Large Landslides on Vancouver Island, British Columbia

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Abstract

As the first phase of Energy, Mines and Resources Canada's long term plan to assess the potential landslide response of Vancouver Island to future earthqukes, an airphoto-based inventory of the island's large landslides was carried out. A total of 34 landslide features, estimated to have involved in excess of 1 million m3 of material, were identified and designated as priority sites for future field investigation. In addition, 40 other smaller, but substantial landslide features, were recorded. All of the 34 priority landslides are located on the northern 2/3s of Vancouver Island. All but one lie in either the North Vancouver Island Ranges or West Vancouver Island Fiordlands physiographic regions - both regions of rugged mountainous terrain that have been subjected to glacial oversteepening. The Karmutsen volcanics are associated with 65% of the priority landslide sites. Rock slides are most common (50%), followed by rock-fall avalanches (32%), then rock slumps (18%). The most common estimated area of ground disturbance is in the range of 200,000 m2 (41%). The majority of the landslides (68%) lie within the Coastal Western Hemlock biogeoclimatic zone which is subject to more than 2500 mm of precipitation annually. It is estimated that 56% of the priority landslides occurred more than 100 years ago, 18% occurred 50 to 100 years ago and 26% occurred within the past 50 years. Of the 26%, or 9, most recent events, 6 of them may be associated with the 1946, 7.3 magnitude Vancouver Island earthquake.

Introduction

This paper summarizes the methods and results of an inventory of large landslides on Vancouver Island, British Columbia [1]. This inventory is the first phase of Energy, Mines and Resources Canada's longer term plan to assess the landslide response of the island, and the west coast of Canada, to future earthquakes. As such, the study also investigated, in general terms, the relationship between the locations of past large landslides, physical settings, and where possible, past seismic activities.

Two previous inventories of landslides of portions of Vancouver Island have been carried out. Mathews [2] presented a summary of an inventory of landslides of central Vancouver Island, which he inferred were the result of the 1946 Vancouver Island earthquake. Howes [3] included an inventory of rock slides and rock slumps in his terrain inventory of northern Vancouver Island. Roger's documentation of soil failures resulting from the 1946 earthquake did not include landslides [4].

During regional geological mapping of portions of Vancouver Island, a number of geologists noted, or inferred, landslides in their study areas. Examples of such references include Gunning [5] and Fyles [6]. Additional references to existing landslides on Vancouver Island appear in a variety of other publications.

Scope and Method

This study covered all of Vancouver Island including the major neighbouring islands (Figure 1). For the purpose of this study, large landslides are defined as those involving in excess of an estimated 1 million m3 of material. Significant landslides, but estimated to be less than 1 million m3 in volume, were also considered.

Types of landslides included in the inventory were rock-fall avalanches, rock slides and rock slumps. Areas of ongoing rock falls, soil slides, debris slides and debris flows, which although common on the island, usually have involved a volume of material much less than 1 million m3.

The study was carried out in three stages. All available references to known large landslides were collected and reviewed in Stage 1. In addition, discussions were held with geologists and engineers familiar with Vancouver Island.

Stage 2 involved 3 phases of airphoto interpretation. Phase 1 was a stereoscopic interpretation of approximately 700, 1:60,000 to 1:70,000 scale, 1986 and 1987 airphotos of the entire Vancouver Island. Any feature that had the appearance of a large landslide on these small scale airphotos, and all rock slide and rock slump features identified in Howes [3], were catalogued.

In Phase 2 all features identified in Phase 1 were re-examined on the most recent, largest scale airphotos available. The dates of the most recent airphotos ranged from 1970 to 1987. The scales of these airphotos varied from 1:10,000 to 1:20,000. From Phase 2 the features were then divided into 3 groups:

Priority A: Landslide features estimated to involve in excess of 1 million m3 of material, plus significant landslide features with an estimated volume less than 1 million m3. Because it is difficult to estimate volumes from airphotos, most landslide features with an estimated area of ground disturbance greater than 50,000 m2, were included in the Priority A group.

Priority B: Landslide features usually smaller than those in Priority A, plus areas of large ongoing rock falls and associated talus deposits. Because of space constraints, this paper will not discuss Priority B landslides further. The reader is referred to VanDine Geological Engineering [1].

