BRITISH COLUMBIA
Ministry of Energy and Mines
Energy and Minerals Division
Geological Survey Branch

RELATIVE LIQUEFACTION AND AMPLIFICATION OF GROUND MOTION HAZARD MAPS OF GREATER VICTORIA

(TRIM 92B.043, 044, 0 53, 054)

Report and Expanded Legend to Accompany British Columbia Geological Survey Geoscience Map 2000-3

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GEOSCIENCE MAP 2000-3

INTRODUCTION

Victoria is located in one of the most seismically active regions of Canada. Vancouver Island has experienced two large earthquakes this century, in 1918 (M=7.0) and 1946 (M=7.3; Rogers, 1998). The latter was the most damaging in western Canada and caused minor damage in the Victoria area, which was 200 km from the epicentre (Hodgson, 1946; Wuorinen, 1974, 1976). In addition, there is potential for very large (M~9) earthquakes on the Cascadia subduction zone west of Vancouver Island (Rogers, 1988, 1994; Clague, 1996). Victoria is more likely to be subjected to strong earthquake ground motions than any other major city in the country (Adams *et al*., 1995).

The effects of earthquakes are not only dependent upon the magnitude of the earthquake and the distance from the source, but they can vary considerably due to local geological conditions. These conditions can be mapped with varying degrees of completeness using existing geological and geotechnical data. It is the objective of this report and the accompanying maps to show those areas of Greater Victoria where the earthquake hazard is increased due to the presence of soils susceptible to liquefaction (Geoscience Map 2000-3a; Monahan *et al*., 2000b) and amplification of ground motion (Geoscience Map 2000-3b; Monahan *et al*., 2000c). Three additional maps relevant to earthquake hazards are also being published as part of this investigation: a map of the Quaternary geology, on which these hazard maps are based (Geoscience Map 2000-2; Monahan and Levson, 2000); a map that shows areas susceptible to earthquake-induced slope instability (Geoscience Map 2000-3c; McQuarrie and Bean, 2000); and a composite map that shows areas susceptible to the amplification of ground motion, liquefaction, and earthquake-induced slope instability hazards (Geoscience Map 2000-1; Monahan *et al.*, 2000a). Preliminary results of this investigation were discussed by Monahan and Levson (1997), Monahan *et al*. (1998), and Valeriote (1997).

An earthquake hazard map of the City of Victoria by Wuorinen (1974, 1976) focused on the amplification hazard. That map was based on the thickness and distribution of Quaternary deposits overlying bedrock, and on eyewitness accounts of the effects of the 1946 Vancouver Island earthquake. The maps described here include all of the Greater Victoria urban area, assess the amplification hazard using modern techniques and data, and also address the liquefaction hazard. The area of this study includes the municipalities of Victoria, Saanich, Oak Bay, Esquimalt, View Royal, Colwood and Langford. Small corridors were added to include Hartland Landfill and the Goldstream River valley upstream to the exit portal of the Kapoor tunnel.

These maps are intended for regional purposes only, such as land use and emergency response planning, and should not be used for site-specific evaluations. Although these maps can be used with other criteria to help planners select potential areas for development, avoid geologically vulnerable areas and prioritise seismic upgrading programs, *the maps do not replace the need for site specific geotechnical evaluations* prior to new construction or upgrading of buildings and other facilities. The qualifications and limitations of these maps are discussed in more detail below.

[1] *The term soil refes here to all unlithified material overlying bedrock.*

SUMMARY OF QUATERNARY GEOLOGY

The lithology, thickness and distribution of the Quaternary sediments are the principal geological factors used for earthquake hazard mapping in the Greater Victoria area (Figure 1). These deposits overlie an irregular, glacially scoured bedrock surface. The depth to bedrock can vary from zero to as much as 30 metres within the space of a city block (Crawford and Sutherland, 1971; Wuorinen, 1974, 1976; Nasmith and Buck, 1998). Bedrock consists of high-grade metamorphics throughout much of the area, metavolcanics and intrusive rocks in Saanich Peninsula, and volcanics in the Colwood area (Muller, 1983; Massey *et al*., 1994).

The oldest Quaternary deposits in the area underlie the Vashon till of the Late Wisconsinan Fraser Glaciation. They occur principally in the central and eastern parts of Saanich Peninsula, where they are up to 60 metres thick, and have commonly been sculpted into a series of north-trending drumlinoid ridges and crag-and-tail features. These deposits are best known from the sea cliffs on the east side of the peninsula. The following units have been recognized, in ascending order: an undated till; interbedded sand and gravel of the non-glacial Pre-Wisconsinan Muir Point Formation; till and glaciomarine deposits assigned to the early Wisconsinan Dashwood drift; sand, silt and gravel of the middle Wisconsinan non-glacial Cowichan Head Formation; and sand and gravel of the late Wisconsinan Quadra Formation, which has been interpreted as proglacial outwash from the advancing glaciers of the Fraser Glaciation (Clague, 1976, 1977; Armstrong and Clague, 1977; Alley, 1979; Howes and Nasmith, 1983; Hicock and Armstrong, 1983; Blyth and Nasmith, 1993, 1995; Blyth, 1996; Nasmith and Buck, 1998).

The Vashon till of the late Wisconsinan Fraser Glaciation overlies bedrock directly in much of the Greater Victoria area. It is a discontinuous unit and is generally less than a few metres thick. However, it is locally up to 15 metres thick, as along the Dallas Road sea cliffs (Hicock *et al*., 1981; Nasmith and Buck, 1998). In the following discussions, the Vashon till and underlying Pleistocene deposits are grouped together as "older Pleistocene deposits", because they are overconsolidated and generally have high shear-wave velocities (Monahan and Levson, 1997).

The Vashon Till is overlain by the Capilano sediments, which were deposited at the close of the Fraser Glaciation when sea level was higher than present (Armstrong, 1981, 1984). The principal units of the Capilano sediments in the Victoria area are the Victoria clay and the Colwood sand and gravel. Shells in these units have provided several radiocarbon dates between 12,100 and 12,750 ^{14}C years B.P. (Dyck *et al*., 1965, 1966; Lowden *et al*., 1971). These deposits are equivalent to those of the Everson Interstade of northwestern Washington (Easterbrook, 1992, Dethier *et al*., 1995).

