near saturation, can create an earthflow. The authors have observed evidence for such events in Capilano Sediments in the Sechelt Peninsula, but we have not identified them in the Clayoquot Sound area. It is possible, however, that such piping failures have occurred in raised deltas or glaciofluvial deposits.

4.4.4 Soil Creep

Creep is the slow (usually imperceptible) downslope movement of soil (Selby, 1993). On steep slopes (over 31°), it is intuitive to envisage the downslope movement of surface soils over time. Soil creep investigations (e. g., Terzaghi, 1953) have usually focused on highly cohesive fine textured soils, but there is little data on creep mechanisms in forested hillslopes.

Despite this, there is little doubt that creep does occur as indicated by stem deformations on conifers. Other phenomena such as snow creep, rolling debris, avalanches, rock slides, wind, and asymmetric branching can deform conifer stems. However, soil creep produces a distinctive curvature that extends over much of the stem (unlike snow creep that produces a basal “pistol-butting”). On most steeper slopes, it is typical to observe up to 10% of trees exhibiting such curvature.

Our observations in The Clayoquot Sound area indicate that soil creep is discontinuous over time and space. It is likely that soil creep is highly localized, only occurring in a certain location when the soil is at or near saturation. Soil creep may be induced or accelerated by the action of wind sway causing displacement in the rootwad.

Soil creep may be a significant contributor to landslide initiation. The more extensive the soil creep, the greater the loss in in-situ shearing strength. We have assumed that such a relationship exists, but there is little or no field evidence to confirm the assumption.

4.4.5 Windthrow

Windthrow is the uprooting of trees by wind. Trees can also be snapped off in a related process termed windsnap. In The Clayoquot Sound area, both windthrow and, to a lesser extent, windsnap is a common event. Most even-aged or discretely two-aged stands in the Sound have developed after a windthrow event. The effects of windthrow on soil erosion have been discussed. It is possible that windthrow acts to trigger landslides. We have observed that a number of landslides have initiated from the boundary areas of logged clearcuts in The Clayoquot Sound area. These may have been induced by windthrow along the timbered edges of the opening. It seems intuitively obvious that the uprooting of trees on steep, potentially unstable ground can trigger a landslide. However, the landslide frequency is higher on logged terrain where windthrow is generally not an issue.

5.0 INTERPRETATIONS FOR TERRAIN STABILITY, SURFACE EROSION POTENTIAL, AND LANDSLIDE-INDUCED STREAM SEDIMENTATION

5.1 Terrain Stability

Each terrain polygon is assigned a terrain stability class. There are five classes, ranging from I through V. We have segregated the terrain stability ratings for clearcuts from those for roads based on the assumption that the two can, in certain terrain conditions, differ substantially.

The terrain stability classes reflect a measure of the probability that a slide will occur. Thus, it is a measure of the hazard. It does not reflect the magnitude of the slide nor does it reflect the probability that the slide will deliver debris into a stream. This is commonly referred to as the consequence or impact. Risk is a term that incorporates the product of hazard and consequence. We do not rank risk per se, but a measure of the probability that landslides will deliver debris into a stream is included in polygons rated III*, IV, or V (see section on landslide-induced stream sedimentation).

The criteria used for ranking terrain polygons for terrain stability class is summarized in Table 3. This was developed by Mr. Terry Rollerson based on the preliminary results of an extensive terrain attribute study carried out on the west coast of Vancouver Island (including Clayoquot Sound). Using these data, we hoped to provide stability rankings for terrain polygons in the most scientifically valid method possible.

Table 3. Terrain Stability Class Definition – Clayoquot Sound Terrain Stability Mapping – Proposed Criteria of Stability Classes

1. Clearcut Stability Criteria

Class	Slope	Natural Failures	Gullies	Variations
I	< 19º (36%)	A	A	W, WG, L, or LG < 5% (< 9%)
II	20º - 25º (36% - 47%) or > 46º (>85%) *	A	A	W, WG, L, or LG < 5º - 19º (9% - 34%)
III **	26º- 46º (49% - 104%)	A	A	W, WG, L, or LG 20º - 25º (36%-47%) Any concave slopes 19º - 26º (36% - 47%) Any concave slopes > 46º (> 104%)
IV	26º- 46º (49% - 104%)	A	P	W, WG, L, or LG > 26º (49%) Imperfectly to poorly drained surficial materials on slopes > 35º (>70%) (e.g., some lower slope stream escarpments)
V	Any naturally unstable slopes	P	A/P	

* Typically bedrock slopes with very little or no surficial materials present

** Any class IIIc areas > 35º and either Mb or Cb should receive a terrain stability field assessment prior to development. Any class IIIc requiring field comments (see above) should be identified by having an asterisk (e.g., IIIc*)

2. Road Stability Criteria

		Natural		

Class	Slope	Failures	Gullies	Variations
I	< 15º (<27%)	A	A/P	
II	15º - 19º (27% - 34%)	A	A/P	W, WG, L, or LG < 15º (< 27%)
III	20º - 30º (49% - 58%)	A	A/P	W, WG, L, or LG 15º - 19º (27% - 34%)
IV	31º - 40º (60% - 84%)	A	A/P	W, WG, L, or LG 20º - 30º (36% - 58%)
V	> 40º	P	A/P	W, WG, L, or LG > 31º (> 60%) Any naturally unstable slopes

Under natural failures and gullies, P stands for present and A for absent. Note that any gullied terrain greater than 26° or 49% is ranked Class IV.

In polygons where the stability differs for clearcuts and roads, both stability rankings must be used with the clearcut stability first (e. g., IVr IIIc). Where the stability class is the same for both, only one symbol is used (e. g., III). Notice that for roads, there is no parallel to the increased slope decreased stability class as in clearcuts. Many polygons between 30° and 40° may receive an IVr for road development but IIIc for clearcuts.

WG and LG are glaciomarine and glaciolacustrine sediments. W and L are marine and lacustrine sediments.

The terrain attribute study generated a large database of terrain polygons with selected attributes (e. g., surficial geology, slope, shape, drainage, etc.) and their associated failure frequency. Thus, the study allows us to identify what proportion of a certain group of terrain polygons (e. g., all polygons with slopes 35° to 37°, straight, colluvial veneers over smooth rock, on northeast aspects) have experienced landsliding.

The Mapping and Assessing Terrain Stability (MATS) guidebook (BC Ministry of Forests, 1995a) defines stability classes by landslide frequency (Table 4). For example, Class III polygons are defined as having a 6% to 30% failure frequency (regardless of polygon size).

Table 4. Relationship between Terrain Stability Class and Likelihood of Landslides after Harvesting or Road Construction

Terrain Stability Class	Likelihood of Landslide Initiation	Percentage of Polygons With One or More Landslides Following Timber Harvesting or Road Construction
I	Negligible	0%
II	Very low	0% - 5%
III	Low	6% - 30%
III*	Moderate	<30%
IV	Moderate	31% - 70%
V	High	71% - 100%

The table addresses landslides greater than 0.05 ha and sidecast road construction practices. The application of appropriate forest management practices and road construction methods should reduce the potential for landslides significantly. Some terrain types will have a different likelihood of failure for road building than for timber harvesting.

By combining the MATS stability class criteria with the failure frequencies calculated in the terrain attribute study, we can arrive at stability criteria mechanically derived for each group of polygons.

Looking at hillslope gradient alone, failure frequency is highest between 30° and 35° then decreases with both increasing and decreasing slope gradient. Thus, steeper slopes above

35°, according to this finding, have a lower failure frequency (and thus stability class) than slopes between 31° and 35°.

The use of the terrain attribute study resulted in some decisions made about stability that were not entirely consistent with our judgement. Our mappers walked many slopes between 35° and 40° with morainal or colluvial blankets, which we deemed to be potentially unstable. Outside of the Clayoquot Sound area, most of us would have typed such terrain as Class IV. For this project, we typed such polygons as Class III (with regard to clearcutting) because, according to the terrain attribute study, they have a lower failure frequency (<30%). Because we are still concerned about the stability of such polygons, we designated them with an III*, which will require an on-site geotechnical assessment prior to any development. On the terrain stability maps, III* is printed as III'.

Finally, note that slopes above 46° are ranked Class II with regard to clearcutting. The assumption is that on terrain so steep, there is little soil mantle present in which failure can occur. If particular polygons exhibit such slopes, but clearly contain a soil mantle, then they were mapped as Class III*. Many of these, if they contain soil, will already have experienced failure or gullying and by definition will be Class IV or Class V.

5.2 Surface Erosion Potential

We have used a five-class system to rank erosion potential as for terrain stability. The classes are defined in Table 5.

Table 5. Surface Erosion Potential Classification

Class[1]	Rating	Description	Management Implications
VL	Very Low	Flat or gently sloping terrain, organic soils, floodplains	Low concern for sediment production. Disturbance of streams could initiate some bank and channel erosion.
L	Low	Gentle slopes. short slopes	Erosion limited to channel and streambanks. Expect minor erosion of fines from ditch lines and disturbed soils. Exercise care not to channelize water onto more sensitive sites.
M	Moderate	Moderately steep and long slopes. Erodible sediments high in silt or fine sands.	Expect some problems with disturbed sediments. Plan additional measures to reduce sediment production where entry into stream network is a potential.
H	High	Moderately steep slopes and highly erodible sediment textures.	Water management critical. Close attention to prevention of soil erosion such as grass/legume seeding is necessary.
VH	Very High	Steep slopes with highly erodible sediments. Active surface erosion or gullies present.	Very high concern. Remedial planning to control erosion is necessary.

[1] Modified from Schwab (1993).

The criteria for evaluating the surface erosion potential are shown in Table 6. The potential is defined as the susceptibility of the soil to surface erosion if the surface has been exposed in road construction or other disturbance. It assumes that the forest floor has been removed. The rankings range from VL (very low) to VH (very high). No actual measures of soil erosion are available, although on an aerial basis, we assume that surface erosion can range from 0 m^3 to as much as 50 m^3 per ha per year. The most extreme cases of surface erosion have been associated with steep gradient ditches alongside logging roads constructed in unconsolidated glaciofluvial sands.

Table 6. Guidelines for Rating Surface Erosion Potential

The ratings in Tables A and B are for materials greater than 1 m in thickness with the exception of bedrock. For materials less than 1 m in thickness, see bedrock ratings in Table B. Except for the symbols for the surface erosion potential ratings (VL to VH), refer to Howes and Kenk (1997) for definitions of symbols used in Table 6A and 6B.

Table A: This table is based on material texture vs. Slope morphology on moderate slopes (16º to 25º). Typical moisture conditions have been accounted for in the slope morphology.

Dominant Texture Decreasing Erodibility	Typical Material	Uniform			Ridge Crest	Scarp	Dissected -V	Irregular h, u, r, m	Single Gully
		Upper	Mid	Lower					
coarse z fine s	LG, W, WG, FG	M	H	VH	M	VH	VH	M	VH
m, c	W, WG, LG	L	M	H	L	H-VH	H	L	H
coarse s, xs, gs	C, F, FG, M	L	M	H	L	H-VH	H	L	H
dzs, dsz	M	L	M	H	L	H-VH	H	L	H
sg, sr, sx	C, F, FG, M	VL	L	M	VL	M-VH	M	VL	M

Table B: Special Cases.

Material or Dominant Texture	Typical Landform	Rating
Bogs	Op, Ob	VL
a, b, x	Ck, Cb	L-M
Resistant bedrock	R	VL-L

How to Adjust the Tables for Special Circumstances:
Surface erosion potential ratings can be adjusted based on the following:
Slope Morphology:
Concave slope - bump rating up 1 grade from the equivalent uniform rating
Convex slopes - bump rating down 1 grade from the equivalent uniform rating
Soil Drainage:
For slopes with abundant seepage, bump class up 1 grade
Slope Steepness:
For slopes >26º, bump rating up 1 grade
For slopes <16º, bump rating down 1 grade
Definitions:
Concave: concave down slope and/or across slope
Convex: convex across slope and straight down slope
Slope morphology: polygon location in relation to the entire slope (i. e., ridge top to valley bottom
Uniform: slope straight in all directions

The interpretation of the table is self-explanatory. Section 1 of the table pertains to slopes between 16° and 25°. The main criteria are dominant soil texture and slope morphology. Silts and fine sands are the textures deemed most susceptible to surface erosion. This is due to the ease of particle detachment under the entraining influence of raindrop splash or running water. Both finer and coarser textures are less susceptible. Clayey soils resist detachment due to cohesive forces acting between particles. Coarser textures contain particles large enough that they are difficult to entrain. Section 2 of the table pertains to special cases, namely bogs, very coarse substrates, resistant bedrock, and materials less than 1 m thick.

We have accounted for special circumstances by adjusting the potential rating up or down by one class depending on conditions in the polygon. These include slope morphology, soil drainage, and steepness.

As indicated above, surface cover is an extremely influential factor, but the classification system assumes no such cover. This is appropriate for road construction surfaces such as fill slopes, cutbanks, ditches, or running surfaces of roads. In addition, poor deflection in logging may result in extensive exposure of mineral soil resulting from scouring by logs during yarding or pulling stumps. Although Table 5 suggests increased concern for erosion with increased rating class, a reasonable standard of care for controlling erosion is necessary in all logging operations. An area subject to concentrated seepage or runoff during high rainfall renders all exposed mineral soil highly subject to erosion. It is believed by some that the most influential factor affecting sediment production in a watershed is the level of skill and care taken in logging operations (Rice and Gradek, 1984).