Very small landslides and other features that were misinterpreted as landslides on the small scale airphotos were discarded from further investigation.

Phase 3 of Stage 2 involved an examination of all Priority A landslide features using airphotos from different years in an attempt to age bracket the date of occurrence of the landslides. This phase was not carried out where it was obvious that the landslide had occurred well before the earliest available airphotos (approximately 1946).

The following information was summarized for each of the Priority A landslide features: location and approximate location of the mainscarp; type and area of ground disturbance; physiographic region, biogeoclimatic zone and annual precipitation; estimated age; a brief description and references.

The common characteristics of the Priority A landslide features were analyzed in Stage 3. An attempt was made to relate the date of occurrence of these events with the known past seismic activity of Vancouver Island.

This study was based largely on the stereoscopic interpretation of BC government airphotos available at the BC Airphoto Library, Victoria, BC. No field checking was carried out. As with any such study, the results are therefore dependent on the availability, scale and quality of the airphotos.

Physical Setting of Vancouver Island

Vancouver Island is the largest island on the west coast of North America. It stretches for approximately 450 km in a northwest- southeast direction between 48^20'N and 50^40'N and between 123^10'W and 128^30'W. Although it is approximately 125 km at its widest point, the average width is only 70 km. The total land area is approximately 32,000 km2.

Physiographically, the island can be divided into 11 regions (Figure 1) [7]. Approximately 75% of the land mass is composed of the three mountainous physiographical regions: North Vancouver Island Ranges, South Vancouver Island Ranges and West Vancouver Island Fiordland. The remaining 25% are made up of plateaux, highlands, lowlands and basins.

The regional bedrock geology of Vancouver Island has been compiled at a scale of 1:250,000 by Muller [8]. The majority of the mountainous regions of the island are underlain by the mid to upper Triassic Karmutsen Formation volcanics (muTR K), the lower Jurassic Bonanza Formation volcanics (lJ B) and Jurassic granitic intrusives (Jg). During the Pleistocene Epoch, glacial activity steepened, and in some cases oversteepened, many of the mountain slopes.

Rogers [9] and Cassidy [10] have most recently reviewed the regional seismicity of Vancouver Island. Since 1899, when records were first kept, six earthquakes with magnitudes 5.3 or greater have been recorded on or near Vancouver Island. Their epicentres and magnitudes are shown on Figure 1. The epicentres of all but the 1946 earthquake are located along the west coast of the island.

Biogeoclimatic zones relate the climate and the ecosystem. For Vancouver Island the biogeoclimatic zones have been summarized on a 1:500,000 scale map prepared by Nuszdorfer et al [11]. Most of the mountainous regions of the island lie within the Coastal Western Hemlock or Mountain Hemlock zones. The highest peaks fall within the Alpine Tundra. The Coastal Hemlock Zone is characterized by abundant annual rainfall and mild temperatures. The Mountain Hemlock Zone has abundant rainfall during the summer months and abundant snowfall during the winter months. The Alpine Tundra Zone has a harsh climate consisting of long, cold winters with an abundant snowfall.

Farley [12] has divided Vancouver Island into 3 approximately northwest-southeast trending annual precipitation zones. From west to east they are: >2500 mm, 1000 mm to 2500 mm and 500 mm to 1000 mm. The western 2/3s of the island is subject to >2500 mm of precipitation annually.

Results of the Study

In total 185 landslide features and/or inferred landslide features were identified during Phase 1 of the airphoto interpretation. During the re-examination of those features on larger scale airphotos in Phase 2, 111 features were discarded from further investigation. Many of these features were snow avalanche tracks, rock falls, soil slides, debris slides or debris flows and other forms of landslides too small to consider for this study. A few of the features identified in Phase 1 were found not to be related to landslides.

Of the remaining 74 landslides features, 34 were grouped into Priority A landslide features and 40 were grouped into Priority B.

The locations of the 34 Priority A landslide features are shown on Figure 1. A unique landslide number including "A", for Priority A, and second letter which refers to the 1:250,000 scale NTS topographic map, is given to each feature. The locations, characteristics, physical settings and estimated ages of movement for each landslide feature are included in Table 1. (The reader is referred to VanDine Geological Engineering [1] for further descriptions, references and references to airphotos for each landslide feature). Table 2 through Table 10 summarize the common characteristics of the 34 Priority A landslide features.