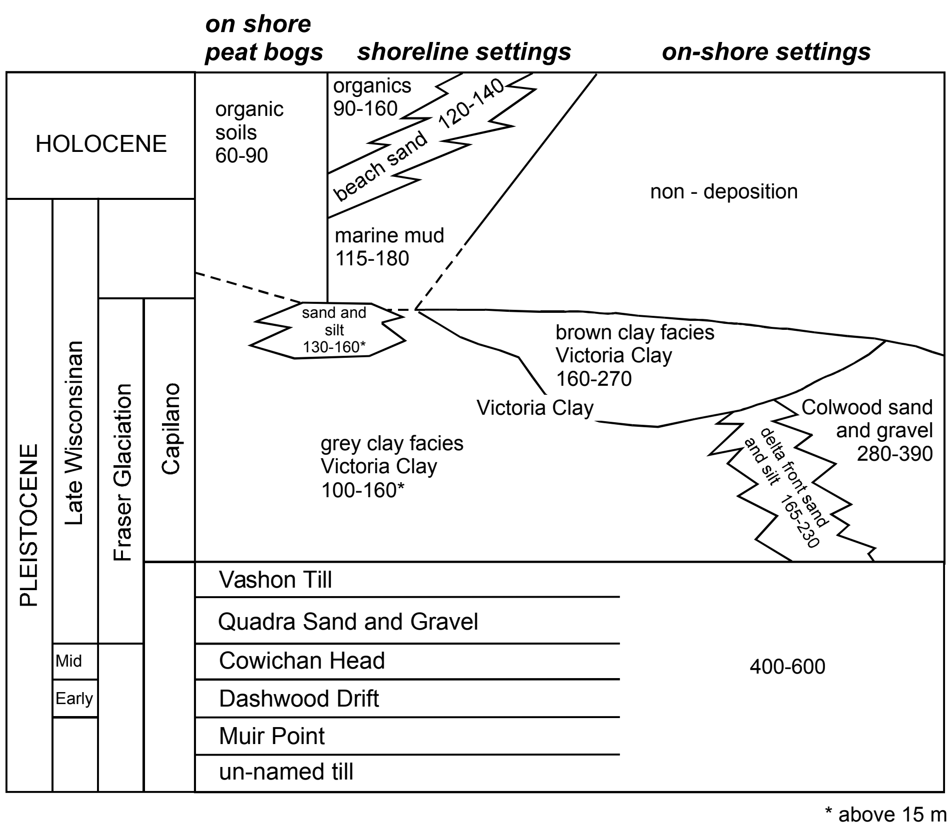

Figure 1. Stratigraphic chart of Quaternary Formations showing range of shear-wave velocities, in m/sec (± 1 standard deviation). From Monahan and Levson, 1997.

The Victoria clay is a unit of glaciomarine clayey silt with scattered pebbles that forms a blanket-like deposit generally below an elevation of 60 metres, but locally up to about 75 metres. It ranges in thickness from zero over bedrock knolls to 30 metres in depressions on the till or bedrock surface. The Victoria clay has three distinct facies. A lower, soft to firm, grey clay (grey clay facies) is in most places gradationally overlain by a desiccated and oxidized crust of stiff, brown clay (brown clay facies) 2 to 5 metres thick (Crawford and Sutherland, 1971; Buchanan, 1993, 1995; Nasmith and Buck, 1998). These two facies were deposited in the same depositional environment and are distinguished on the basis of post-depositional changes. The Victoria clay commonly coarsens slightly upward, and a sand facies occurs locally near the top. The sand facies varies over very short distances from clean, medium sand, up to several metres thick, to sand beds less than 1 metre thick interbedded with either grey or brown clay (Figure 2). Where the sands occur above the water table, they are heavily oxidized. The sand facies is interpreted to represent shoreline and nearshore deposits formed as sea level fell during deglaciation (Monahan and Levson, 1997; Nasmith and Buck, 1998).

The brown clay facies of the Victoria clay is at the surface in most of the Victoria area. However, in closed depressions and other low-lying areas, the brown clay facies is absent and the Victoria clay is gradationally overlain by up to 6 metres of organic silt and peat that represent lake and bog deposits (Nasmith and Buck, 1998). Deposition of organic soils commenced before the end of the Pleistocene, based on radiocarbon dates from the base of these deposits (Dyck *et al*., 1966), and continued throughout the Holocene (*e.g.* Lowdon *et al*., 1971). They are referred to here as Holocene organic soils. The upper part of the grey clay facies is slightly overconsolidated where overlain by the brown clay facies, but normally consolidated where overlain by Holocene organic soils (Figure 2; Nasmith and Buck, 1998).