5.3 Landslide-Induced Stream Sedimentation

Another interpretation shown on our maps is the landslide-induced stream sedimentation (LISS). This three class system (Table 7) is used to rate the probability that a slide initiating in any polygon will travel downslope and deliver debris to a stream, lake, or ocean identifiable on 1:20,000 scale air photos. Used together with the terrain stability class, this information gives a reasonably complete picture of the risk of logging or road building in that polygon. The LISS designation is only provided in polygons ranked Class III*, IV, or V for terrain stability.

Table 7. General Guidelines for Landslide-Induced Stream Sedimentation Classification

Class	Criteria	Interpretation
1	Downslope terrain is concave, irregular, or benchy. Downslope gradient <15º (Distance to watercourse) No air photo or field evidence of landslides entering watercourses.	Low likelihood that a landslide originating in this polygon will reach a perennial watercourse. Post-event surface erosion of the landslide scar and deposition zone will result in no or only limited stream sedimentation.
2	Downslope gradient 15º to 30º (Distance to watercourse) Limited air photo or field evidence of landslides entering watercourses.	Moderate likelihood that a landslide originating in this polygon will reach a perennial watercourse. Post-event surface erosion of the landslide scar and deposition zone will result in some additional stream sedimentation.
3	Downslope terrain is convex or uniform. Downslope gradient >30º (Distance to watercourse) Clear evidence of landslides entering watercourses is visible on air photos or in the field.	High likelihood that a landslide originating in this polygon will reach a perennial watercourse. Post-event surface erosion of the landslide scar and deposition zone will result in additional stream sedimentation.

6.0 MANAGEMENT CONCERNS AND RECOMMENDATIONS

The main objective of this exercise is to provide a planning tool to resource managers to ensure that development activities do not accelerate the natural rate of sediment movement from hillslopes to stream channels.

It must be remembered that Clayoquot Sound is a geologically active area that has a relatively high natural rate of sediment movement. Landslides occur in undisturbed forests without any human influence. Natural blowdown of trees is a natural occurrence; where it occurs in riparian corridors, it may trigger small landslides that deliver sediment directly to channels. Blockage of channel flows by windthrow trees or roots can also increase sediment yield. Stream and bank erosion also have natural rates, which in particular places and times, may also reach levels much higher than average historic ones.

While we should strive to minimize any change in the natural rate of sediment transfer, we should also be aware that it would be difficult and even unwise to attempt to reduce the rate of natural processes below their historic rate. To eliminate all landsliding would have undesirable effects. For example, a reduction in the rate of sediment transferred to streams would result in accelerated streambed degradation, possibly with the result of increased sediment delivery to valley bottom mainstems.

6.1 Road Construction

Road construction is the activity with the greatest potential to produce sediment. In The Clayoquot Sound area, as in many other areas in the coast, landslides initiating from roads have had a widespread and substantial impact on streams and fish habitat.

There are several ways to manage this impact. By far the most economical and environmentally sound way to minimize erosion and sediment production is simply to avoid building road in sensitive terrain. Our terrain/terrain stability maps provide an effective planning tool to accomplish this. In development planning, roads should as much as possible be located to avoid Class III*, IV, V, IVr, and Vr areas. In many cases, the careful location of roads to avoid unstable areas not only minimizes the risk of landsliding but commonly avoids very costly construction.

Reduction of the amount of road constructed will also greatly reduce site loss (from erosion and slope failures) on all terrain. Development plans which reduce the total length of active roads, with a judicial combination of conventional and unconventional harvesting methods (especially helicopter), will have a lower overall impact.

Where proposed roads cross terrain with potential stability problems (e. g., IIIr, IIIc*, IV, V, IVr, Vr), an on-site inspection by a qualified geoscientist or engineer is required. This investigation will assess the geological hazards and may indicate feasibility of construction. It will also determine the need for special construction methods or strategies: for example, special management of spoil, stabilization of cutslopes or fillslopes, scheduling constraints (e. g., avoid construction under conditions of high soil moisture), special blasting techniques, extra supervision, or final certification by a professional engineer. Another alternative is to plan for early retirement of the road to a permanent or semi-permanent deactivation or to call for seasonal deactivation prior to heavy fall rains.

Special attention to stream crossing structures is always justified especially in the flashy hydrologic regimes and copious streamflows found in The Clayoquot Sound area. In the past, inadequate cross-drain density, inadequately sized culverts or bridges, poor placement and poor construction of structures have caused damaging landslides. Culverts and bridges must be designed for the 100 year flood (except on temporary or seasonal roads) and must be designed not only for the passage of water but also for the passage of any future woody debris and bedload. Forest engineers should also be aware that upstream logging will probably change (if temporarily) the amount of woody debris and bedload transported by the stream.

Under the Forest Practices Code and as suggested in the Clayoquot Sound Scientific Panel for Sustainable Management, all stream courses crossing the road line must be culverted. Sizing of culverts has become rather routine, involving methods outlined in the *Forest Road Engineering Guidebook* (B. C. Ministry of Forests, 1995c). These methods provide a means of estimating the sizing to convey 100-year floods based on cross-stream area. The estimates do not always take into consideration debris and bedload.

Pipe culverts are routinely used to convey the water from small streams across roads on steep hillslopes, but in practice, they are placed at a gentle slope. Consequently, bedload may accumulate at the intake of the pipe thus reducing its capacity. The result may be a washed out culvert or diverted drainage across the road. Forest engineers must therefore be cognizant of these effects and understand where to modify the routine procedures.

Forest roads must be planned, built, monitored, and deactivated with a view to minimizing an acceleration of sediment transfer. In addition to minimizing the effect of landslide initiation, there should be plans to minimize surface erosion. The application of appropriate mixtures of grass and legume seed on exposed surfaces, particularly fillslopes and ditches near stream crossings, should be routine. Hay bales, silt fences, gravel surfacing, and hydroseeding are some of the erosion-control products that should be available to operational managers. Emergency erosion control plans should be in place so that the necessary procedures can be promptly followed if sudden changes in weather occur.

Similarly, avoid allowing subgrade construction to extend too far ahead of the finished road, and ensure that, even at the pioneering stage, stream crossing structures allow the unimpeded passage of water. End-hauled material should be carefully placed away from sensitive terrain and should be seeded to minimize soil erosion. The road surface should also be properly ballasted with gravel or crushed rock. Failure to follow any of these simple recommendations has resulted in excessive erosion and sedimentation in the past in The Clayoquot Sound area. There is no excuse for these events to occur again.

6.2 Clearcuts

Clearcut logging should have a minimal effect on soil erosion providing extensive soil exposure does not occur and provided the forest floor remains intact. Blocks should be laid out to minimize poor deflection or ground-lead yarding. Better than average deflection (or full suspension) may be necessary on certain sensitive soils. Steeply graded back-spar trails (e.g., skid-trails running up and down the fall line) will create erosion, but this can be avoided with routine water bars and trail rehabilitation. Where soil exposure occurs after logging, the application of grass and legume seed is usually advisable.

Streamside management prescriptions have now become a routine procedure as they should. On a block specific basis, these will specify how streams or gullies will be managed. Gully assessments will prescribe how to manage these active environments; prescriptions will range from the retention of large buffers to no buffer retention and “fall-and-yard-across”. The retention of buffers must be accompanied by a blowdown hazard assessment and, if necessary, prescription of treatments to reduce that hazard. In the past, too many buffers have suffered blowdown thereby negating any benefits and, in some cases, creating a more deleterious impact than if no buffer had been left.

Where buffers have not been prescribed, extra care is required for harvesting in, near, and/or across streams and gullies. Falling and yarding away is often desirable but not always feasible. Stream reaches in which such a prescription is mandatory must be clearly marked; those in which it may be acceptable to bridge leaning trees and yard across should also be identified. Two potential impacts should be recognized - damage to banks during cross-stream yarding and accumulation of logging slash in creek channels. Based on assessments of bank sensitivity and the potential for the stream to transport sediment and introduced debris, both impacts must be addressed in the streamside management prescription.

In The Clayoquot Sound area, there is an opportunity for forest management to be a showcase of excellence. We hope that with these resource inventories we will make our contribution towards that goal.

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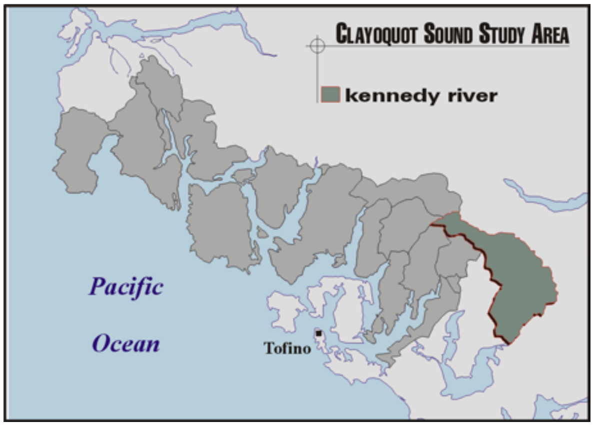


1.0 INTRODUCTION

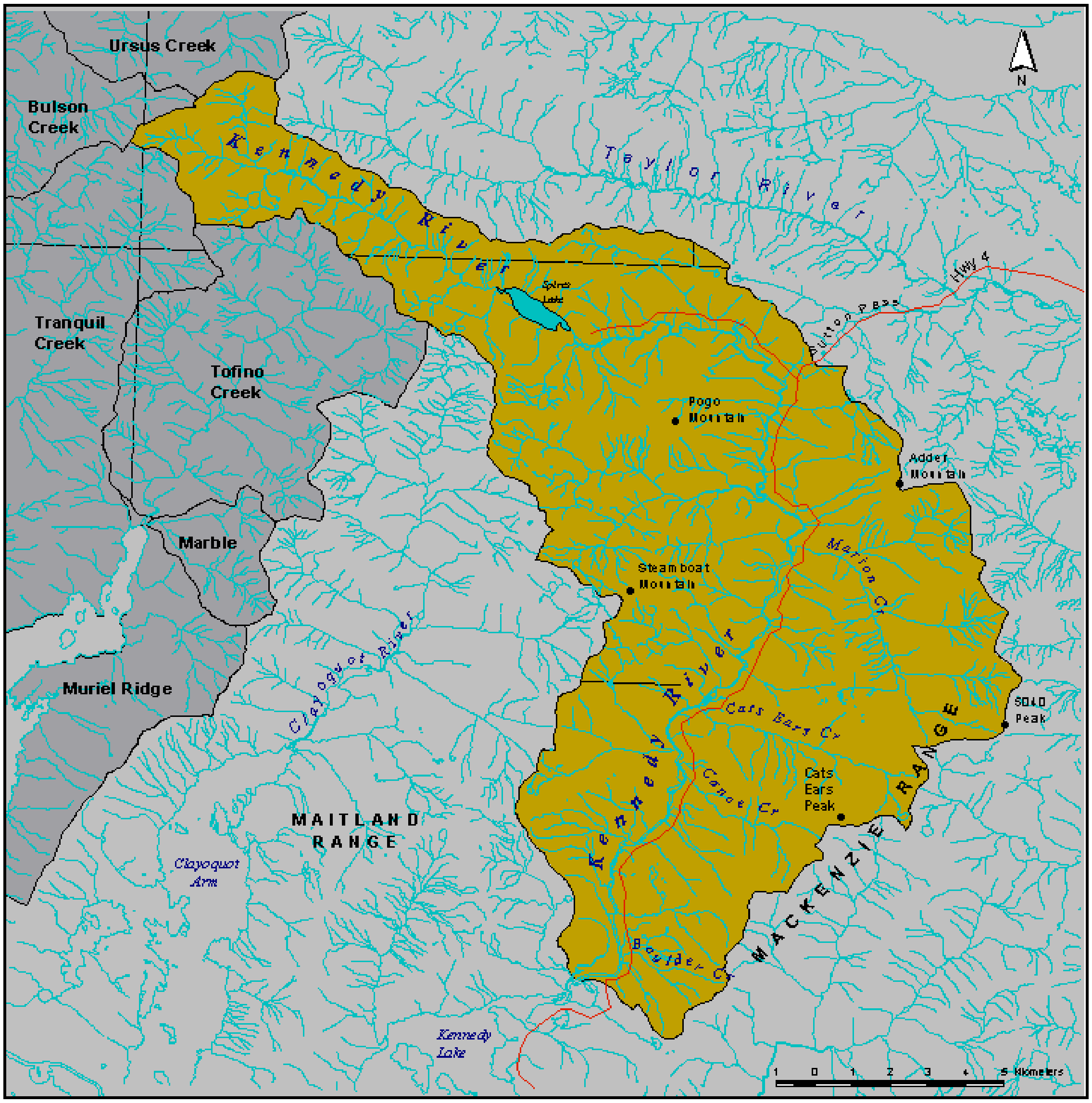
The Kennedy River study area includes the entire Kennedy River drainage upstream of Kennedy Lake. The area consists of watersheds 282, 286, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304, 306, 307, and 309 (refer to the numbered watershed map in Appendix II) for a total size of approximately 20,553 ha.

This section of the report includes a description of the Kennedy River study area, results of the fieldwork, and subsequent interpretations. General recommendations related to any further development in the area are provided.