As shown on Figure 1 and in Table 2, geographically, large landslides are limited to the northern 2/3s of Vancouver Island, that is the area roughly north of the 49th parallel of latitude. Fifty per cent of the large landslides occur within the 1:250,000 scale NTS map sheet 92F.

Table 3 indicates that rock slides are the most common of the large landslide types (50%), followed by rock-fall avalanches (32%) then rock slumps (18%). As shown in Table 4, the most common estimated area of ground disturbance by these 34 features is approximately 200,000 m2 (41%).

Table 5 indicates that all but one large landslide feature lie either in the North Vancouver Island Range or West Vancouver Island Fiordland physiographic regions -- both are regions of rugged mountainous terrain and have been subjected to glacial steepening. The majority of these features (68%) are associated with the Coastal Western Hemlock biogeoclimatic zone (Table 6) and are subject to more than 250 cm of precipitation annually (74%) as shown in Table 7.

Table 8 shows that 47% of the large landslides are underlain by volcanic rock formations, 18% occurred in intrusive rock types and 27% occurred in areas where there are both volcanic and intrusive rock formations. The Karmutsen volcanics (muTR K) are associated with 65% of the large landslides.

Of the 34 large landslides, it is estimated that 56% occurred more than 100 years ago (Table 9). It is estimated that 18% occurred 50 to 100 years ago and 26% occurred within the past 50 years. The years of occurrence of the recent large landslides, whether known or inferred, are presented in Table 10. When these dates are compared to the dates of the known significant earthquakes over the same period, it appears that the 1946 Vancouver Island earthquake may have had the greatest seismic impact on the occurrence of large landslides on Vancouver Island in the recent past.

Conclusions

The majority of the large landslides on Vancouver Island have occurred in the mountainous central and northern regions of the island. These areas of high relief are also regions of abundant annual precipitation.

A large majority of these large rock-fall avalanches, rock slide and rock slumps occurred in association with either volcanic or intrusive rock formations. The Karmutsen volcanics were associated with 65% of the landslides.

Of the occurrences in the past 50 years, the 1946 earthquake possibly has had the greatest seismic impact on slope stability.

It is difficult to conclude from this study, however, which factors of topography, geology, rainfall and/or the location and character of the past earthquakes, have been the controlling factors. The findings of this study have been discussed, in general terms, with both W.H. Mathews and D.E. Howes in light of their earlier inventories ([2] and [3] respectively). Both agree that the numbers of large landslides noted and inventoried during this present study, and the relationships of these landslides with their physical settings, are generally consistent with the findings from their earlier studies.