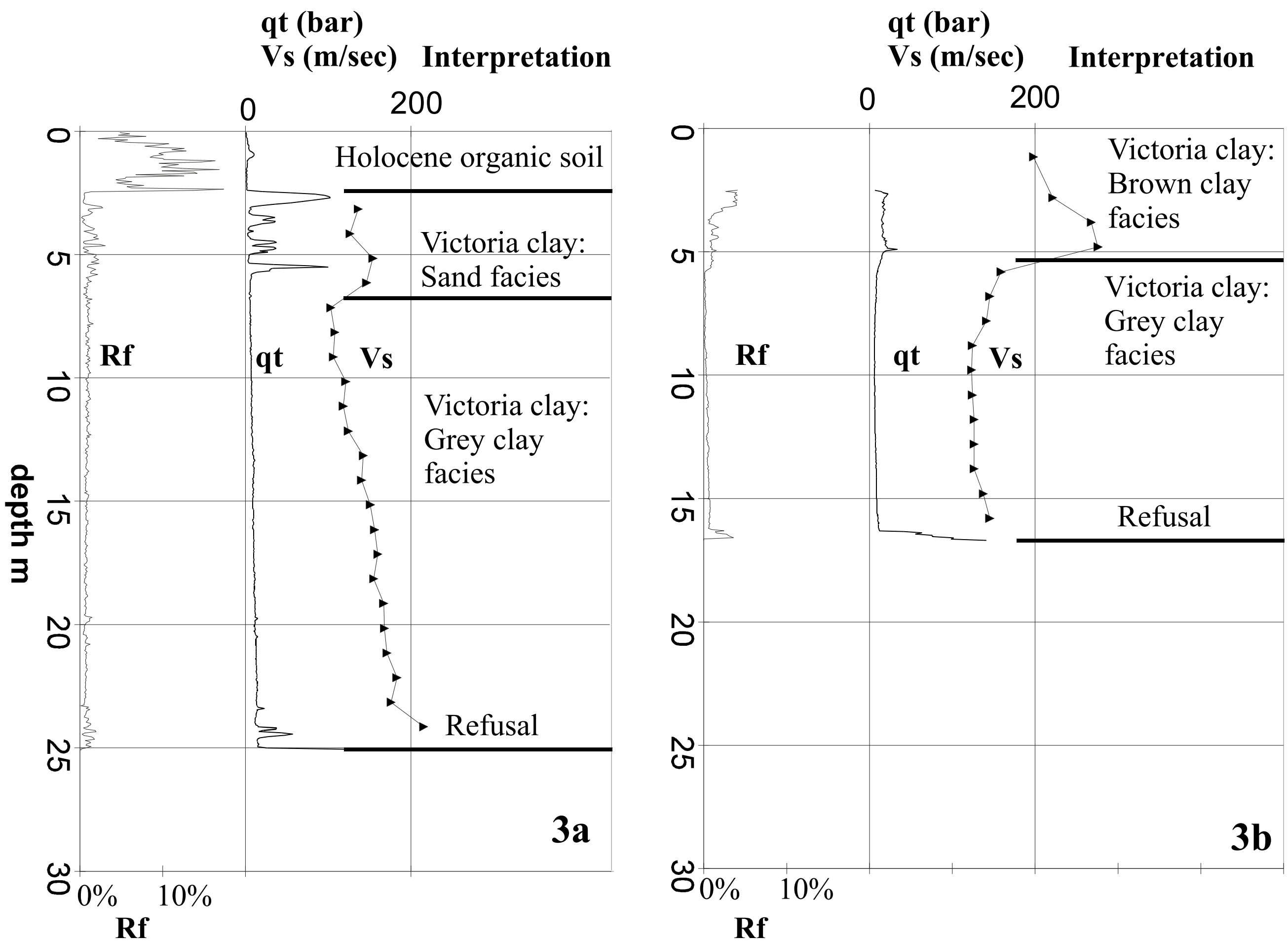

Figure 2. SCPT profiles through Victoria clay, Rf = friction ratio, qt = tip resistance, Vs = shear wave velocity: 2a) Victoria clay overlain by Holocene peat and organic soil (map unit O1); note that grey clay facies is normally consolidated (Vs and qt increase with depth) and presence of sand facies at top of clay; 2b) grey clay overlain by brown clay (map unit C2), note that upper part of grey clay is slightly overconsolidated (Vs and qt decrease with depth).

The Colwood sand and gravel is a glaciofluvial outwash and deltaic deposit that occurs at the surface over much of Colwood and Langford (Figure 3). It has been described briefly by Howes and Nasmith (1983), Blyth and Levson (1993), Huntley (1995) and Yorath and Nasmith (1995). The maximum known thickness of the Colwood sand and gravel is 30 metres, and the thickness is probably greater over much of the delta and outwash plain. These deposits overlie bedrock near the margins of the delta and outwash plain, but in the gravel pits south of Esquimalt Lagoon they overlie older Pleistocene deposits that are locally over 50 metres thick. In exposures in these gravel pits, topset deposits a few metres thick overlie gravel and sand foreset deposits dipping 15° to 25° to the southeast.

The delta and outwash plain is between 60 and 90 metres elevation and its apex is located on the Goldstream River upstream of Langford. Its surface has been incised by late-stage glaciofluvial channels and contains closed depressions interpreted to be kettles. Some of these channels and depressions are still occupied by creeks and lakes, and are in part filled with peat. Silts occur in some abandoned channel deposits in the topset of the delta. Wood found in topset deposits of the Colwood delta during this study yielded a radiocarbon date of 12,360$\pm$70 ^{14}C years B.P. (Beta 109128).

Deposits of silt up to several metres thick interbedded with sands have been observed in testholes and exposures on the delta slope on the northeast and southeast sides of the delta (Figure 4). These are interpreted to represent distal and lateral foreset deposits (Monahan and Levson, 1997). Similar sediments likely underlie other parts of the delta plain. The slope northwest of Esquimalt lagoon is interpreted to be the flank of a large kettle rather than the primary delta slope, because the delta prograded around the lagoon without filling it (Howes and Nasmith, 1983; Yorath and Nasmith, 1995).

In the vicinity of Happy Valley Road, glaciofluvial sands and gravels are overlain by 1 to 2 metres of silt interpreted to be a late-stage glaciolacustrine deposit. In the valley of Millstream Creek, immediately upstream from the Colwood delta and outwash plain, up to 14 metres of stiff clay and interbedded fine sand occurs in testholes and surface exposures. These deposits are interpreted here to represent glaciolacustrine deposits marginal to the Colwood delta and outwash plain, and similar deposits are inferred to occur in other small valleys adjacent to the Colwood delta and outwash plain.

In shoreline and nearshore settings, the brown clay facies of the Victoria clay extends below modern sea level, because relative sea level fell below its modern position in the latest Pleistocene and earliest Holocene (Mathews *et al*., 1970; Clague *et al*., 1982; Hutchinson, 1992). The extent of sea level fall was at least 25 metres, because brown clay has been reported in boreholes examined in the course of this study up to this depth below modern sea level, and may have been as much as 50 metres (Linden and Schurer, 1988). In these settings, the brown clay facies is overlain by Holocene marine mud deposited during the Holocene rise in sea level (Figure 5; Crawford and Sutherland, 1971; Nasmith and Buck, 1998). Holocene marine muds are locally overlain by prograding shoreline sands, derived from erosion of nearby sandy head-

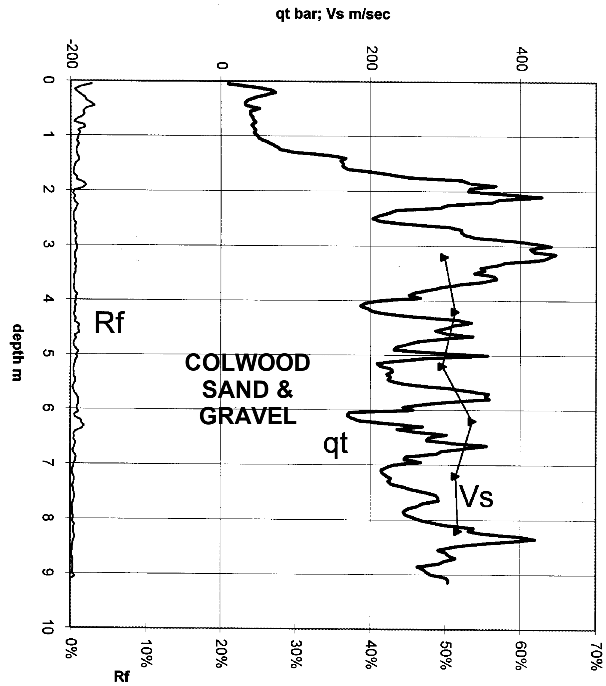

Figure 3. SCPT profile through sands and gravels of Colwood delta and outwash plain (map unit G1), Rf = friction ratio, qt = tip resistance, Vs = shear wave velocity.