2.0 PHYSICAL ENVIRONMENT

2.1 Location

The Kennedy River is located at the eastern extent of the Clayoquot Sound study area. The mouth of the river (where it enters Kennedy Lake to the south) is approximately 34 km east-southeast of Tofino, and the headwaters of the river are located 31 km northeast of Tofino. The mid and lower reaches of the Kennedy River are well known to many people because Highway 4, the frequently traveled highway between Port Alberni and Tofino, is located adjacent to the river for more than 20 km. The highway enters the Kennedy River drainage at Sutton Pass, the divide between the Kennedy River and Sutton Creek, a tributary of the Taylor River (see Photo 1 on following page).



Kennedy River Study Area

Photo 1

View to the north of the mid-valley of the study area. Sutton Pass is the low-elevation pass visible in the distance. Highway 4 and the Kennedy River are in the center of the photo.

The Kennedy River is a large drainage system that is adjacent to several other drainages. These include Taylor River and Ursus Creek to the north, Bulson Creek to the west, Tranquil Creek, Tofino Creek, and Clayoquot River to the southwest, Nahmint River to the east, and Effingham River and Toquart River to the southeast. The Taylor River drains into Sproat Lake west of Port Alberni, the Nahmint River drains into Alberni Inlet, and Effingham River and Toquart River both drain into Barkley Sound. Ursus Creek, Bulson Creek, Tranquil Creek, Tofino Creek, and Clayoquot River all drain into Clayoquot Sound. All of these except for Clayoquot River have been mapped as part of the multi-year terrain inventory project, and the results of that mapping and details of each area are presented reports prepared in 1997 and 1998 for Year One and Year Two portions of this Terrain Inventory project. Edge matching between the Kennedy River study area and Ursus, Bulson, Tranquil, and Tofino Creeks was necessary to create seamless, continuous, terrain and terrain stability maps of this region.

2.2 Physiography

The Kennedy River occupies a large, expansive drainage. From the headwaters to its entrance into Kennedy Lake, the river flows more than 45 km downstream. In the upper third of the drainage, the valley axis is oriented northwest/southeast. Near Sutton Pass, the river has a sharp bend and the remainder of the drainage is generally oriented north-south (Photo 2).

Photo 2

Kennedy River drainage. This view is from the southern end of the study area near the headwaters of Canoe Creek, looking at the west side of the valley. Highway 4 and the river are both visible in the valley bottom.

Elevations in the study area range from 20 m above sea level at Kennedy Lake to 1521 m a.s.l. along the narrow ridgeline between Kennedy River and Tranquil Creek.

In the upper third of the drainage, the valley is narrow and there are scattered gully systems, tributary creeks, and small alpine lakes. The headwaters consist of three small valleys that join and form the main valley stem occupied by the Kennedy River. Much of the drainage divide in the headwaters is defined by sharp aretes and prominent bedrock peaks. Steep bedrock-controlled slopes with shallow soils are common throughout this part of the study area (see Photo 3 on following page).

Photo 3

View is upstream in the Upper Kennedy River valley. Bedrock-dominated slopes are common in this part of the study area. Most of what is visible in the photo lies within the Kennedy River watershed. The photo was taken at the helicopter drop-off site adjacent to Observation Site MO-068.

Deeper deposits are restricted to the lower slopes and typically range from 2 m to 5 m. In the headwaters, there is a lateral moraine with materials greater than 20 m deep (see Photo 4 on following page). This deep deposit is unique in the area. Along its upper reaches, the Kennedy River is incised several meters in till and colluvial deposits, the river averages 8 m in width, and there is a minor floodplain in only a few areas.

Approximately 6 km west of Sutton Pass, a massive, catastrophic rockslide occurred in the early 1970s in bedrock of the Island Plutonic Suite. The scar is more than 500 m wide and nearly 500 m long, and material is continuously ravelling and failing from the scar surface (see Photo 5 on following page). The rockslide deposits blocked the Kennedy River forming Spires Lake (see Photo 6 following).

Photo 4
Large lateral moraine in the headwaters of the Kennedy River. The deposit is more than 20 m deep.

Photo 5
Large rockslide that dammed the Kennedy River resulting in the creation of Spires Lake.

Photo 6
Spires Lake

The lake is approximately 500 m wide at its widest point and over 2 km long. The flooding killed many trees, which persist as snags to this day. The lake is also known as Snag Lake.

Downstream of Spires Lake, the main valley is wider, the tributary creeks are larger, and the river is wider. At the outflow of Spires Lake, the Kennedy River is an average of 10 m wide, and at the inflow to Kennedy Lake, more than 30 km downstream, the river averages more than 25 m in width. Along these reaches, the river is incised in bedrock as well as till, fluvial, glaciofluvial, and colluvial deposits. Bedrock is commonly exposed along the mid-reaches forming rapids in places (see Photo 7 on following page).

The terrain in the lower two-thirds of the watershed is bedrock controlled with numerous outcrops and massive bluffs. Many slopes are steep with shallow soils. Gentle slopes are primarily associated with the valley and creek bottoms, and wide ridges (see Photo 8 on following page).

Photo 7

Typical bedrock reach along the mid valley. Note that the vegetation on the top of the bank appears to be growing directly on bedrock with minimal soil present.

Photo 8

View is to the north of the Lower Kennedy River valley. Bedrock outcrops are abundant in the area and are found at all elevations. All of the terrain in the photo lies within the Kennedy River watershed.

Numerous tributary creeks enter the Kennedy River from both sides of the valley along the mid and lower reaches, and these include: Mercer, Marion, Bos, Cats' Ears, Canoe, TR-17, Kerr, Boulder, and Cedar Creeks. Of these, Marion Creek and Cats' Ears Creek are large valleys that have been extensively logged over the last 50 years (Photo 9).

Photo 9

View is looking downstream in the Marion Creek valley. The Kennedy River valley is visible in the distance.

Several of the other tributary valleys are characterized by steep sidewalls, narrow valley bottoms, and extensive bedrock outcrops. Some of these slopes are subject to frequent snow avalanching that has stripped the hillside of much of the vegetation.

2.3 Hydrology

There is a moderate amount of high elevation ground in the Kennedy River drainage and as a result, snow accumulation in the winter months is abundant (see Photo 10 on following page). For this reason, snowmelt in the spring and early summer produces significantly high levels of stream discharge.

Rainfall is important to the river's hydrologic pattern in the fall and early winter months. The rainfall is primarily generated from frontal storms with orographic effects. Storms in the early fall often result in floods that are significant in transporting sediment, as these first large flows entrain much of the sediment stored in gullies and streams during the summer. Therefore, sediment load probably reaches a peak during October or November storms and declines gradually with each subsequent storm as the sediment supply in the channels diminishes.

Photo 10

The Kennedy River adjacent to Highway 4. The view is towards the northwest looking upstream. This is mid valley at an elevation of 80 m above sea level. The photo was taken on February 21, 1999.

2.4 Glacial History and Surficial Materials

The landscape in the Clayoquot Sound area was modified during the recent Pleistocene glaciations, and the Kennedy River study area is no exception to this. Refer to Section 3.4 for a detailed description of the glacial history of Clayoquot Sound. Evidence of glaciation in the Kennedy River drainage includes: prominent u-shaped valleys, razor sharp aretes (see Photo 11 on following page), glacially smoothed bedrock with glacial striations, extensive morainal deposits, glaciofluvial sediments, and glaciolacustrine sediments.

Many of the slopes in the study area are dominated by bedrock bluffs and outcrops, and the surficial material in these areas, where present, is primarily colluvium. Morainal deposits and organics occur on the upper slopes that are less steep. The lower and mid slopes and valley bottoms are blanketed by morainal deposits with fluvial and glaciofluvial sediments present in places. Colluvial deposits on the lower slopes are associated with the mouths of gullies and bedrock outcrops. A few scattered deposits of lacustrine and glaciolacustrine sediments are found in the lower valley near Kennedy Lake.

With the onset of deglaciation approximately 13,000 years ago, a redistribution of many of the glacial materials began via fluvial and mass movement processes. In general, gullies are incised in bedrock on the upper slopes (these may be pre-glacial) and in morainal, colluvial, fluvial and glaciofluvial deposits on the lower and mid slopes. Sediment is entrained and transported downstream in the gullies to the numerous creeks in the area, where most of the material is sorted and deposited as fluvial sediments. Debris slides and debris flows that initiate on the upper or mid slopes rework the entrained materials and deposit them on the lower slopes in colluvial cones and fans. This redistribution of material is ongoing throughout the area.

Photo 11
Rugged bedrock ridgelines are typical of the drainage divide between the Kennedy River and Tofino and Tranquil Creeks.

2.5 Bedrock Geology

The bedrock geology in the area is a complex of several bedrock types (refer to the bedrock geology map on the following page and the legend in Appendix III). The bedrock in the upper third of the watershed is dominated by Jurassic-aged rocks of the Island Plutonic Suite. These include granodiorite, quartz diorite, diorite, quartz monzonite, agmatite, feldspar porphyry, gabbro, and aplite (Massey et al., 1994).

Rocks of the Island Plutonic Suite also dominate the bedrock in the remainder of the study area, but there are pockets of other formations including the Parson Bay Formation (Triassic age), Quatsino Formation (Triassic age), and Bonanza Group (Jurrassic age). In most places within the study area, the Parson Bay and Quatsino Formations are similar and have been mapped by Massey et al. as one unit. These formations are sedimentary rocks and include argillite, siltstone, shale, limestone, sandstone, and breccia. Rocks of the Bonanza Group include basalt, andesite, dacite, rhyolite, tuff, breccia sandstone, argillite, conglomerate, and minor occurrences of limestone.

Insert Bedrock Geology Map

Massive outcrops of limestone dominate the landscape on the upper western slopes of the study area including Pogo Peak and Steamboat Mountain. The limestone has chemically weathered into razor sharp fluting and rills (Photo 12) and may contain karst features such as caves and sinkholes.

Photo 12
Rills and flutes are typical erosional features of the limestone found in the region.

Some of the rocks in the study area are flat lying, folded, well bedded, well jointed (Photo 13), and may act as slip planes upon which slope failures initiate.

Photo 13
Well jointed, highly fractured bedrock visible in a road cut.

The massive rockslide that resulted in the creation of Spires Lake (described in Section 2.2) occurred in rocks of the Island Plutonic Suite. In several places within the drainage area, there is evidence that a glacier eroded bedrock into a smooth, polished surface, a common characteristic in glacial terrain (see Photo 14 on following page). Some of these outcrops are more than 30 m tall and continuous, prominent grooves. At a smaller scale, glacial striations are visible on the bedrock surface where small rocks entrained in ice were in contact with the rock as the ice moved.

Photo 14
Glacially polished bedrock.
A large groove is prominent on the lower portions and numerous fine glacial striations are visible across the surface, oriented parallel to the ice flow direction.

Major and minor faults are common in the Kennedy River drainage. Several of the major valleys, including Upper Kennedy River, Marion Creek, and Cats' Ears Creek, follow these zones of weakness in the bedrock.

3.0 METHODS

3.1 Previous Work

Although the Kennedy River watershed has been extensively logged over the last fifty years, terrain stability mapping had not been done for this area prior to this project.

3.2 Fieldwork

Fieldwork was completed in nine days in September 1998. At this time, four teams lead by Brad Harrold, Jason Hindson, Marian Oden, and Pamela Williams completed twenty foot traverses and sixteen combination foot-truck traverses (see terrain stability traverse map following). Tofino was used as the base camp, and access to the study area was by two four-wheel drive trucks and by helicopter. Four-wheel drive was needed to access some of the semi-deactivated logging roads. Numerous openings were available for helicopter landing spots including large bedrock outcrops, river gravel bars, and roads.

On four of the field days, all four teams accessed the area by helicopter and conducted lengthy foot traverses. On three of the field days, all four teams traveled by truck to the area with two teams per truck. On these days, one team drove an extensive network of roads looking at road cuts and doing short foot traverses adjacent to the road, while the other team was dropped off and conducted a lengthy foot traverse in non-roaded areas. Inclement weather restricted helicopter travel one day, and the back-up plan of truck access was used. Morning fog was a problem on the other two field days, and on these days, two teams traveled to the study area by truck while the other two teams waited in Tofino for the fog to lift. When it finally did, shortened foot traverses were conducted in remote areas.

Photo 15

Typical bedrock slope that is common throughout the study area and that was considered inaccessible for a ground traverse. These types of slopes were field checked from the air or from across a valley.

Insert Traverse Map

The traverses were evenly distributed throughout the area with several traverses in the main valley stem and several in the larger tributary valleys. Sampling intensity was low for terrain with steep bedrock slopes (see Photo 15 on page 48) and for terrain dissected by deep, closely spaced, bedrock ravines. Some landing spots were available for these areas, but surrounding bluffs and numerous bedrock ravines would have made traveling through these areas treacherous. In addition, slopes frequently subject to snow avalanches with minimal soil and/or considered to be inoperable timber were not traversed for similar reasons. Marian Oden viewed areas considered inaccessible (e.g., lack of landing spots, dangerous terrain) or inoperable during a helicopter overview flight on September 14, 1998.

Sampling intensity was higher in all other areas and was highest on roaded terrain. The initiation zones of many of the natural debris slides and debris flows were ground checked. After close inspection of the air photos with the completion of each traverse, the terrain observed in the field was considered to be representative of the surrounding terrain.