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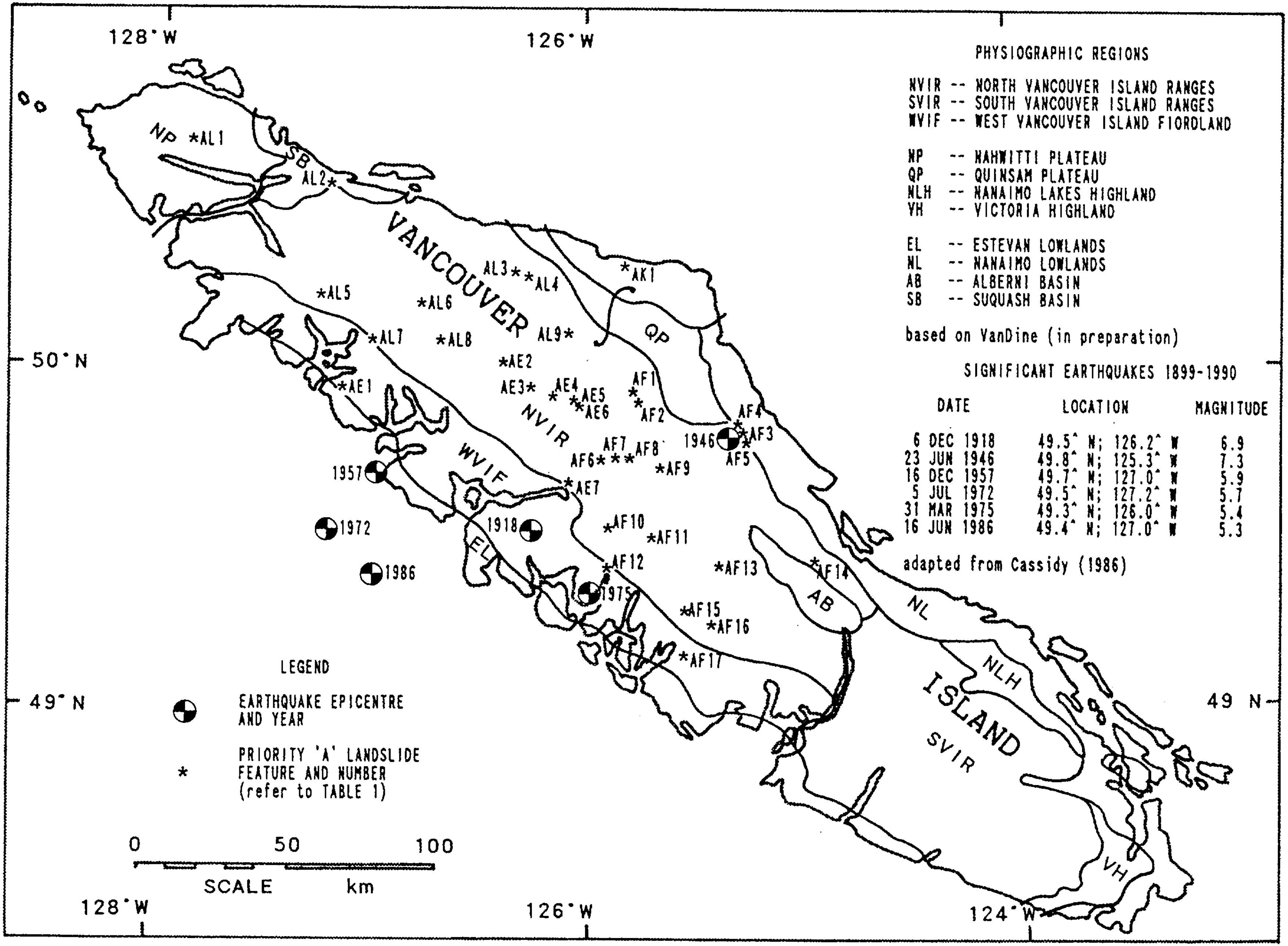