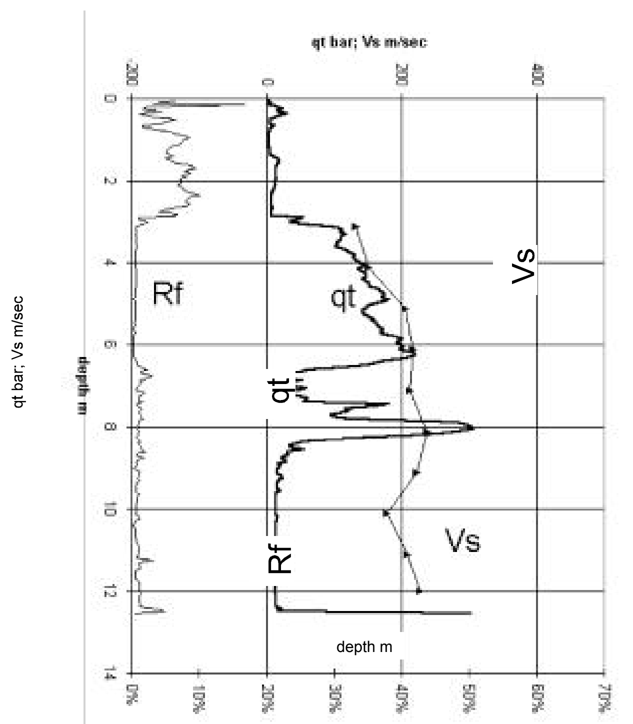

Figure 4. SCPT profile through lateral foreset deposits of Colwood delta (map unit G2), Rf = friction ratio, qt = tip resistance, Vs = shear wave velocity. From Monahan and Levson, 1997.

lands. Shoreline sands are in turn locally overlain by peat (Figure 6). In some places, shoreline peat deposits are overlain by recent beach sands and intertidal sediments, possibly reflecting earthquake-related elevation changes (Clague, 1989; Clague and Bobrowsky, 1990; Bobrowsky and Clague, 1992; Mathewes and Clague, 1994; Clague, 1996; Monahan and Levson, 1997).

GEOLOGICAL MAPPING

The initial step in evaluating the variation of earthquake hazards in the Victoria area was the preparation of a geological map that shows the thickness and distribution of Quaternary stratigraphic units (Monahan and Levson, 2000). Subsurface geological data on which the geological map is based include: over 5000 geotechnical borehole logs obtained from a variety of public and private agencies; several hundred water well logs obtained from the Groundwater Section of the Ministry of the Environment and that are available on the internet (http://www.env.gov.bc.ca/wat/gws/); nearly 3000 engineering drawings for municipal sewer and water lines, that commonly show where bedrock was encountered in excavations; and data from a shear-wave testing program conducted to determine the average shear-wave velocities for the principal Quaternary geological units (Monahan and Levson, 1997).

Geological map units were defined on the basis of these data (Table 1) and in part to coincide with the U.S. National Earthquake Hazard Reduction Program (NEHRP) definitions of site classes for susceptibility to amplification of ground motion (Table 2; Building Seismic Safety Council, 1994). Map unit boundaries were interpreted on the basis of the subsurface data, airphotos (~1:20,000 black and white dated 1974 and ~1:5000 colour dated 1990) and large-scale topographic maps (1:2000 to 1:5000). Soils maps by Day *et al*. (1959) and Jungen (1985) also provided useful information. Limited field checking was conducted.

In areas with little or no subsurface data, the subsurface conditions are largely *inferred* from topographic and geomorphic evidence. For example, scattered bedrock with thin soil cover (unit R2), generally occurs in hills and upland areas, and thick soft glaciomarine clays (units C2 and O1) generally occur in low-lying areas. Also in areas little or no subsurface data, map unit C1 was applied to areas of sloping ground between occurrences of units R2 and C2, and in these areas represents an uncertain proportion of both these units. To assist the user in determining the accuracy of the subsurface geological mapping, sites where subsurface geological data were obtained are shown on the accompanying geological map and amplification hazard and liquefaction hazard maps.

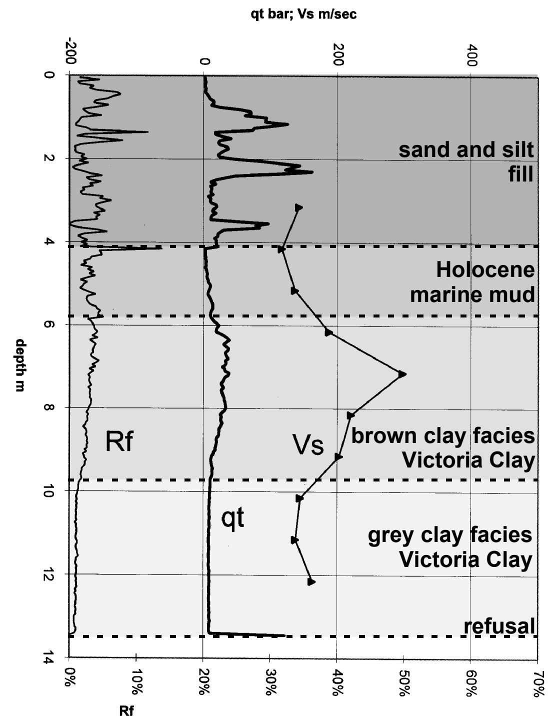

Figure 5. SCPT profile through fill, Holocene marine mud, brown clay facies, and grey clay facies, near Empress Hotel (map unit FC2), Rf = friction ratio, qt= tip resistance, Vs = shear wave velocity. From Monahan and Levson, 1997.