3.3 Air Photo Correction

With the completion of the fieldwork, terrain polygon labels and line placement were corrected where necessary based on the field observations. Terrain polygon lines were added, modified, or deleted, and each polygon label was amended using standard British Columbia terrain mapping conventions (RIC, 1996; Howes and Kenk, 1997). The air photos were reviewed in-house by Gordon Butt, *P.Geo.,* and then correlated by Steve Chatwin, *P.Geo.* (FRBC terrain mapping correlator) for external quality control.

3.4 Reliability

The terrain maps are presented at a scale of 1:20,000 and are based on air photos with an average scale of 1:17,000 at sea level. The air photo scale is suitable for the map scale produced as polygon size and density represents the complexity of the landscape.

There are approximately 1,040 terrain polygons in the Kennedy River study area excluding lakes. During the fieldwork, 410 polygons were ground checked with detailed plots (39% of the study area), and 197 polygons were visually checked (19% of the study area). Visual checks include 116 from the ground (i.e., a bedrock outcrop or colluvial cone seen across the valley) and 81 from the air (colluvial cones and bedrock).

This terrain stability mapping is based on field sampling of 607 polygons for a total sampling of 58% of the Kennedy River drainage. With 410 polygons ground checked in an area that is 20,553 ha, there is an average of 2 ground checks per 100 ha. Both of these values (58% and 2 ground checks per 100 ha) are within the range for Terrain Survey Intensity Level B.

The mapping of subsurface materials is based on experience in air photo interpretation, field observations, and knowledge of hillslope processes. Many of the slopes in the study area are covered with dense vegetation and are mantled by a complex of materials, both of which affect the reliability of the mapping not field checked. Identification of the subsurface materials, along with deposit depth and material distribution, was based on evidence on the surface, shallow soil pits, soils exposed by blowdown, stream and river banks, gully sidewalls, and landslide scars. No subsurface drilling or boring was done.

This study area has also been mapped for terrestrial ecosystems. Detailed field checks for that type of mapping include gathering information on the surficial material type and texture within a given terrestrial ecosystem polygon. For this area, dozens of field cards were assessed by Marian Oden, and any information pertinent to terrain stability mapping (and considered reliable depending on the terrain knowledge of the terrestrial ecosystem mapper) was recorded separately. At that point, information from 64 terrestrial ecosystem field checks was considered to be useful. With this information, the terrestrial ecosystem air photos were reviewed in conjunction with the terrain mapping air photos. Polygons that did not have a detailed terrain stability field check but did have a detailed terrestrial ecosystem field check were identified and recorded on the terrain mapping air photos. This information was then incorporated in the terrain label. The result of this exercise was that the material type and texture were positively identified for approximately 20 additional polygons not checked during the terrain stability mapping fieldwork.

4.0 SURFICIAL GEOLOGY

In general, the surficial materials in the area are deposited as a blanket (greater than 1 m) on the lower and mid slopes and taper to a veneer (less than 1 m) on the upper slopes. Many of the bedrock-controlled slopes lack any surficial material or are covered by only a thin veneer (less than 0.25 m) of mineral or organic soil. The deepest deposits are associated with a lateral moraine in the upper valley and the valley bottom deposits of till, fluvial and glaciofluvial sediments, and lacustrine and glaciolacustrine sediments. The morainal deposits are estimated to be greater than 20 m in depth, and the other deposits are likely to range in depth from 5 m to 15 m. The surface expression of these deeper deposits reflects the nature of the material rather than the profile of the underlying bedrock.

Many of the polygons are a complex of more than one type of material or a combination of bedrock and one or more materials. Terrain labels can consist of one, two, or three materials. Labels with one or two materials are common in the Kennedy River study area and labels with three materials are less common.

4.1 Colluvium (C)

Colluvium is the most common surficial material in the study area and has been mapped in more than 680 polygons or more than 50% of the terrain. There are three distinct types of colluvial deposits in the area, which are distinguished by the source and depositional environment. A colluvial veneer (Cv) or blanket (Cb) is common on the moderately steep to steep mid and upper slopes. These slopes are typically bedrock controlled, and the colluvium is a result of eroded bedrock ravelling or falling downslope and weathering into a clast-rich mineral soil. The matrix texture of this material is commonly a silty sand (zs), and rubble-sized clasts (angular particles 2 mm to 256 mm) occupy 50% to 90% of the material volume. These soils are unconsolidated, highly permeable, and are often complexed with a morainal veneer or blanket (e.g., Cv/Mv).

There are a few scattered colluvial cones (Cc) in the area located at the base of bedrock bluffs and outcrops (see Photo 16 on following page). These terrain features are comprised of rubble (r), blocks (a), or a combination of the two clast sizes (x). Coarse fragments occupy approximately 70% to 100% of the material volume, and fine sediments, where present, comprise an interstitial sandy or silty sandy matrix. These deposits are unconsolidated and highly permeable, and the depth of the material is estimated to range from 2 m to greater than 5 m on the lower end of the cone.

The third type of colluvial deposit is a product of rapid mass movements. Some of the hillslopes in the Kennedy River study area are naturally unstable and have been subject to slope failures in the past (e.g., debris slide, debris flow). The deposition zones of these events are colluvial cones or fans (Cf) formed by the chronic supply of material from mass movements interspersed with fluvial deposition (see Photo 16 on following page). The deposits are poorly sorted and are comprised of a mixture of fine and coarse fragments ranging in size from sand, silt, and clay to blocks and boulders. The shape of the coarse fragments ranges from angular to rounded. These deposits are common at the mouths or along the lower reaches of gullies and creeks. Those fans that are derived predominantly from colluvial processes are labeled Cf and those that are derived predominantly from fluvial processes (but may include a lesser amount of colluvium) are labeled Ff. The material is unconsolidated and fairly permeable, and the depth of the deposits is estimated to range from 2 m to greater than 5 m.

Photo 16

Large colluvial cone at the base of a deep bedrock gully.
Material is continuously supplied to the cone from the gully.

4.2 Weathered Bedrock (D)

Highly fractured and jointed bedrock is present along ridge tops and on some of the numerous bedrock hummocks throughout the study area. The bedrock has weathered and has not been removed by any geomorphic agent (e.g., water, gravity, or wind). This material is not common but is thick enough within a polygon (less than 1 m deep) for identification. The material typically consists of unconsolidated rubble or blocks and is well drained.

4.3 Fluvial (F)

Fluvial deposits are common along the length of the Kennedy River and in the valley bottoms of several of the larger tributary creeks. There are minimal fluvial deposits in the smaller valleys. In the mid and lower reaches of the main valleys, there are well developed floodplains (Fp) consisting primarily of sandy gravels including boulders (see Photo 17 on following page). In general, coarser sediments are in the upper valleys and the average clast size decreases downstream. The exception to this is at the confluences with the tributaries, large gullies, and creeks. These side valleys supply sediment continuously, and those that are subject to debris flows periodically supply a large volume of sediment of all sizes. Since deglaciation, the creeks and rivers have eroded the glacial sediments in the upper valleys and deposited these in the mid and lower valleys, burying other glacial deposits. The fluvial sediments are highly permeable, and the depth of most of the deposits is estimated to range from 2 m to greater than 5 m.

Photo 17
Typical bank of the Kennedy River composed of fluvial sediments.

Photo 18
Fluvial deposit greater than 5 m deep. It is an erosional slope present near the confluence of the Kennedy River and a small tributary. This photo was taken at Observation Site JH-067.

Within the floodplains, there are sections that periodically flood and a significant amount of sediment is transported downstream. These deposits are considered to be active (FAp). In places, the river erosion has resulted in oversteepened banks (Fs, Fsk) that are likely to be susceptible to failure if disturbed. Many polygons in the valley bottom are a combination of fluvial and morainal materials (e.g., Mj/Fj, Fb/Mb) as the two materials grade into one another with indistinct boundaries.

4.4 Glaciofluvial (FG)

Glaciofluvial sediments in this area were deposited by meltwater during deglaciation. There are several deposits in the Kennedy River study area. These deposits are primarily moderately well to well sorted sandy gravels, and in one exposure, lenses of fine sands and silts were observed. The deposits are estimated to be 5 m to 20 m deep and are moderately well to well drained.

The majority of the glaciofluvial deposits within the study area are restricted to the mid reaches of Marion Creek and the mid to lower reaches of Kennedy River. A massive deposit at the confluence of the Kennedy River and Cats' Ears Creek is presently used as a gravel pit by the B. C. Ministry of Transportation and Highways (Photo 19).

Photo 19

Deep glaciofluvial deposits on the east side of Highway 4 used as a gravel pit by the Ministry of Transportation and Highways. This photo was taken at Observation Site JH-068.

In places, post-glacial incision through the deposits has resulted in oversteepened banks (FGs, FGk) that are susceptible to failure and chronic ravelling. In several places, the glaciofluvial deposits are complexed with till deposits (e.g., FGpb/Mu).

Minor deposits of glaciofluvial sediments were mapped in the bottom of an upper basin in the southern end of the study area. The deposition of these sediments above the main valley bottom likely occurred during a period of deglaciation. The bottom of the basin had a gentle enough slope to promote the deposition of outwash materials.

4.5 Lacustrine (L)

Lacustrine sediments are not common in the Kennedy River study area. These lake sediments have been mapped in only three polygons, and all three are located adjacent to the river's entrance into Kennedy Lake. The polygons are immediately upstream of this large lake, and it is likely that the level of the lake was higher in the past and lacustrine sediments were deposited in areas that are only slightly higher in elevation than the current lake level.

The material is characterized by visible horizontal bedding planes of fine sands and silts. The average depth of the material is greater than 5 m and may be as deep as 15 m. The material is imperfectly to moderately well drained. In all three polygons, the sediments are a minor component within a large polygon composed of fluvial materials with a terrain label of sgFp//zsLp. In these polygons the terrain is gently sloping with a gradient of less than 5º.

4.6 Glaciolacustrine (LG)

Glaciolacustrine sediments are not common in the Kennedy River study area. These lake sediments associated with glacial lakes have been mapped in only four polygons, all of which are located adjacent to the lower reaches of the river. The sediments were likely deposited along the shoreline of glacial lakes 1 km and 5 km upstream of the present day inflow of the Kennedy River into Kennedy Lake. Glacial lakes in these areas may have been a result of the temporary damming of the Kennedy River by ice flowing out of one or two moderate sized tributary valleys downstream of the deposits. In this case, the sediments would be considered to be glaciolacustrine. Alternatively, it is possible that the level of Kennedy Lake has been significantly higher in the past than its present day level, in which case, the sediments would be considered to be lacustrine. For either classification, the material characteristics, properties, and behaviors are similar. The material is characterized by visible bedding planes of clay, silt, and fine sand (Photos 20 and 21).

Photo 20
Road cut that has exposed glaciolacustrine deposits overlying bedrock. Bedding planes are evident. This photo was taken at Observation Site PW-030.

Photo 21
Close-up view of an unweathered face of glaciolacustrine sediments. This photo was taken at Observation Site PW-030. Red knife handle is approximately10 cm long.

The average depth of the material is greater than 3 m and may be as deep as 15 m. The material is imperfectly to moderately well drained. In all four polygons, the glaciolacustrine sediments are complexed with other materials. Two of the polygons are complexed with fluvial deposits (e.g., sgFp/cszLGp) and two are complexed with colluvium (e.g., sLGpj//Cf).

4.7 Till (M)

Morainal material, or till, is common throughout the study area, and it covers nearly 50% of the terrain. It is generally absent on the steeper slopes (greater than 35°) and blankets (Mb) the lower and mid slopes. Deeper deposits (Mj, Ma) are present primarily in the valley bottoms and are dissected by major and minor creeks, and by the Kennedy River. In places the stream erosion has resulted in oversteepened banks (Ms) that may be susceptible to failure if disturbed. As described in the Physiography section of this study area section, there is a large lateral moraine in the headwaters of the drainage (see Photo 22 on following page). The material is fairly well consolidated and coarse fragments occupy 60% to 80% of the material volume (see Photo 23 on following page). The surface expression of the thinner deposits (Mx, Mv, Mb) is a reflection of the profile of the underlying bedrock. Much of the terrain at higher elevations is bedrock controlled with numerous outcrops and bedrock hummocks. The till deposits in these areas typically mantle (Mw) the underlying irregular bedrock, with a till veneer (less than 1 m deep) on the steeper slopes adjacent to a deep pocket (1-3 m deep) of till in the troughs. The surface expression coincides with the irregularity of the bedrock.

Photo 22

Large lateral moraine present in the headwaters of the Kennedy River.
The erosional slope was created by the undercutting action of an adjacent creek.
This photo was taken at Observation Site MO-121.

Photo 23

Close-up view of the coarse fragment content of the lateral moraine at Observation Site MO-121.

Photo 24

Weathered zone of till overlying unweathered till. This photo was taken at Observation Site PW-011.

Since the morainal material was deposited during glaciation, the upper meter has weathered (Photo 24).

The weathered till has a sandy (s), silty sandy (zs) or sandy silty (sz) matrix texture and is fairly permeable. The unweathered material typically has a silty sandy texture and is generally highly consolidated and impermeable. The coarse fragments in both the weathered and unweathered zones are variable in size, and occupy 30% to 80% of the material volume. The clast roundness ranges from sub-angular to round.