FIGURE 1--VANCOUVER ISLAND: PHYSIOGRAPHY, EARTHQUAKE EPICENTRES & LOCATION OF PRIORITY 'A' LANDSLIDE FEATURES

TABLE 1--Summary of landslide features

LANDSLIDE NUMBER	LOCATION				CHARACTERISTICS			PHYSICAL SETTING				AGE
1	GEOGRAPHIC LOCATOR *2*	NTS *3*	UTM *4*	LAT & LONG *5*	APPROX. MAINSCARP ELEV. (m) *6*	TYPE OF LANDSLIDE *7*	APPROX. AREA (*1000 m2) *8*	PHYSIO-GRAPHIC REGION *9*	BIOGEO-CLIMATIC ZONE *10*	ANNUAL PRECIP. ZONE *11*	BEDROCK GEOLOGY *12*	ESTIMATED AGE *13*
AE1	Ship Peak	92E/14	9U XF3338	49^57'N 127^08'W	950	Rock slump	100	WVIF	CWH	>250 cm	lJ B	Ancient
AE2	Mount McKelvie North	92E/15 & 92L/02	9U XF7242	50^00'N 126^35'W	900	Rock-fall avalanche	200	NVIR	CWH	>250 cm	muTR K	Ancient/ recent
AE3	Mount Alava/ Conuma Creek	92E/15 & 92E/16	9U XF7929	49^53'N 126^30'W	1200	Rock-fall avalanche	200	NVIR	MH/AT	>250 cm	muTR K	Recent 1974?
AE4	Conuma Peak	92E/16	9U XF9522	49^49'N 126^18'W	1100	Rock slide	200	NVIR	MH/AT	>250 cm	Jg	Ancient
AE5	Gold River North	92E/16	9U YF1321	49^48'N 126^02'W	900	Rock slide	200	NVIR	CWH	>250 cm	Jg/ muTR K	Ancient/ recent
AE6	Gold River South	92E/16	9U YF1421	49^48'N 126^02'W	900	Rock slide	100	NVIR	CWH	>250 cm	Jg/ muTR K	Ancient/ recent
AE7	Muchalat Inlet East	92E/09	9U YF1205	49^40'N 126^03'W	850	Rock slide	100	NVIR	CWH	>250 cm	muTR K	Ancient
AF1	Upper Campbell Lake North	92F/13	10U CL1026	49^52'N 125^39'W	600	Rock slide	200	NVIR	CWH	>250 cm	muTR K	Ancient
AF2	Upper Campbell Lake South	92F/13	10U CL1023	49^50'N 125^38'W	900	Rock slide	1,600	NVIR	CWH	>250 cm	muTR K	Ancient
AF3	Constitution Hill Middle	92F/14	10U CL4217	49^48'N 125^12'W	500	Rock slide	200	NVIR	CWH	100-250 cm	Tg/ muTR K	Ancient
AF4	Constitution Hill North	92F/14	10U CL4219	49^49'N 125^12'W	300	Rock slump	100	NVIR	CWH	100-250 cm	Tg/ muTR K	Ancient
AF5	Constitution Hill South	92F/14	10U CL4216	49^47'N 125^12'W	450	Rock slide	100	NVIR	CWH	100-250 cm	Tg/ muTR K	Ancient
AF6	Butterwort Creek	92F/13	10U BL9315	49^45'N 125^53'W	1600	Rock-fall avalanche	400	NVIR	MH/AT	>250 cm	muTR K	Recent 1946?
AF7	Mount Colonel Foster	92F/13	10U BL9416	49^46'N 125^51'W	1500	Rock-fall avalanche	800	NVIR	MH/AT	>250 cm	muTR K	Recent 1946
AF8	Cervus Creek North	92F/13	10U BL9916	49^46'N 125^47'W	1600	Rock-fall avalanche	400	NVIR	MH/AT	>250 cm	muTR K	Recent 1946?
AF9	Adrian Creek	92F/12	10U CL1913	49^45'N 125^31'W	1500	Rock-fall avalanche	50	NVIR	MH/AT	>250 cm	muTR K	Old
AF10	Splendor Mountain	92F/12	10U BK8994	49^33'N 125^55'W	1200	Rock-fall avalanche	50	NVIR	MH/AT	>250 cm	Jg	Recent <1957
AF11	Mount Thelwood	92F/12	10U BK0492	49^33'N 125^42'W	1200	Rock slide	50	NVIR	MH/AT	>250 cm	Jg	Old
AF12	Moyeha Bay	92F/05	10U BK8878	49^25'N 125^56'W	400	Rock slide	200	WVIF	CWH	>250 cm	Jg/ muTR K	Ancient
AF13	Oshinow Lake	92F/06	10U CK3378	49^26'N 125^18'W	800	Rock slide	400	NVIR	CWH	>250 cm	muTR K	Ancient
AF14	Mount Joan	92F/07	10U CK5876	49^25'N 124^56'W	1100	Rock slide	1,600	NVIR	MH/AT	100-250 cm	muTR K	Ancient
AF15	Thunderbird Creek	92F/05	10U CK1170	49^21'N 125^36'W	1000	Rock-fall avalanche	200	NVIR	CWH/MH	>250 cm	Jg/ muTR K	Recent 1957-1970
AF16	Kennedy River	92F/06	10U CK2362	49^17'N 125^27'W	750	Rock slide	400	NVIR	CWH	>250 cm	Jg/ muTR K	Recent 1970?
AF17	Clayoquot Arm	92F/04	10U CK1351	49^11'N 125^33'W	650	Rock slide	50	WVIF	CWH	>250 cm	PMns	Recent <1957
AK1	Prince of Wales Range	92K/05	10U CL0381	50^22'N 125^47'W	600	Rock slide/ avalanche	400	NVIR	CWH	100-250 cm	muTR K	Recent 1946?
AL1	Hushamu Lake	92L/12	9U WG8115	50^41'N 127^51'W	600	Rock slump	200	NP	CWH	100-250 cm	uTR PB	Ancient
AL2	Cluxewe River	92L/11	9U XG2805	50^35'N 127^11'W	200	Rock slide	50	NVIR	CWH	100-250 cm	T VS	Ancient
AL3	Claud Elliot Creek	92L/07	9U XF7576	50^19'N 126^33'W	1050	Rock-fall avalanche	200	NVIR	CWH	100-250 cm	Jg	Old
AL4	Mount Elliot	92L/07	9U XF7875	50^18'N 126^30'W	1200	Rock-fall avalanche	200	NVIR	MH/AT	100-250 cm	Jg	Old
AL5	Kauwinch River	92L/03	9U XF2565	50^13'N 127^15'W	750	Rock slump	200	NVIR	CWH	>250 cm	Jb/ lJ B	Ancient
AL6	Wolfe Lake	92L/02	9U XF5363	50^12'N 126^46'W	1000	Rock slump	1,600	NVIR	CWH	>250 cm	uTR Q/ muTR K	Ancient
AL7	Tahsish Inlet East	92L/03	9U XF3850	50^06'N 127^04'W	450	Rock slump	200	WVIF	CWH	>250 cm	lJ B	Ancient
AL8	Kaouk River	92L/02	9U XF5450	50^05'N 126^51'W	1000	Rock-fall avalanche	800	NVIR	MH/AT	>250 cm	Jg/ uTR PB	Old late 1920s
AL9	Gerald Creek	92L/01	9U YF0856	50^07'N 126^05'W	1200	Rock slide	200	NVIR	CWH	>250 cm	muTR K	Old