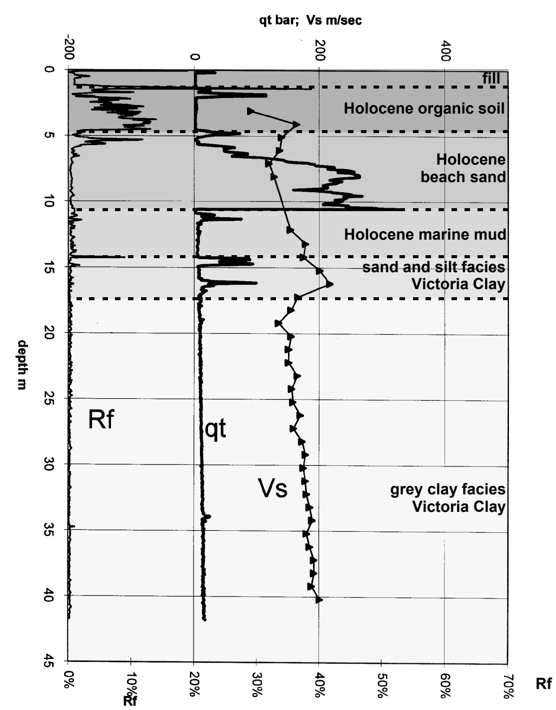

Figure 6. SCPT profile through Holocene peat, Holocene beach sand, Holocene marine mud and Victoria clay, Cadboro Bay (map unit O5), Rf = friction ratio, qt = tip resistance, Vs = shear wave velocity. From Monahan and Levson, 1997.

TABLE 1
GEOLOGIC MAP UNITS AND HAZARD RATINGS

Unit	Description	NEHRP Site Class	Amplification Hazard	Liquefaction Hazard
Areas with Anthropogenic Fill at the surface				
F	Anthropogenic fill	variable	*	high to very high**
FC2	Fill over unit C2 (thick soft clay)	D-E	moderate to high	high to very high**
FC1	Fill over unit C1 (variable and intermediate thicknesses of clay)	C-E	low to high	high to very high**
FG	Fill over unit G1 (Colwood sand and gravel)	D (locally D-E)	moderate (locally moderate-high)	high to very high**
FT	Fill over unit T (thick older Pleistocene deposits)	D-E	moderate to high***	high to very high**
FR2	Fill over unit R2 (thin soil cover over bedrock)	C-D	low to moderate	high to very high**
Areas with Holocene deposits at the surface				
S4	Holocene beach sands	variable	*	high to very high
S3	Stream deposits	variable	*	high to very high
S2	Goldstream delta deposits	D	moderate	high to very high
S1	Alluvial fan and fan delta deposits	variable	***	moderate to very high
O5	Holocene peat over Holocene beach sand	E-F	high to very high	high to very high
O4	Holocene peat over glaciolacustrine deposits	D-F	moderate to very high	low to moderate
O3	Peat over sand and gravel of the Colwood delta and outwash plain	D-F	moderate to very high	low to moderate
O3a	Closed depressions, interpreted to be kettles	D-F	moderate to very high	low to moderate
O2	Upland peat deposits*****	D-F	moderate to very high	very low to low
O1	Holocene peat over the grey clay facies of the Victoria clay	E-F	high to very high	very low to moderate

Areas with Holocene deposits at the surface

S4	Holocene beach sands	variable	*	high to very high
S3	Stream deposits	variable	*	high to very high
S2	Goldstream delta deposits	D	moderate	high to very high
S1	Alluvial fan and fan delta deposits	variable	***	moderate to very high
O5	Holocene peat over Holocene beach sand	E-F	high to very high	high to very high
O4	Holocene peat over glaciolacustrine deposits	D-F	moderate to very high	low to moderate
O3	Peat over sand and gravel of the Colwood delta and outwash plain	D-F	moderate to very high	low to moderate
O3a	Closed depressions, interpreted to be kettles	D-F	moderate to very high	low to moderate
O2	Upland peat deposits*****	D-F	moderate to very high	very low to low
O1	Holocene peat over the grey clay facies of the Victoria clay	E-F	high to very high	very low to moderate

TABLE 1 CONTINUED
GEOLOGIC MAP UNITS AND HAZARD RATINGS

Unit	Description	NEHRP Site Class	Amplification Hazard	Liquefaction Hazard
	Areas with Capilano deposits (latest Fraser Glaciation) at the surface			
C5	>3 metres of the grey clay facies of the Victoria clay over thick (>10 metres) older Pleistocene deposits	D-E	moderate to high	very low to low
C4	>5 metres of the Victoria clay and <3 metres of the grey clay facies, over thick (>10 metres) older Pleistocene deposits, as well as areas where units C3 and C5 cannot be differentiated with data available	C-E	low to high	very low to low
C4a	>5 metres of the Victoria clay and <3 metres of the grey clay facies, over thick (>10 metres) older Pleistocene deposits	C-D	low to moderate	very low to low
C4b	Areas where units C3 and C4 cannot be differentiated with data available, but the grey clay facies of the Victoria clay is <3 metres	C-D	low to moderate	very low to low
C3	<5 metres of the Victoria clay over thick (>10 metres) older Pleistocene deposits	C	low****	very low
C2	>3 metres of the grey clay facies of the Victoria clay, under the brown clay facies and over thin (<10 metres) older Pleistocene deposits	D-E	moderate to high	very low to low
C2a	Victoria clay over lower slopes of Colwood delta	D-E	moderate to high	very low to moderate
C1	Areas where units R2 and C2 cannot be differentiated with data available; also includes areas with >5 metres of the Victoria clay but <3 metres of the grey clay facies	C-E	low to high	very low to low
G4	Glaciolacustrine (?) deposits marginal to the Colwood delta	C-D	low to moderate	very low to low
G3	Late stage glaciofluvial channel on Colwood delta and outwash plain	D	moderate	low to moderate
G2	Distal and lateral foreset sands and silts of the Colwood delta	D	moderate	low to moderate
G1	Sand and gravel of the Colwood delta and outwash plain	D	moderate	very low to low*****
	Areas with Older Pleistocene Deposits (Vashon Till and older) at the surface			
T	Thick (>10 metres) older Pleistocene deposits	C	low ****	very low
Ta	Older Pleistocene at the surface indicated by smooth topography, but borehole data indicate that bedrock is locally shallow (<10 metres)	C	low****	very low
T/C3	Intermediate between units T and C3, typically areas with a discontinuous cover of Victoria clay over thick (>10 metres) older Pleistocene deposits	C	low****	very low
	Areas with bedrock at or near the surface			
R2	Thin soil cover over bedrock with scattered outcrops; generally <5 m of Victoria clay over <10 m of older Pleistocene; in Colwood delta, <5 m of Colwood sand and gravel over bedrock; in upland areas, <10 m sediment over bedrock	A-C	very low to low	very low
R2a	Areas of unit R2 where 5 to 10 metres of older Pleistocene deposits can be mapped	C	low	very low
R1/2	Areas of thin soil cover and nearly continuous outcrop undifferentiated	A-C	very low to low	very low
R1	Bedrock; nearly continuous outcrop	A-B	very low	very low