4.8 Organic (O)

There are two types of organic soil identified in the Kennedy River study area. One type is associated with small bogs and seepage areas. The areas are imperfectly to poorly drained and typically the material has accumulated over another surficial material (e.g. till). There are very few of these deposits in the area.

The other type of organic soil is an accumulation of leaf litter, twigs, and branches. Also termed ‘folisols’, these soils are a very thin (x) or thin veneer (v) directly over bedrock. These soils can support the growth of large trees, and in the study area, they occur on moderately steep to steep, bedrock slopes, typically free of other surficial materials (Photo 25).

Photo 25
Western redcedar growing on bedrock with minimal soil present on the growing surface.

They are complexed with bedrock and common terrain labels are Rs/Ox, Rh/Ox, and Rs/Ov. The material is well drained.

5.0 GEOMORPHOLOGICAL PROCESSES

5.1 Snow Avalanches (-A)

There is a significant amount of high-elevation terrain and terrain above treeline in the study area, and as a result, snow avalanches are common in the study area affecting approximately 25% of the terrain. Several large polygons in the central western portion of the drainage are frequently subject to avalanches and entire hillsides are dissected by numerous avalanche tracks (Photo 26).

Photo 26

South-facing hillslope of Pogo Peak (elevation 1,490 m a.s.l.) in a large tributary valley of the Kennedy River. The numerous lineations down the slope are snow avalanche tracks. The Kennedy River valley is visible in the distance.

The geomorphological process label is included in the polygons where the avalanches are triggered as well as the downslope polygons that are affected by the events. Snow avalanches play an important role in transporting entrained debris to the valley bottom.

5.2 Braiding Channel (-B)

The Kennedy River is large and dynamic, and the majority of the river is a single well defined channel. However, in the headwaters, the channel has split into two channels and flows around a small island composed of coarse fluvial and colluvial sediment. Downstream of the island, the two channels join into one and remain as such for numerous kilometers. Although this divergence and convergence is present for only approximately 450 m, it is considered to be a braiding channel.

5.3 Irregularly Sinuous Channel (-I)

The Kennedy River and several of the tributary creeks in the study area are large and transport a significant volume of sediment. For almost its entire length, the Kennedy River has an irregularly sinuous channel with a single, well defined channel. The mid and upper reaches of Marion Creek (Photo 27) and of Cats' Ears Creek have similar characteristics to the Kennedy River but at a smaller magnitude.

Photo 27
Typical reach and gravel bar of Marion Creek.
This photo was taken at Observation Site JH-053.

Along these creeks and river, the average channel gradient is less than 15°. These reaches consist primarily of fluvial deposits. There are numerous large gravel bars (Photo 28), back channels, and side channels (Photo 29) along the Kennedy River, and the river has an active floodplain 50 m to 500 m wide.

Photo 28

Large gravel bar upstream of Spires Lake along the upper reaches of the Kennedy River.

Photo 29

One of several side channels along the upper reaches of the Kennedy River (Observation Site MO-082). This side channel is more than 40 m from the main channel. Although the channel was inactive when the photo was taken (September 12, 1998), there is evidence that a significant volume of water flows through this side channel during periods of high discharge of the main river channel.

For a majority of the remaining reaches downstream, the river and creeks have characteristics of a gully, with a moderately steep channel gradient (15°-30°), well defined sidewalls at least several meters high, and no floodplain. Along several reaches, the Kennedy River is incised in bedrock with a moderately steep channel gradient.

5.4 Anastamosing Channel (-J)

As described in previous sections, the Kennedy River has an irregular single channel for the majority of its length. In the headwaters, one polygon is delineated around the upper reaches of the river where several channels exist. The area is immediately downstream of the confluence of two of the three valleys that comprise the headwaters, and at least four definable channels are present. Upstream of the confluence, both valleys have excessively steep bedrock channels, and at the confluence the channels change from a gradient steeper than 30º to a gradient less than 10º. The channels converge and diverge around small islands within the polygon. These conditions exist for approximately 300 m, and immediately downstream of these reaches, the channels converge into a single channel with large gravel bars and an extensive floodplain.

5.5 Surface Seepage (-L)

Areas of surface seepage are scattered around the study area. Materials affected by these imperfectly to moderately well drained conditions include till, colluvium, and organics. Many of these areas support shrubs and deciduous trees including devil's club (*Oplopanax horridus*) and skunk cabbage (*Lysichiton americanum*), and the slope gradient ranges from gentle to steep. These areas are often associated with avalanche tracks but are not restricted to the tracks. In most places, the poor drainage is a result of the presence of fine particles (silt and clay) in the matrix of the material. These areas may be more susceptible to mass movements than well drained materials or comparable slopes.

5.6 Rockfall (-R"b) and Rockslides (-R"r)

Rockfall is a common type of rapid mass movement that occurs throughout the study area (Photo 30 on following page). Much of the terrain is bedrock controlled with minimal surficial materials, and much of the bedrock in the area is highly fractured and jointed. Erosion from bluffs and along gully sidewalls is common. Rockfall is initiated from approximately 8% of the slopes (or 1,712 ha) within the study area. The average rockfall event is small and travels a short distance. This is evident by the fact that only six polygons (covering an area of 411 hectares) downslope of the initiation of the events are affected by rockfall.

Much of the rockfall occurs within gully systems where the material accumulates in the channel and is eventually transported downstream during episodes of high discharge. There are only a few areas where the material accumulates at the base of a bedrock outcrop as a talus cone or apron.

Photo 30
One of many areas subject to rockfall in the study area.

Rockslides are less common than rockfall in the area. The distinction between the two processes is that rockfall involves falling, bouncing, and rolling of dislodged bedrock pieces, and rockslides involve the sliding of the pieces. The only terrain subject to a rockslide is the large rockslide that dammed the Kennedy River and created Spires Lake, as described in a previous section. This massive bedrock failure was likely a combination of falling and sliding, and the terrain label indicates that both processes are considered important (i.e., Rs-R”br). The scar is approximately 500 m wide and 500 m long. The deposit is hummocky and is composed of a jumble of coarse fragments ranging in size from rubble to huge boulders.

For both types of events, the geomorphological process label is included in the polygons where the failures were triggered, as well as the downslope polygons that were affected by them.

5.7 Debris Flows (-R”d), Debris Slides (-R”s), and Slumps (-R”u)

Debris flows, debris slides, and slumps are scattered throughout the area and affect more than 10% of the terrain. Debris flows have initiated in polygons covering approximately 580 ha, and debris slides have initiated in polygons covering 920 ha. There are only a handful of slumps identified in the study area, and these polygons delineate only 21 hectares. Debris flows usually travel longer distances downslope than any other type of slope failure. This is evident by the fact that debris flows have affected downslope polygons equalling 691 ha, while debris slides have affected only 170 ha, and slumps have remained within the initiation polygon.

Several of the slope failures (both naturally occurring and logging induced) have directly deposited material in sensitive fish-bearing creeks and rivers, while many have indirectly contributed sediment to these watercourses. A majority of the slope failures occurred in shallow soils and have scoured the transport zone to bedrock. Natural rehabilitation of these bedrock tracks will be a lengthy process.

Much of the terrain that is subject to these types of rapid mass movements is subject to more than one process. Many of the terrain labels are a complex of two or three processes, particularly in gullied terrain, where a distinction between a slide and a flow is sometimes difficult to identify. Within smaller gullies, it is sometimes difficult to determine after the fact if the surficial material slid down the gully or if it was saturated and flowed downstream. Furthermore, most debris flows are triggered by debris slides so it is appropriate to include the initiation of both types of processes within a given gully system subject to a debris flow. Where the mass movement transformed from a debris slide to a debris flow is not always easily identified, particularly for those areas with air photo interpretation only. As a result, the label for a number of the polygons subject to rapid mass movements has a complex of subclasses.

Typical initiation zones for natural failures include steep bedrock slopes with veneers of colluvium or till, or gully sidewalls composed of deep till deposits or colluvium undercut by fluvial action. Gully sidewall failures are more common than open-slope failures. Debris slides or slumps within gully systems commonly deposit in the channel and are later transported downstream. The volume of most of the debris slides is estimated to range from 50 m^3 to 1000 m^3. The volume of the debris slumps is estimated to be less than 50 m^3.

The majority of the naturally occurring debris flows in the study area have initiated on mid or upper slopes in till or colluvium and quickly channelized into steep gullies. Many of the larger gully systems are inherently unstable and debris flows occur frequently (on a geologic time scale), flushing out any material that may have accumulated between events. The volume of the debris flows is estimated to range from 1000 m^3 to 10,000 m^3, depending on several factors including distance traveled to the deposition zone and the amount of material entrained in the transport zone.

Much of the study area has been extensively logged over the last thirty to fifty years and there are several small slope failures related to pre-Forest Practices Code logging activities. Several of the logging-related slope failures are in Marion Creek. A few of the failures in the study area initiated from roads and are a result of poor road construction techniques and poor water management. Others are open slope failures and are likely a result of root-strength loss related to tree removal. In one of these areas, permanent road deactivation was being done at the time the fieldwork was done for this project. The main objective of this work is to stabilize or eliminate fill slopes and any oversteepened road material. In comparison to other watersheds in the Clayoquot Sound area, logging of the slopes within the Kennedy River study area have not induced extensive hillslope failures.

For debris flows, slides, and slumps, the geomorphological process label is included in the polygons where the slope failure was triggered (e.g., -R"s) as well as the downslope polygons that were affected by the event (e.g., -Rs). In most places, an on-site symbol on the map is used to delineate the extent of the failure.

In order to distinguish between natural slope failures and logging-induced failures, an additional character or subtype was created for this project and added to the terrain symbol for the initiation of a rapid mass movement (-R"). For a road-related landslide, '1' was added to the symbol (e.g., -R1"s), for clearcut-related failures '2' was added (e.g., -R2"s), and if there are slides within the polygon that initiated from both roads and open slopes within a clearcut, the subtype '3' was added (e.g., -R3"s). If there is no number, the slope failure occurred naturally. This additional symbology is used only for the polygon containing the initiation zone.

5.8 Gully Erosion (-V)

Gullies are a significant conduit for transporting material downslope. The terrain in much of the study area is bedrock controlled with shallow surficial materials present. As a result, the majority of the gullies are incised in bedrock with a thin veneer or shallow blanket of material on the upper sidewalls. In some cases, short reaches are incised in bedrock less than 1 m, and immediately downstream, the channel is incised more than 3 m (Photo 31).

Photo 31
Bedrock-controlled creek.
The channel and sidewalls are composed of bedrock and in this reach, there are minimal surficial materials. The channel profile is stepped and there are numerous short waterfalls.
Immediately downstream of this location, the channel gradient is steeper and there is a gully incised more than 3 m in bedrock and colluvium.
This photo was taken at Observation Site JH-087.

In general, only the lower reaches of gullies are incised in surficial materials deeper than 2 m.

There are numerous gullies throughout the study area (approximately 19% of the terrain). Many of the larger gullies are deep bedrock ravines along fault lines that are incised more than 50 m (Photo 32 following).

Photo 32
Hillslope dissected by deep gullies incised in bedrock.
This type of terrain is common in the study area.

These gullies are susceptible to continuous rockfall and debris slides. There are many gullies dissecting long, continuous slopes throughout the area, and these are typically incised less than 15 m. These are susceptible to debris slides and debris flows, and there is evidence that many of these gullies are frequently subject to debris flows.

6.0 INTERPRETATIONS FOR TERRAIN STABILITY, SURFACE EROSION POTENTIAL, AND LANDSLIDE-INDUCED STREAM SEDIMENTATION

6.1 Terrain Stability

Approximately 50% of the terrain in the study area is considered to be potentially unstable or unstable with a terrain stability Class of III*, IV, or V. This is likely a result of the dominance of steep bedrock throughout the region. This terrain is not restricted to any one type of surficial material, drainage, slope morphology or position, and those polygons that are classified as terrain stability Class III*, IV, or V include a wide variety of attributes and are present throughout the Kennedy River study area.

Terrain stability was assessed with regard to both road construction and clearcut harvesting, and if the stability class differs between the two activities, two classes are presented (see Section 5.1 for details). Subscript ‘r’ is used for the stability class related to road construction and subscript ‘c’ is used for the stability class related to clearcut harvesting (e.g., IVr, IIIc). In the Kennedy River study area, more than half (approximately 57%) of the terrain in the area has separate stability classes for road construction and for clearcut harvesting. Within the 57% of the terrain that has a single stability class, 22% is considered to be Class IV and 23% is rated as Class V.

With regard to road construction, 30% of the terrain is rated Class IVr, and 5% is rated Class Vr. With regard to clearcut harvesting, 2% of the terrain is rated Class IVc and none is rated Class Vc. Approximately 17% of the terrain is rated Class III*. The terrain in these polygons is rated Class III according to the stability criteria (closely linked to slope gradient), but because of the presence of deeper surficial materials or of imperfect or poor drainage, a more conservative stability rating was appropriate. As for Class IV and V, a geotechnical assessment conducted by a terrain specialist is required prior to any development of terrain classified as Class III*. On the terrain stability maps, III* is printed as III’.

6.2 Surface Erosion Potential

The rating of surface erosion potential is based on surficial material texture, slope gradient, slope morphology and position. More than 65% of the terrain has a low (L) or moderate (M) rating. Approximately 11% of the terrain has a high (H) or very high (VH) rating. These ratings represent a range of terrain attributes. Only two polygons have a VH rating. These polygons include silty, sandy till and sandy glaciofluvial sediments. In both cases, the materials comprise oversteepened erosional slopes. The majority of these areas are rated terrain stability Class III*, IV, or V.