* * Refer to next page for accompanying notes.

NOTES to accompany TABLE 1--Summary of landslide features

1 LANDSLIDE NUMBER -- First letter refers to Priority. Second letter refers to 1:250,000 scale NTS map sheet beginning with 92. Refer to FIGURE 1.
2 GEOGRAPHIC LOCATOR -- The closest named geographic feature.
3 NTS -- 1:50,000 scale National Topographic System map.
4 UTM -- Universal Transverse Mercator, 1000 m grid.
5 LAT & LONG -- latitude and longitude to the nearest minute.
6 APPROXIMATE MAINSCARP ELEVATION (m) -- estimated from 1:50,000 scale map.
7 TYPE OF LANDSLIDE -- based on Varnes [13].
8 APPROXIMATE AREA -- area of ground disturbance, rounded to nearest size grouping. Not to be used to calculate volumes.
9 PHYSIOGRAPHIC REGION -- based on VanDine [7]. Refer to FIGURE 1 and TABLE 5.
10 BIOGEOCLIMATIC ZONE -- based on Nuszdorfer et al [11]. Refer to TABLE 6.
11 ANNUAL PRECIPITATION ZONE -- based on Farley [12].
12 BEDROCK GEOLOGY -- based on Muller [8]. Refer to TABLE 8.
13 ESTIMATED AGE -- Refer to TABLE 9.

Refer to text for further details.

TABLE 2--Landslide features vs. NTS map sheet

1:250,000 NTS TOPOGRAPHIC MAP	GEOGRAPHIC CO-ORDINATES	NUMBER OF LANDSLIDES	%
92B	48^-49^ N; 122^-124^ W	0	0
92C	48^-49^ N; 124^-126^ W	0	0
92E	49^-50^ N; 126^-128^ W	7	21
92F	49^-50^ N; 124^-126^ W	17	50
92G	49^-50^ N; 122^-124^ W	0	0
92K	50^-51^ N; 124^-126^ W	1	3
92L	50^-51^ N; 126^-128^ W	9	26
102I	50^-51^ N; 128^-130^ W	0	0
TOTAL NUMBER OF LANDSLIDES		34	100

NOTE: Map sheets do not cover similar size areas of Vanc. Isl.

TABLE 3--Landslide features vs. landslide type

TYPE OF LANDSLIDE	NUMBER OF LANDSLIDES	%
Rock-fall Avalanches	11	32
Rock Slides	17	50
Rock Slumps	6	18
TOTAL NUMBER OF LANDSLIDES	34	100

NOTE: Classification of landslides based on Varnes (1978).

TABLE 4--Landslide features vs. area of ground disturbance

AREA OF GROUND DISTURBANCE (m2)	NUMBER OF LANDSLIDES	%
50,000	5	15
100,000	5	15
200,000	14	41
400,000	5	15
800,000	2	6
1,600,000	3	9
TOTAL NUMBER OF LANDSLIDES	34	101

NOTE: Disturbed areas include both area of depletion and area of accumulation. They are intended for relative comparisons only and should not be used for volume calculations.