*Amplification variable, dependent upon adjoining map unit and underlying deposits
** Liquefaction hazard variable, but potentially high to very high; *see* text.
*** Amplification high because of thick fill
**** Amplification hazard may locally be greater than NEHRP ratings based on SHAKE results and the effects of historic earthquakes; *see* text.
***** Liquefaction hazard may locally be higher due to shallow or perched water table

TABLE 2
CATEGORIES FOR SOIL SUSCEPTIBILITY TO AMPLIFICATION
[DEFINITIONS FROM BUILDING SAFETY COUNCIL (1994);
DESCRIPTIVE SUSCEPTIBILITY RATINGS FROM KLOHN-CRIPPEN 1994]

Site Class	General Description	Definition (V_{s30}=average shear-wave velocity in upper 30 m, m/sec)	Susceptibility Rating
A	Hard rock	V_{s30}>1500	Nil
B	Rock	760<V_{s30}<1500	Very Low
C	Very dense soil and soft rock	360<V_{s30}<760; or >3 m of soil over bedrock, where V_{s30}>760 m/sec	Low
D	Stiff soils	180<V_{s30}<360	Moderate
E	Soft soils, or soil profile with >3 m soft silt and clay	V_{s30}< 180; or >3 m silt and clay with plasticity index >20, moisture content >40%, and undrained shear strength <25 kPa	High
F	Peats or highly organic clays	Peat thickness > 3 m	Very High (?)

RELATIVE AMPLIFICATION OF GROUND MOTION HAZARD MAP (Geoscience Map 2000-3b)

Amplification of ground motion refers to the increase in the intensity of ground shaking that can occur due to local geological conditions, such as the presence of soft soils. The amplification hazard map was prepared by assigning a relative amplification hazard rating or range of hazard ratings to each geological map unit (see also Table 1). Although this map is colour-coded as to the level of relative hazard, the geological map units are shown on the map and indicated by the appropriate label in each polygon (see legend and Map 1, Geoscience Map 2000-3b). The amplification hazard for each geological map unit is estimated on the basis of the NEHRP site classes for susceptibility to amplification.

NEHRP Site Class Definitions

The NEHRP site classes for amplification are defined primarily on the basis of the average shear-wave velocity in the upper 30 metres (V_{S30}; Table 2; Building Seismic Safety Council, 1994; Finn, 1996). V_{S30} is calculated using equation 1, which in effect calculates a shear-wave travel time in the upper 30 metres:

Equation 1

$$V_{S30} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{V_{Si}}}$$

Where d_i is the thickness and V_{Si} is the shear-wave velocity of any layer between 0 and 30 metres.

The descriptive susceptibility ratings shown on Table 2 are from Klohn-Crippen Consultants Ltd. (1994).

The NEHRP site classes range from "hard rock" and "rock" (site classes A and B respectively), in which V_{S30} exceeds 760 m/sec and which have no to very low susceptibility to amplification, to "soft soil" (site class E), in which V_{S30} is less than 180 m/sec and which has a high susceptibility to amplification. Furthermore, site classes A and B are limited to sites with less than 3 metres of soil over bedrock; and site class E also includes sites underlain by more than 3 metres of soft clay or silt, which is defined as having a plasticity index greater than 20%, a water content greater than 40% and an undrained shear strength less than 25 kPa. Site class F includes areas with greater than 3 metres of peat and is potentially susceptible to very high amplification.

[2]*The critical periods of ground period for specific buildings or building types should be determined by a qualified structural engineer.*

NEHRP Amplification Factors

The amplification factor is the amount by which the intensity of ground motion during an earthquake is *multiplied* due to soil conditions. Amplification factors for the NEHRP site classes for various intensities of ground motion on bedrock (expressed as a fraction of "g", the acceleration due to gravity) and for short and long period ground motions are shown in Table 3 (Building Seismic Safety Council, 1994; Finn, 1996). Short period ground motions typically affect short buildings and long period ground motions typically affect tall buildings, such as high rise structures[2]. Both short and long period ground motions occur during an earthquake, but usually one type dominates depending on earthquake magnitude and distance from the source. The NEHRP amplification factors are average values based on a large number of site response analyses, largely for California sites (Finn, 1996), and are being adapted for use in the 2000 building code in Canada. It should be noted that the NEHRP amplification factors are expressed relative to bedrock (*i.e.* site class B), whereas in the Canadian building codes, amplification is expressed relative to "firm ground", equivalent to NEHRP site class C (National Research Council of Canada, 1995).

TABLE 3
NEHRP AMPLIFICATION FACTORS (MODIFIED FROM BUILDING SEISMIC SAFETY COUNCIL, 1994)

a) short period motions (0.1 to 0.5 seconds)

Site Class	Approximate peak ground acceleration on bedrock				
	0.1 g	0.2 g	0.3 g	0.4 g	0.5 g
A	0.8	0.8	0.8	0.8	0.8
B	1	1	1	1	1
C	1.2	1.2	1.1	1	1
D	1.6	1.4	1.2	1.1	1
E	2.5	1.7	1.2	0.9	-
F	-	-	-	-	-

b) long period motions (approx. 1 second)

Site Class	Approximate peak ground acceleration on bedrock				
	0.1 g	0.2 g	0.3 g	0.4 g	0.5 g
A	0.8	0.8	0.8	0.8	0.8
B	1	1	1	1	1
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	-
F	-	-	-	-	-

Table 3 shows that ground-motion amplification diminishes as the strength of ground-shaking (*i.e.* acceleration) increases, because of the non-linear behaviour of soils. This reduction is more pronounced for short period ground motions than for long period ground motions. For example, at ground shaking levels of 0.1 g on bedrock (10% of the force of gravity, and approximately the onset of damage in buildings not designed to be earthquake resistant), short period ground motions can be amplified by a factor of 2.5 on soft soils of site class E (*i.e.* 0.25 g; see Map 2, Geoscience Map 2000-3b). Such was the case during the 1989 Loma Prieta earthquake. In the San Francisco Bay area, which was 100 km north of the epicentre, peak ground acceleration was amplified from less than 0.1 g on firm ground to 0.25 g on nearby soft soil sites (Clough *et al*., 1994). Consequently damage was concentrated in areas underlain by soft soils. However, at ground shaking levels of 0.4 g on bedrock (0.4 g is the current building code design acceleration for Victoria; National Research Council of Canada, 1995), amplification of short period ground motions due to soft soils is minimal, and all areas will be shaken strongly but more or less equally (*i.e.* 0.4 g; see Map 4, Geoscience Map 2000-3b). For long period ground motions, amplification also diminishes as the strength of ground motions increase, but can still be significant at O.4 g (Maps 3 and 5, Geoscience Map 2000-3b).