Approximately 23% of the terrain has a very low (VL) rating. This is an indication of the bedrock-dominated landscape typical of the Kennedy River drainage. These areas are associated with either bedrock slopes that may contain a very thin or thin veneer of coarse material in parts of the polygon or organic plains with a slope gradient of less than 5°.

6.3 Landslide-Induced Stream Sedimentation

All polygons with a terrain stability Class of III*, IV, or V (50% of the terrain) were assigned a rating for landslide-induced stream sedimentation (LISS). Polygons with terrain stability ratings of Class I, II, or III were not assigned a value of LISS. This interpretation is a general guideline for the likelihood that a landslide initiated in a given polygon will deliver sediment to a downslope stream, lake, or ocean. Of the unstable and potentially unstable terrain, 54% has a high likelihood (Class 3) of delivering a landslide to a watercourse, 28% has a moderate likelihood (Class 2), and 18% has a low likelihood (Class 1). The relatively high number for LISS Class 3 is a reflection of the fact that much of the unstable and potentially unstable terrain is within gully systems and because the study area has an extensive network of watercourses. In polygons that include areas with different LISS ratings, the more conservative rating (higher number) is assigned.

7.0 MANAGEMENT CONCERNS AND RECOMMENDATIONS

Approximately 50% of the terrain in the Kennedy River study area is considered to be unstable or potentially unstable. Much of this terrain is bedrock controlled and is characterized by steep slopes with shallow, well drained soils. For these polygons, the terrain has been given a hazardous rating partly because of the steep slope gradient. The most sensitive terrain units in the area are the erosional slopes in unconsolidated material such as ablation till and glaciofluvial sediments, the headwalls and steep sidewalls of the numerous creeks and gullies, and steep, uniform slopes scattered throughout the study area. Because of the fine texture of the material, lacustrine and glaciolacustrine sediments can be subject to slope failures. Where they do occur and where they have been conventionally logged, no slope failures have been observed. This is probably due to gentle slopes, however, rather than their inherent stability.

The study area has been extensively logged, and this activity appears to have increased the incidence of slope failures by only a small margin. Slope failures presumed to be logging related have occurred in only 16 polygons for a total area of 364 ha (2% of the entire study area). This is in contrast to the 1,521 ha (7.1% of the entire study area) associated with naturally occurring slope failures. This is primarily due to a higher proportion of Class IV and V terrain in the unlogged terrain.

Careful planning of road locations, construction techniques, cutblock locations, and yarding techniques are important. Terrain with stability Classes III*, IV, or V may or may not be suitable for logging and should be reviewed in a detailed geotechnical assessment. Careful planning of road location in order to avoid sensitive slopes, unstable sections of gullies, and vulnerable stream reaches is recommended. Creek and gully crossings will require judicious planning. Except for crossings, roads should be placed well away from watercourses in order to minimize sediment delivery to the numerous creeks, rivers, and lakes in the area. Adequately spaced drainage structures should be installed, and drainage courses should be maintained during road construction and along the final road location. Existing watercourses should be preserved and should not be overloaded from careless ditching and culvert placement.

Great care should be taken to maintain the natural streamside or riparian zone conditions. Potential hazards in gullies should be assessed prior to road construction and logging, and the management of logging debris near and within a gully system should be considered. Care should be taken to leave ample buffer strips where necessary, and the potential for blowdown should always be taken into consideration.

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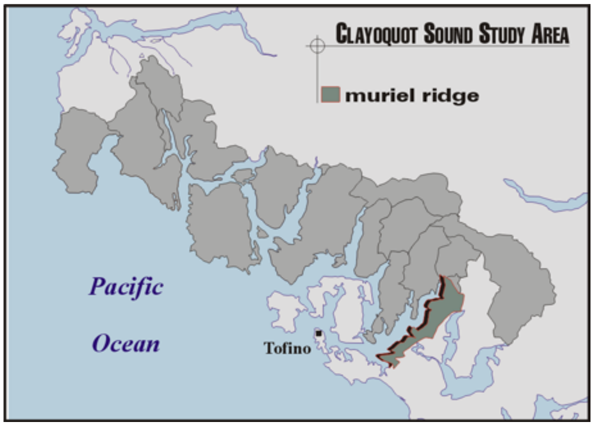
MURIEL RIDGE STUDY AREA



1.0 INTRODUCTION

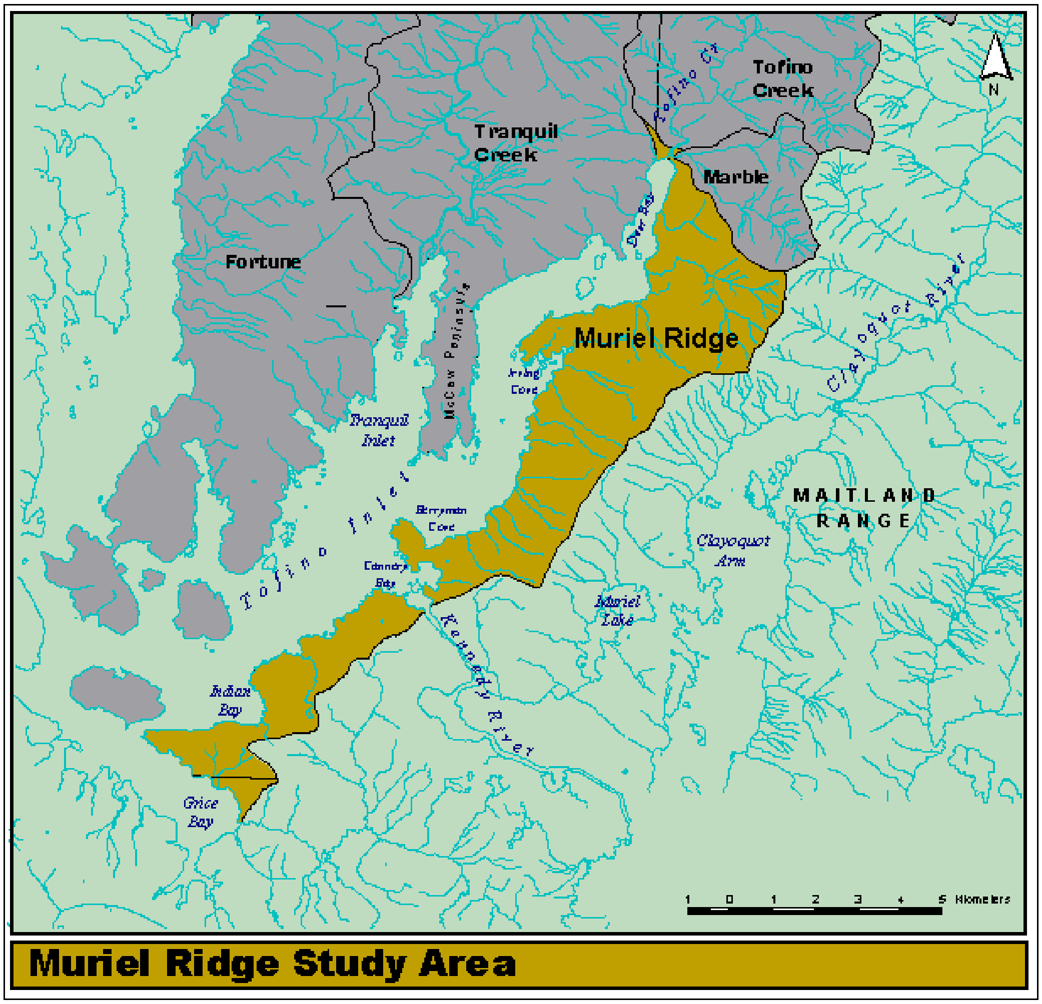
The Muriel Ridge area is made up of the following watersheds: 348, 349X, 351X, 354, 356X, 358X, 360, 363X, and 380X for a total size of 3632 ha. This section includes a description of the study area, results of the fieldwork, and subsequent interpretations. General recommendations related to future development in the area are provided.

Within this study area, Madrone Consultants Ltd. (Madrone) mapped two small portions in 1995. In this previous project, the Muriel Ridge area was approximately 700 ha in size and located at the centre of the current Muriel Ridge project area; the Tofino Inlet area was approximately 800 ha and centred on the mouth of the Kennedy River. Work completed in 1998 for the current project included mapping the entire study area on 1996 air photos using the previous mapping as a reference.

2.0 PHYSICAL ENVIRONMENT

2.1 Location

The Muriel Ridge area is situated on the eastern side of the Clayoquot Sound area. The project boundary includes the northwest facing slope that drains into Tofino Inlet stretching from Grice Bay in the south to the mouth of Marble Creek in the north.



2.2 Physiography

The portion of the Muriel Ridge study area that lies south of the mouth of the Kennedy River (the southern third of the study area) is part of the Estevan Coastal Plain of the Insular Mountains Physiographic Region. The terrain located north of the mouth of the Kennedy River (the northern two thirds of the study area) lies within the Vancouver Island Range of the Insular Mountains Physiographic Region (Holland, 1976). The portion of the study area that lies within the Estevan Coastal plain consists of low-lying, hummocky terrain. The portion of the study areas that lies within the Vancouver Island Ranges consists generally of moderately steep terrain with rounded ridge tops. The watershed at the northern edge of the project area contains the steepest terrain and most rugged topography.

The Estevan Coastal Plain elevations rise from sea level to about 300 m at the highest hillock with the average elevation being about 125 m. Elevations range from sea level to about 800 m at the middle of the study area. The basin at the northern end of the study area has the greatest relief in the study area with elevations rising from sea level to about 1,250 m at the ridge tops.

2.3 Hydrology

The study area consists of one long, continuous slope on the southeast side of Tofino Inlet. The slope contains a series of steep creeks and gullies that drain directly into the Inlet. The watershed southwest of Marble Creek is the largest drainage basin in the study area (see Photo 1 on previous page). The mouth of the Kennedy River drains into Tofino Inlet in the lower third of the study area.

The Muriel Ridge area contains lower elevations, therefore, on an average year rainfall rather than snowmelt influences streamflow in the creeks. The creeks flow mostly in response to rainfall, consequently, the highest discharges are in the winter. The creek draining the northern basin more likely flows in response to snowmelt rather than rainfall in the spring months.

Sediment loads in the creeks likely reach peak volumes during the rainy fall months, entraining sediments that have accumulated during the summer.

Photo 1

The delta of the northern waterhsed is in the foreground. The topography of this portion of the study area is the most rugged.

2.4 Glacial History and Surficial Materials

All but the highest peaks in the Clayoquot Sound area were overridden by ice in the most recent glaciation. This event deposited till, glaciofluvial, and glaciomarine sediments. Post-glacial processes have reworked some glacial sediments and weathered bedrock to redistribute them as colluvium and fluvial sediments.

The northern watershed is dominated by steep, rocky slopes with a discontinuous veneer of colluvium generally covering the mid and upper slopes and a mantle of till mostly overlying the moderately steep, mid and lower slopes. The moderately steep slopes of the mid section of the Muriel Ridge area consists of bedrock-controlled slopes discontinuously covered by till and colluvium. A discontinuous mantle of till covers the lowlands and Corning Point where the till typically infills the depressions and bedrock outcrops at the high points. Weathered bedrock on the gentler slopes and colluvium derived from weathered bedrock often forms a discontinuous veneer in this terrain.

Remnant terraces of glaciofluvial sediments and pockets of glaciomarine sediments are located in many of the low-lying areas along the mid and southern end of the Muriel Ridge area. These deposits are evidence of the higher relative sea levels that existed during and immediately following Fraser glaciation. These glacial deposits have been eroded during the Holocene Epoch (post-glacial time) by creeks and the Kennedy River that have graded to present day sea level, thus creating terraces.

During post-glacial times, bedrock and surficial materials eroded from mid and upper slopes are re-deposited as colluvial veneers and blankets on lower slopes and as colluvial cones and fans at gully mouths.

2.5 Bedrock Geology

Most of the northern watershed is underlain by volcanic and metamorphic bedrock of the Undifferentiated Sicker Group; the mouth of the creek is underlain by metamorphosed sedimentary bedrock of the Buttle Lake Group. The central portion of the study area is underlain by plutonic bedrock of the Island Plutonic Suite. The Estevan Coastal Plain is underlain mostly by plutonic and metamorphic bedrock of the West Coast Cyrstalline Complex and, to a lesser extent, Volcanic bedrock of the Karmutsen Formation (Massey et al., 1994). (See bedrock geology map on the following page).

Insert Bedrock Geology Map

3.0 METHODS

3.1 Pre-Fieldwork

The study area was mapped by Polly Uunila, *G.I.T.*, of EBA Engineering Consultants Ltd. (EBA) onto the 1:17,000 scale, 1996, colour, air photos using Madrone's 1995 mapping as a guide. The terrain symbol and slope steepness range were added to each polygon.

3.2 Fieldwork

In 1995, Marian Oden and Art Klassen of Madrone completed three traverses that are located with in the current project area. For the present project, fieldwork was carried out by crew leaders Polly Uunila and Bruce Maxwell September 14 to 18, 1998 (see Traverse Map on following page). Including the three traverses by Madrone, a total of 11 days were spent field checking.