TABLE 5--Landslide features vs. physiographic region

PHYSIOGRAPHIC REGION		NUMBER OF LANDSLIDES	%
North Vancouver Island Ranges	(NVIR)	29	85
South Vancouver Island Ranges	(SVIR)	0	0
West Vancouver Island Fiordland	(WVIF)	4	12
Nahwitti Plateau	(NP)	1	3
Quinsam Plateau	(QP)	0	0
Nanaimo Lakes Highland	(NLH)	0	0
Victoria Highlands	(VH)	0	0
Estevan Lowlands	(EL)	0	0
Nanaimo Lowlands	(NL)	0	0
Alberni Basin	(AB)	0	0
Suquash Basin	(SB)	0	0
TOTAL NUMBER OF LANDSLIDES		34	100

NOTE: Physiographic regions based upon VanDine (in preparation). Refer to Figure 1.

TABLE 6--Landslide features vs. biogeoclimatic zone

BIOGEOCLIMATIC ZONE		NUMBER OF LANDSLIDES	%
Alpine Tundra	(AT)	0	0
Mountain Hemlock/Alpine Tundra	(MH)	11	32
Coastal Western Hemlock/Mt.Hemlock	(CWH/MH)	1	3
Coastal Western Hemlock	(CMH)	22	65
Coastal Douglas Fir	(CDF)	0	0
TOTAL NUMBER OF LANDSLIDES		34	100

NOTE: Biogeoclimatic zones based on Nuszdorfer et al (1985).

TABLE 7--Landslide features vs. annual precipitation

ANNUAL PRECIPITATION (cm)	NUMBER OF LANDSLIDES	%
>250	25	74
100 - 250	9	26
50 - 100	0	0
TOTAL NUMBER OF LANDSLIDES	34	100

NOTE: Annual precipitation zones based on Farley (1979).

TABLE 8--Landslide features vs. underlying bedrock geology

BEDROCK GEOLOGY FORMATIONS		NUMBER OF LANDSLIDES	%
late Tertiary volcanics	(T VS)	1	3
lower Jurassic Bonanza volcanics	(lJ B)	2	6
mid/upper Triassic Karmutsen vol.	(muTR K)	13	38
Jurassic island granitic intrusive	(Jg)	5	15
Jurassic westcoast granitic instru.	(PMns)	1	3
Tertiary granitic instrusive/vol.	(Tg/muTR K)	3	9
Jurassic granitic intrusive/vol.	(Jg/lJ B)	1	3
Jurassic granitic intrusive/vol.	(Jg/muTR K)	5	15
Jurassic granitic intrusive/sed.	(Jg/uTR PB)	1	3
upper Triassic Parson Bay sed.	(uTR PB)	1	3
upper Triassic Quatsino sed./vol.	(uTR Q/muTR K)	1	3
TOTAL NUMBER OF LANDSLIDES		34	101

NOTE: Refer to Muller (1977) for full descriptions of the bedrock formations.

TABLE 9--Landslide features vs. estimated age of occurrence

RANGE OF ESTIMATED AGE OF OCCURRENCE	NUMBER OF LANDSLIDES	%
Recent -- less than 50 years old	9	26
Old -- 50 to 100 years old	6	18
Ancient -- 100s to 1000s of years old	19	56
TOTAL NUMBER OF LANDSLIDES	34	100

NOTE: As determined from Phase 3 of study and from other sources.

TABLE 10--'Recent' landslides, estimated year of occurrence and years of significant earthquakes

LANDSLIDE NUMBER	ESTIMATED YEAR OF OCCURRENCE	YEAR OF SIGNIFICANT EARTHQUAKE
		1946
AF6	1946 ?	
AF7	1946	
AF8	1946 ?	
AK1	1946 ?	
AF10	< 1957	
AF17	< 1957	
		1957
AF15	1957 - 1970	
AF16	1970 ?	
		1972
AE3	1974 ?	
		1975
		1986

NOTE: Refer to TABLE 1 for details of landslides and FIGURE 1 for details of earthquakes.