Consequently, amplification of acceleration in Victoria may be minimal for short period ground motions in the event of a large earthquake in close proximity to the city (*i.e. all* areas shaken strongly; Map 4 Geoscience Map 2000-3b), but could be significant for a large earthquake a few tens of kilometres distant and generating moderate shaking on firm ground in the city (Map 2, Geoscience Map 2000-3b). However, a moderate shaking event is *much more likely* to occur than a strong shaking event. For example in the Victoria area, shaking of 0.1 g on firm ground is more than ten times as likely to occur as shaking of 0.4 g on firm ground. Thus, areas underlain by to NEHRP site class E soils and assigned high amplification hazard (Map 1, Geoscience Map 2000-3b) will be subjected to potentially damaging ground motions *much more often* than areas assigned a low hazard. The variation in ground motion predicted using the amplification factors shown here does not exceed the seismic design criteria of the current building code (National Research Council of Canada, 1995), but could be significant for structures not governed by the seismic provisions of the code as well as older structures.

Application of NEHRP Site Classes to Amplification Hazard Ratings in Victoria

Shear-wave velocity data were derived from 15 seismic cone penetration tests (SCPTs) and 4 spectral analysis of surface wave tests (SASW) in the Victoria area (Appendix 1). These techniques are described by Robertson *et al*., 1992 and Stokoe *et al*., 1994, respectively. The shear-wave velocity data were used to develop a shear-wave velocity model for the principal Quaternary geological units (Table 4; Monahan and Levson, 1997), so that V_{S30} could be estimated in each geological map unit. The average shear-wave velocity of bedrock was assumed to be 1500 m/sec.

TABLE 4
SHEAR-WAVE VELOCITIES OF THE QUATERNARY UNITS
(MODIFIED FROM MONAHAN AND LEVSON 1997)

Stratigraphic unit	most common map units	number of sites	number of values	V_s average (V_s av) m/sec	V_s av ± 1 standard deviation m/sec	V_s minimum m/sec	V_s maximum m/sec
Anthropogenic fill	F	4	5	140	112-167	102	180
Holocene organic soils	O1, O2, O3, O3a, O4, O5	3	9	85	52-113	40	164
Holocene beach sand	S4, O5	1	4	131	122-140	120	140
Holocene marine mud	FC2, O5, S1	2	4	147	121-173	117	178
Victoria clay, sand facies	R2, C1-C5, O1,	2	7	165	131-199	126	217
Victoria clay, brown clay facies	R2, C1-C5	9	31	213	166-260	121	298
Victoria clay, grey clay facies	C1, C2, C4, C5, O1, O5	10	126	147	114-180	89	279
Victoria clay, grey clay facies <15 m depth*	C1, C2, C4, C5, O1, O5	9	69	132	104-160	89	214
Colwood delta top	G1	2	15	335	282-388	225	425
Colwood delta distal and lateral foreset sands and silts	G2	1	10	199	165-233	133	237
Older Pleistocene	R2a, T, Ta, T/C3, C3-C5	3	17	499	420-577	350	650

* V_s normally increases with depth in normally consolidated deposits such as the the grey clay facies, so that the values on this line should be used to estimate the V_s profile where the grey clay facies is shallower than 15 m.

Map units in which bedrock is near the surface (R1 and parts of R1/2 and R2) are assigned to NEHRP site classes A and B (very low susceptibility to amplification). Map units consisting of stiff and/or dense soils 3-10 metres thick over bedrock (R2a, and parts of R1/2, R2, G4 and C1) and those dominated by older Pleistocene deposits (T, Ta, T/C3, C3 and parts of C4a, C4b and C4), have estimated V_{S30} greater than 360 m/sec, and are assigned to NEHRP site class C (low susceptibility to amplification). Map units consisting of deposits of the Colwood delta and outwash plain and related deposits (G1, G2, G3, and parts of G4, O3, O3a and O4; Figures 3 and 4; Table 4), and thick accumulations of the brown clay facies of the Victoria Clay (parts of C4, C4a and C4B) have estimated V_{S30} between 180 and 360 m/sec, and are assigned to NEHRP site class D (moderate susceptibility to amplification). Although the subsurface conditions of the Goldstream River delta are unknown, the delta is inferred to be underlain by firm to stiff silts and sands meeting the criteria for NEHRP site class D.

In map units with more than 3 metres of the grey clay facies of the Victoria Clay (C2, C5, O1 and O5, and parts of C1 and C4; Figure 2), estimated V_{S30} generally varies from 150 m/sec to 360 m/sec, meeting the criteria for NEHRP site classes D and E. Because the grey clay facies commonly meets the criteria for soft clay, much of these units could also be assigned to NEHRP Site Class E on the basis of soft clay thickness greater than 3 metres (Table 2). However, not all of the grey clay facies is soft. In deeper occurrences, the shear strength exceeds 25 kPa due to the normal increase of shear strength with depth. Furthermore, the upper part of the grey clay facies is commonly slightly overconsolidated where overlain by the brown clay facies (Figure 2; Nasmith and Buck, 1998), and sandy intervals occur locally in the grey clay facies; and in these cases the grey clay does not meet the criteria for soft clay. Consequently, the map units in which the grey clay facies is overlain by the brown clay facies (C2 and C5 and parts of C1and C4) are assigned to site classes D and E (moderate to high susceptibility to amplification). In the map units in which the brown clay is absent (O1 and O5), the grey clay is generally thicker and normally consolidated throughout, and these units are assigned to site class E (high susceptibility to amplification).

Areas underlain by more than 3 metres of peat (parts of map units O1, O2, O3, O3a, O4 and O5; Figure 6) are assigned to Site Class F (very high susceptibility to amplification). The lower end of the hazard range for map units O1 and O3 to O5 are defined in preceding paragraphs, but map unit O2 is not well known form borehole data and is conservatively given a lower hazard range of moderate.

The NEHRP site classes assigned to Holocene sands and most anthropogenic fills (map units S1, S3, S4, and F - including FR2, FG, FC1, FC2 and parts of FG) are variable, depending on the deposits these materials overlie. However, some thick loose fills overlying older Pleistocene deposits and part of the Colwood delta have estimated V_{S30} between 170 and 270 m/sec, and are assigned to site classes D and E (moderate to high susceptibility to amplification).