The area was accessed by four-wheel drive truck and helicopter. The truck was used to access the lower elevation, active and semi-deactivated roads, and the helicopter was used to access the upper elevation, permanently deactivated roads. As safety permitted, traverses were planned to cover as much potentially unstable (Terrain Stability Class IV) and unstable (Terrain Stability Class V) terrain as possible, as well as, a representative of all terrain types. Trucks were used to reach the commencing point of the foot traverses and to check road cuts. For two of the eight traverses that EBA carried out, one crew was dropped off at the ridge tops by helicopter while the other crew used the truck. Traverses were planned so that the crew dropped off by helicopter in the morning was picked up at the road at the end of the day by the other crew.

Sampling density was lowest in the northern watershed because many of the slopes were too steep to safely traverse; moreover, these slopes are typically inoperable. Otherwise, the distribution of field sites are evenly located throughout the study area.

3.3 Air Photo Correction

After completion of the fieldwork, the mapping was completed based on field observations and air photo interpretation. Drainage class, terrain stability class, surface erosion potential class, and landslide-induced stream sedimentation class were added to each polygon. The study area is adjacent to watersheds that were previously mapped as part of the Clayoquot Sound Terrain Inventory. These include Tranquil (Year One), Tofino Creek (Year One), and Marble (Year 2). Muriel Ridge mapping was edge-matched to these watersheds to create seamless and continuous terrain and terrain stability maps of the area. The mapping was reviewed internally by Gordon Butt, *P.Geo.*, of Madrone and reviewed externally by Steve Chatwin, *P.Geo.*, for stage two quality assurance.

3.4 Reliability

The entire watershed has 240 polygons; of these, approximately 103 were checked giving 43% percent polygons checked, and there are three checks per 100 ha. For those slopes that have been logged, the character of the landscape is easier to interpret on the air photographs. In forested areas, a cover of dense vegetation obscured terrain features so that mappers had to make inferences based on experience and judgement. The air photos are a good scale for this level of terrain mapping; however, they are dark so the line work, symbols, and labels are difficult to read.

Insert Traverse map

4.0 SURFICIAL GEOLOGY

4.1 Colluvium (C)

The characteristics and surface expression of colluvium varies based the origin and mode of deposition of the material. The distribution and characteristics of each will be described.

Debris flow fans and cones (e.g., Cf-Rd, Cc-Rd) commonly develop at the lower ends of most gullies and steep creeks. They have accumulated as a result of repeated debris flows interbedded with fluvial deposition throughout post-glacial time. The material is poorly sorted, and the deposit tends to become finer up slope. The material is composed of angular to subrounded clasts from pebble to boulder in size, and the matrix texture is sand (s). Coalesced colluvial fans (Cj-Rd) are mapped in polygons 84 and 110, mapsheet 92F.012.

In the map area, colluvial veneers and blankets (Cv, Cb) are a common form of colluvium. This type of colluvium is derived from loosened and weathered bedrock and glacial drift that has moved downslope by slow processes such as soil creep. In the study area, this material is mostly found on moderately steep and steep slopes where bedrock outcrops (for example, in the northern drainage basin, the mid and lower slopes of the mid portion of Muriel Ridge, and the steepest slopes of the lowlands). The material typically consists of loosely packed rubble or blocks with interstitial silty sand (zs) or sandy silt (sz).

Rockfall colluvium deposits are common at the foot of cliffs. Talus slopes (aCk-Rb) flank cliffs, and talus cones (aCc-Rb) have formed where rockfall is funnelled down gullies. Landforms formed by rockfall are uncommon in the map area; one talus slope was mapped in polygon 18, mapsheet 92F.013. Talus is loosely packed, non-cohesive, well drained, and relatively dry. Blocky talus slopes and cones are usually stable.

4.2 Weathered Bedrock (D)

Weathered bedrock has been modified in situ by mechanical weathering and is commonly forms a thin cover. It is usually developed on gentle slopes and has not been moved by gravitational processes. Mechanically weathered bedrock is typically rubbly, contains various percentages of interstitial silty sand, and is loose and well drained. This material is commonly found in the gentle undulating, bedrock-controlled terrain in Corning Point upslope from Irving Cove and the southern third of study area.

4.3 Fluvial (F)

Fluvial sediments are restricted to valley bottoms and have been mapped in nine polygons. Deltas (see Photo 1) and fans have formed at the lower ends of all the larger creeks in the northern two-thirds of the Muriel Ridge area. The material typically consists of loosely packed sandy gravel (sg) or gravely sand (gs), and where these sediments are not flooded, the sites are usually imperfectly drained.

4.4 Glaciofluvial (FG)

Remnants of glaciofluvial sediments are discontinuously located in the low-lying areas along the edge of the inlet (see Photos 3 and 4 following).

Photo 2
Raised deltaic, interbedded sands, and pebbles exposed in a road cut along Deer Bay main near the mouth of the Kennedy River.

Photo 3
Moderately well bedded, sandy gravels located at site BM4. High roadcuts in unconsolidated sediments such as glaciofluvial sediments are prone to sloughing and erosion. Minimizing the height and reducing the angle of cutslopes is recommended to avoid ditch blockages.

Where the material exists in the study area, it is usually a thick deposit; however, in polygons 82, 86, and 118, mapsheet 92F.012, there is a veneer of glaciofluvial sediments overlying glaciomarine sediments. Glaciofluvial sediments tend to be sandy gravel (sg) with varying degrees of bedding. The material is loosely packed, porous, and permeable, and because these landforms are usually terraces raised above current creek levels, the sediments are generally well drained. Deposits of glaciofluvial sediments may be good sources of aggregate.

4.5 Till (M)

In the northern third of the area, till is generally absent on the upper slopes, a veneer of till overlies most of the mid slopes, and a blanket of till covers most of the lower slopes.

In the mid-portion of the study area, till blankets the surface on continuous, uniform slopes gentler than about 35°. These slopes are most common on the upper slopes and ridge tops. The moderate and moderately steep, mid and lower slopes have undulating and hummocky terrain where mantles of till form a discontinuous cover, infilling the depressions.

The lowlands are undulating and hummocky terrain where mantles of till infill depressions discontinuously throughout the area.

Weathered till is generally about 0.5 m in thickness and usually has a sandy silt (sz) matrix texture and less commonly a silty sand (zs) texture. The unweathered material, where found, mostly has a silty sand (zs) matrix texture and less commonly a sandy silt texture (sz). Tills underlain by the bedrock of the Island Plutonic Suite tend to have a predominantly sandy matrix (s). The till is moderately to highly consolidated. Clasts are mostly subangular to subround and comprise 30% to 70% of the material volume.

Photo 4

A veneer of highly consolidated basal till overlying bedrock in a road cut at site PU5.
The upper half metre (orange layer) is weathered.

4.6 Organic (O)

Although folisols formed by the accumulation of leaf litter and branches form very thin veneers on most slopes particularly in higher elevations, this material was not mapped. Organic sediments are only mapped where they exist in peat bogs; peat bogs form in poorly drained depressions (for example, on bedrock). Bogs are uncommon in the study area but are located in polygons 136 and 161, mapsheet 92F.012.

4.7 Glaciomarine (WG)

Glaciomarine sediments were mapped in 14 polygons scattered along the low-lying areas in the lower two thirds of the Muriel Ridge area. In many of the polygons, till, glaciofluvial sediments, and/or bedrock are mapped in the same polygon. Where observed, the material is a laminated deposit with a silt and clay texture (m) and often embedded with shells (y). Although dropstones are commonly found in Glaciomarine sediments, none were seen in the study area. This deposit has poor permeability and is moderate and imperfectly drained. Forty metres above sea level was the highest elevation that glaciomarine sediments were observed within the study area; however, pockets of this material may be found in other polygons along the inlet below 50 m.

5.0 GEOMORPHOLOGICAL PROCESSES

5.1 Snow Avalanches (-A)

Snow avalanches are not common in this area. They do occur from the headwaters of the watershed at the northern end of the Muriel Ridge area. Snow avalanches play an important role in transporting entrained debris to the valley bottom.

5.2 Rockfall (-R”b)

Rockfall is a common type of mass movement process and occurs in the northern two thirds of the study area. Where steep outcrops of bedrock are highly fractured and have closely spaced joint sets, rockfall occurs. This process is most common in the bedrock gullies and bluffs of the Undifferentiated Sicker Group. Polygon 56, mapsheet 92F.023, is the only polygon in which rockfall has constructed a sufficiently large talus slope to be mapped.

5.3 Debris Flows (-R”d) and Debris Slides (-R”s)

Debris slides and debris flows are the most common mass movement process. They occur from the moderately steep and steep terrain in the northern two-thirds of the Muriel Ridge area. Debris slides commonly initiate near the headwaters of gullies. Small slides from the gully walls or accumulated colluvium in the gully bottom can trigger debris flows during heavy rainfall and spring run-off. Debris slides have initiated in colluvial and till veneers on moderately steep and steep slopes.

There are 29 polygons in the Muriel Ridge area where debris slides and debris flows were mapped, and in many of these polygons, there are multiple slide events. A large percentage of the central portion of the study area has been extensively logged, and of the 29 polygons containing slides, 66% of the polygons have development related failures. Of the polygons with development related slides, 79% of the polygons contain open-slope failures (see Photo 5 following), 11% contain road-related slides (see Photo 6 and 7 following), and 10% contain both road and open-slope slides.

Photo 5

Headscarp of open slope, debris slide in a clearcut located at site PU10. The failure initiated in a veneer of till and colluvium and the failure plane is bedrock.

Photo 6

Located at the centre of the photo is the transport and deposition zone of a slide initiating from side cast (see Photo 7 for headscarp).

Photo 7

The headscarp in this photo was taken at site PU17. The failure initiated in side cast and the weathered layer of the till below. The failure plane is the surface of the unweathered, highly consolidated, basal till (see photo 6 for the transport and deposition zone).

5.4 Gully Erosion (-V)

Gullies on the upper slopes have incised through the veneers of till and colluvium into the underlying bedrock. Where these gullies have exploited joints, the gullies can be quite deep. On lower slopes, gullies may be largely or entirely incised into surficial materials.

There are numerous gullies on the moderately steep and steep slopes in the northern two thirds of the study area. Natural and development related slides have initiated in many of these gullies. Although there may not appear to be recent debris slide and flow activity in a gully, the presence of colluvial cones and fans at the base of these gullies suggest natural failures have occurred in the past and will likely occur in the future.

6.0 INTERPRETATIONS FOR TERRAIN STABILITY, SURFACE EROSION POTENTIAL, AND LANDSLIDE-INDUCED STREAM SEDIMENTATION

6.1 Terrain Stability

With respect to clearcutting, 2% of the polygons were rated terrain stability Class IIIc, 10% of the polygons are IVc, and 6% of the polygons are class V. The Class IIIc' slopes generally are those polygons with slopes that are steeper than 35º (without gullies) and have surficial materials (mostly till) that is thicker than 2 m. In this study area, there were not any slopes that met these criteria. Polygons with stability Class IVc are those slopes that are steeper than 25º and are dissected. Polygons with stability Class V are those polygons that contain unstable terrain.

The terrain stability classes with respect to road building are closely linked to slope gradient. In general, polygons with slope gradients between 30° and 40° are terrain stability IVr, and polygons with slopes greater than 40° and polygons of any slope that are currently unstable are terrain stability Class Vr. Because much of the study area has slopes greater than 30°, 19% of the polygons have terrain stability Class IVr and 16% of the polygons are terrain stability Class Vr.

The greatest density of potentially unstable and unstable terrain is in the northern drainage basin; this contains the terrain with the steepest slopes and most rugged topography in the study area. The mid portion of the Muriel Ridge area contains a moderate amount of terrain stability class terrain IV and V where moderately steep and steep terrain is not as extensive. The lowlands are the most stable area with no terrain polygons rated as potentially unstable for clearcutting and unstable for clearcutting or road building.

6.2 Surface Erosion Potential

Surface erosion potential ratings refer to removal of material, particle by particle, by running water from bare exposed ground. Those areas most susceptible to erosion are road cuts, ditches, roads, and landings. It is also assumed that the potential for erosion is greater on steeper slopes.

Generally, the steeper the slope the higher the road cut. However, on steeper slopes with thin surficial materials (i.e., veneer), the road cuts are mostly bedrock and the ditch lines are bedrock; therefore, the potential for erosion is very low (VL). Where roads are built across steeper slopes with thick surficial materials, high road cuts of bare soil are exposed, and the ditchlines consist of unconsolidated materials. These polygons have the potential for high (H) or very high (VH) surface erosion.

In the study area, 14% of the polygons have high (H) surface erosion potential and <1% of the polygons have very high (VH) surface erosion potential. These numbers are low because a majority of the steeper slopes have thin (<1.0) cover of surficial materials; therefore, road cuts are largely bedrock. Polygons with high and very high ratings tend to be on the mid, moderately steep to steep slopes, generally blanketed with till or glaciofluvial sediments.

6.3 Landslide-Induced Stream Sedimentation

All polygons with a terrain stability Class of III*, IV or V (35 % of the polygons) were assigned a rating for landslide-induced stream sedimentation (LISS). Of the unstable and potentially unstable terrain, 24% of the polygons have a high (3) likelihood of transporting material to a watercourse and 7% of the polygons have a moderate (2) likelihood of transporting material to a watercourse. The density of LISS ratings 2 and 3 are greatest in the rugged topography in the northern drainage, but these numbers are relatively low for the project area as a whole.

7.0 MANAGEMENT CONCERNS AND RECOMMENDATIONS

Glaciomarine sediments are sensitive and highly erosive. Building roads through these deposits should be done with care and preferably after consultation with a registered professional engineer or geoscientist. Loose, unconsolidated sediments such as glaciofluvial sediments are prone to slumping and erosion when exposed in steep, high road cuts. To avoid problems, cutslope height should be minimized and cutslope angle should be less than 30°.

The Muriel Ridge area is relatively small, but it straddles two contrasting physiographic units. The topography ranges from steep and rugged, characteristic of many watersheds in the Vancouver Island Ranges, to low-lying and hummocky, typical of the Estevan Coastal Plain. The central portion is a gradation between the two ends.

Because terrain stability is closely linked to slope steepness, the highest amount of unstable and potentially unstable terrain occurs in the rugged terrain to the north and the most stable terrain in the gentler terrain to the south. The mid portion is a gradation between the two.

Slope instability is common throughout the most rugged topography in the study area; however, slides related to logging development are more numerous. Of the 19 polygons that contain logging related slides, 80% of the polygons have open slope failures, 10% of the polygons contain road-related failures, and 10% of the polygons contain a combination of road-related and open slope failures. The ratio of open slope failures to road-related failures is much higher in this area than other areas. Professionals carrying out terrain stability assessments should be aware of this as it will influence their assessments and there final recommendations. Without further study, it is unclear as to why the number of polygons containing road-related failures is so low as compared to the number of polygons containing open slope failures.

Gully and stream course density in the northern two-thirds of the study area is quite high, typical of this region. Consequently, 67% of the polygons that are terrain stability Class IV and V have a landslide-induced stream sedimentation of high (3).

In general, the northern third and the upper and mid slopes of the central portion of the study area are the most sensitive to development. Proposed development in polygons rated Class IIIc, III*, IV, V (clearcut and road stability ratings), and H and VH should be minimized particularly where the higher ratings for terrain stability, surface erosion potential, and landslide-induced stream sedimentation coincide. If logging is to occur on slopes rated Class IIIc, III*, IV, and V (for clearcut and road stability ratings), they should be examined by a registered professional geoscientist or engineer.

For general recommendations for clearcut harvesting and road building and maintenance, refer to Section 6.0 in the opening chapter of this report.

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APPENDICES

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Appendix I

Clayoquot Year Three
Terrain Photo Inventory by Study Area

Clayoquot Year Three
Terrain Photo Inventory by Study Area

Kennedy River Study Area

30BCC96005: 158-162
30BCC96007: 215-220
30BCC96008: 39-51
30BCC96008: 55-66
30BCC96008: 149-159
30BCC96008: 163-174
30BCC96009: 3-14
30BCC96009: 89-99
30BCC96009: 114-125
30BCC96009: 197-206
30BCC96010: 12-19

Muriel Ridge Study Area

30BCC96005: 51-54
30BCC96005: 113-109
30BCC96005: 141-147
30BCC96009: 22-19
30BCC96009: 80-84
30BCC96009: 135-130
30BCC96009: 187-191
30BCC96010: 32-28

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Appendix II

Clayoquot Numbered Watershed Map

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Appendix III

Bedrock Geology Legend

Legend – Bedrock Geology Maps

Layered Rocks:

QUATERNARY

Qal	Unconsolidated glacial till, marine clays and poorly sorted alluvium

MIOCENE to PLIOCENE

Na	ALERT BAY VOLCANICS: basaltic to dacitic lava, tuff, breccia, conglomerate (2 - 8 Ma) (92L, 102I)
Tus	Unnamed sediments: cobble conglomerate, age unknown (92L, Malcolm Island)

UPPER EOCENE to OLIGOCENE

CARMANAGH GROUP

Tc	Siltstone, shale, sandstone, pebble to boulder conglomerate; molluscan faunas common (Refugian to Zemorrian) Includes ESCALANTE (92E), HESQUIAT (92C, E) and SOOKE (92B, C) formations

?PALEOCENE TO EOCENE

Ec	CHUCKANUT FORMATION: cross-bedded sandstone and pebbly sandstone, pebble conglomerate (92B, Tumbo and Cabbage islands)
Em	METCHOSIN IGNEOUS COMPLEX: isotropic and layered gabbro and leucogabbro, trondhjemite (Em1, Em1a, formerly Sooke Gabbro), diabase feldspar diabase, feldspar diabase, microgabbro and basalt sheeted dykes (Em2), submarine basalitic pillowed flows, hyaloclastite breccia, tuff, massive basalt, rare limestone (Em3), subaerial amygdaloidal basalt flows, minor breccia (Em4) (50 - 56 Ma) (92B, C)
Ef	FLORES VOLCANICS: subaerial andesite to rhyolite welded tuff, ash-flow tuff, tuff breccia, dacite to rhyolite sills, minor basalt dukes (50 - 55 Ma) (92F, E)

UPPER CRETACEOUS
Nanaimo Group

uKN	Boulder, cobble and pebble conglomerate, coarse to fine sandstone, siltstone, shale, coal (Santonian to Maastrichtian) Includes BENSON, COMOX HASLAM, EXTENSION, PENDER, PROTECTION, EAST WELLINGTON, TRENT RIVER, CEDAR DISTRICT, DE COURCY, DENMAN, NORTHUMBERLAND, LAMBERT, GEOFFREY, SPRAY, GALIANO, MAYNE, GABRIOLA, HORNBY and SUQUASH formations (92B, C, F, L)

LOWER to UPPER CRETACEOUS
Queen Charlotte Group

KQ	Conglomerate, greywacke, siltstone, shale, and minor coal (Albian to Cenomanian) Group is undifferentiated on Vancouver Island (92E, L, 102I)

MIDDLE JURASSIC TO LOWER CRETACEOUS
Kyuquot Group

JKk	Siltstone, shale, greywacke, calcareous grit and conglomerate (Callovian to Barremian) Includes KAPOOSE (92E), ONE TREE (92E), AND LONGARM (92L, 102I) formations

MISSISSIPPIAN TO LOWER PERMIAN
Buttle Lake Group

CPB	Undifferentiated Buttle Lake Group (92E, F, L, K) limestone, greywacke, argillite, chert. May include significant volumes of Mount Hall Gabbro sills (CPB + ITri)
IPs	ST. MARY'S LAKE FORMATION: volcanic sandstone and conglomerate, graded sandstone-argillite, cherty argillite, chert, limestone-argillite (Lower Permian) (92F)
PPm	MOUNT MARK FORMATION: massive crinoidal limestone, bedded calcirudite and calcarenite, chert, cherty argillite and siltstone, marble (Upper Pennsylvanian to Lower Permian) (92B, C, F)
MPf	FOURTH LAKE FORMATION: ribbon chert, cherty tuff, graphitic argillite, thinly bedded intercalated sandstone-siltstone-argillite, volcanic sandstone and conglomerate, interbedded argillite and crinoidal limestone, massive and pillowed basalt with intercalated cherty sediment (Lower Mississippian to Upper Pennsylvanian) (92B, C, F)
MPn	NANOOSE COMPLEX: interbedded chert-argillite, sandstone-argillite rhythmites, crinoidal limestone (?Middle Pennsylvanian), chert, olistostromal melange, basalt pillowed flows (92F)

?MIDDLE TO UPPER DEVONIAN

Sicker Group

Ds	Undifferentiated Sicker Group: basalt to rhyolite volcanic tuff, breccia, argillite, cherty tuff, pillowed flows, tuffaceous sediment (92E, F)
uDm	MCLAUGHLIN RIDGE FORMATION: thickly bedded tuffite and lithic tuffite, breccia, tuff, feldspar and quartz-feldspar crystal tuff, lapilli tuff, rhyolite, dacite, laminated tuff, jasper, chert, hematite-chert iron formation (92B, C, F)
Dn	NITINAT FORMATION: pyroxene-feldspar phyric agglomerate, breccia, lapilli tuff, massive and pillowed flows, massive tuffite, laminated tuff, jasper and chert (92B, C, F)
Dd	DUCK LAKE FORMATION: pillowed and massive basalt flows, monolithic basalt breccia and pillow breccia, chert, jasper and cherty tuff, felsic tuffs, massive dacite and rhyolite, magnetite-hematite-chert iron formation(92B, C, F)

PALEOZOIC TO JURASSIC

PMw	WEST COAST CRYSTALLINE COMPLEX: quartz diorite, tonalite, hornblende-plagioclase gneiss, quartz-feldspar gneiss, amphibolite, diorite, agmatite, gabbro, marble and metasediments. Includes the WARD-COLQUITZ COMPLEX (92B, C, F, E, L)
Pma	Amphibolite within West Coast Complex (probably Sicker Group or Karmutsen Formation protolith) (92E)

JURASSIC TO CRETACEOUS

Leech River Complex

JKls	Metasediments: slate, phyllite, quartz-biotite schist, quartz-feldspar-garnet-biotite schist, metagreywacke, meta-arkose, minor interbedded metavolcanics (92B, C)
JKlv	Metavolcanics (“Survey Mountain volcanics”): metabasalt, metarhyolite, chlorite schist, ribbon chert, cherty argillite (92B, C)

TRIASSIC TO CRETACEOUS

Mp	PACIFIC RIM COMPLEX: green, aphanitic volcanic breccia and massive flows, small diorite intrusions, minor pillowed flows and chert, grey limestone lenses (“UCLUTH VOLCANICS”, Carnian to middle Norian); pillow lava, tuff and chert (Lower Jurassic); mudstone-rich melange (Valangian to Aptian); sandstone-rich melange (?Lower Cretaceous) (92E, F)

LOWER JURASSIC
Bonanza Group

lJBV	Undivided volcanics of the Bonanza Group: massive amygdaloidal and pillowed basalt to andesite flows, dacite to rhyolite massive or laminated lava, green and maroon tuff, feldspar crystal tuff, breccia, tuffaceous sandstone, argillite, pebble conglomerate and minor limestone (Sinemurian to Pliensbachian)
lJH	HARBLEDOWN FORMATION: argillite, greywacke-argillite, turbidite, chert, silty limestone, calcareous siltstone and feldspathic sandstone (Sinemurian to lower Pliensbachian) (92L)

MIDDLE TO UPPER TRIASSIC
Vancouver Group

uTrp	PARSON BAY FORMATION: thinly bedded black argillite, siltstone and shale, calcareous argillite, grey and black limestone and shaly limestone, minor tuffaceous sandstone, grit and breccia Includes corralline limestones of Sutton Limestone (Norian)
uTrq	QUATSINO FORMATION: thick bedded, grey to black, micritic and stylolitic limestone, medium to thin bedded limestone and calcareous siltstone, minor oolitic and bioclastic limestone, garnet-epidote-diopside skarn (Camian)
uTrs	Undifferentiated Parson Bay and Quatsino formations (92B, C, F)
uTrkq	Intermixed micritic limestone and basaltic flows, transitional between the Karmutsen and Quatsino formations (92L)
uTrk	KARMUTSEN FORMATION: Basalt pillowed flows, pillow breccia, hyaloclastite tuff and breccia, massive amygdaloidal flows, minor tuffs, interflow sediment and limestone lenses (Carnian)
mTrd	“DAONELLA” BEDS (informal name): laminated to graded black shales and siltstones (Ladinian) Includes abundant diabase sills of Mount Hall Gabbro (92D,L)

Intrusive Rocks:

EOCENE TO OLIGOCENE

Twc	WALKER CREEK INTRUSIONS: gneissic or unfoliated biotite-hornblende trondhjemite, quartz-feldspar-muscovite-tourmaline pegmatite (92B, C; within Leech River Complex)
Tw	MOUNT WASHINGTON INTRUSIVE SUITE: quartz diorite, feldspar-hornblende dacite porphyry (includes volcanic breccias of the Mount Washington area) (42 - 32 Ma) (92F, L)

?PALEOCENE TO EOCENE

PEc	CLAYOQUOT INTRUSIVE SUITE: quartz diorite, granodiorite, quartz monzonite, dacite porphyry (45 - 60 Ma). Probably coeval with the Flores Volcanics (92E, F)

CRETACEOUS

Kg	Known or suspected Cretaceous intrusions within Wrangellia (probably related to Coast Plutonic Complex): hornblende-biotite granodiorite, quartz monzonite, tonalite, quartz porphyry, hornblende-feldspar porphyry (120 Ma) (92F, K)

EARLY TO MIDDLE JURASSIC

JI	ISLAND PLUTONIC SUITE: granodiorite, quartz diorite, quartz monzonite, diorite, agmatite, feldspar porphyry, minor gabbro and aplite (170 - 185 Ma)
Jm	Minor intrusions consanguineous with the Island Plutonic Suite: feldspar porphyry, hornblende porphyry, augite porphyry, dacite, basalt (92B, C, F)

LATE TRIASSIC

ITri	MOUNT HALL GABBRO: diabase, feldspar diabase, gabbro, glomeroporphyritic diabase and gabbro, minor diorite (215 - 230 Ma) Coeval with Karmutsen Formation

LATE DEVONIAN

IDsi	SALTSPRING INTRUSIVE SUITE: granodiorite, feldspar porphyry, quartz-feldspar porphyry, coeval with McLaughlin Ridge Formation (365 - 360 Ma) (92B)

Appendix IV

Field Data Form