Shake Analyses

Shake analyses were conducted at seven sites to provide further insights into the amplification hazard. SHAKE is a computer program for estimating site response due to ground shaking using a one dimensional site-specific soil column and earthquake record as input data (Schnabel *et al*., 1972). In these analyses, the following earthquake sources were considered, which represent two out of many possible scenarios that could affect the city:

1) a strong local earthquake, with a peak acceleration on bedrock of 0.34 g. This earthquake was modelled using 5 records from the Loma Prieta and Northridge earthquakes.
2) a subduction earthquake, with a peak acceleration on bedrock of 0.12 g. This earthquake was modelled using 2 records from the 1985 Mexico City Earthquake.

The results of SHAKE analyses are dependent upon the specific earthquake records used.

The results of the SHAKE analyses are summarized in Appendix 2. At most sites, amplification of acceleration is lower for the local earthquake than for the subduction earthquake, because amplification diminishes at higher intensities of ground motion on firm ground and the subduction earthquake has more long period ground motions (Table 3). However, the limited results do not faithfully replicate the NEHRP amplification factors. Sites with thick NEHRP site class C and D soils, amplified acceleration as much or more than sites with NEHRP site class D and F soils, possibly because of resonance in the soil column. The SHAKE analyses suggest that with the right earthquake and ground conditions, significant amplification can occur in all map units where a significant thickness of sediments overlies bedrock.

Effects of Historic Earthquakes

The effects of historic earthquakes in the Victoria area are generally consistent with the NEHRP site classes. Damage in the City of Victoria from the 1946 Vancouver Island earthquake was concentrated in areas underlain by soft soils (map unit O1 and parts of C2) and the effects were the least where bedrock is near surface (map units R1, R1/2 and R2; Hodgson, 1946; Wuorinen, 1974, 1976). A survey of 125 sites following the May 1996 M_w=5.1 Duvall, Washington earthquake, indicated that it too was felt most strongly on soft soils and least strongly where bedrock is near surface (Levson *et al*., 1998). However, limited results from this survey indicate that the Duvall earthquake was felt nearly as strongly on older Pleistocene deposits (map units C3, T and R2a; NEHRP site class C) as on some soft soils (map unit C2; NEHRP site classes D and E).

Limitations of the NEHRP Site Classes for Amplification Hazard Mapping

The NEHRP site classes have been defined on the basis of a large number of site response analyses and reflect the amplification hazard in a general way. However, their use has some specific limitations, which must be understood. The decrease in amplification factors with an increase in the intensity of ground motions due to the non-linear behaviour of soils (Table 3) has been discussed above. Furthermore, the SHAKE analyses and observations during historic earthquakes indicate that amplification factors may in some circumstances differ from those predicted by use of the NEHRP site classes. These differences are probably largely due to resonance.

NEHRP site classes do not specifically address amplification due to resonance in the soil column. In amplification due to resonance, amplification factors for specific periods of ground motion that coincide with the natural periods of the site can be much greater than shown in Table 3. Amplification due to resonance can be particularly damaging to structures whose natural periods match those of the site (Reiter, 1990; Rial *et al*., 1992). The fundamental period (T) of a site can be estimated by:

Equation 2

$$T = 4\frac{H}{V}$$

Where: H = thickness of the soils; and V= average shear-wave velocity of the soils.

Equation 2 defines the site period at low strain, but due to the non-linear behaviour of soils, the site period experienced at large strain during an earthquake is somewhat greater. However, equation 2 provides reasonable order of magnitude estimates of site periods (compare low strain periods and site periods derived from the SHAKE analyses in Appendix 2). The average shear-wave velocity, and thus the site period, can be estimated where the stratigraphy is known using the shear-wave velocity model discussed above (Table 4). Periods for the SCPT sites using equation 2 are reported in Appendix 1. Amplification due to resonance must be analysed on a site-specific basis.

The natural period of a building can be roughly estimated by multiplying the number of stories by 0.1 second. However, there are many exceptions to this rule, and a qualified structural engineer should be consulted to provide the natural period for a specific building or building type.

The NEHRP site classes do not address amplification of ground motion due to topography, which can exceed amplification due to soil conditions in some cases. High amplification is commonly experienced on hills, ridges and the tops of cliffs (Geli *et al*., 1988; Finn, 1994; Somerville, 1998), which are generally underlain in the Victoria area by thin and/or dense soils and bedrock (map units R1, R1/2, R2, and T). Consequently, the very low and low hazard ratings assigned to these map units may not apply on such topographic features. Amplification due to topography is poorly understood and not readily quantified at this time.

The NEHRP Site Classes do not address amplification due to three-dimensional effects, such as the focusing of energy by buried bedrock structures, or basin edge effects (Somerville, 1998). Amplification due to three-dimensional effects can be as great as amplification due to soil.

The amplification hazard map reflects variations in earthquake hazard due to soil conditions, which are applicable to most earthquakes that will affect the region. Topographic and three-dimensional effects are more dependent on the earthquake location and direction of seismic energy.

RELATIVE LIQUEFACTION HAZARD MAP
(Geoscience Map 2000-3a)

Liquefaction is the transformation that occurs when earthquake shaking (or other disturbance) causes a saturated granular soil (*e.g.* sand) to lose its strength and behave like a liquid. Liquefaction can be one of the major causes of damage during an earthquake. The susceptibility of a site to liquefaction is dependent upon the depth to the water table and the density, grain size and age of the underlying deposits (*e.g.* Youd and Perkins, 1978).

This map was prepared by assigning a hazard rating or range of hazard ratings to each geological map unit based on these criteria and a suite of quantitative analyses using a modified version of PROLIQ2 and similar probabilistic analyses (Monahan *et al*., 1998). Although this map is colour-coded as to the level of hazard, the geological map units are shown on the map and indicated by the appropriate label in each polygon (see legend). PROLIQ2 (Atkinson *et al*., 1986) estimates the probability that liquefaction will occur at a site by combining Seed's method of determining liquefaction susceptibility (Seed *et al*., 1985) with the probabilistic seismic model developed for the National Building Code of Canada (National Research Council of Canada, 1995). However, the severity of surface disruption caused by liquefaction is a function of the depth and thickness of the liquefied units. Consequently, Klohn-Crippen Consultants Ltd. introduced the term "probability of liquefaction severity" (PLS), in which a depth-weighting function is applied to the layer by layer probabilities of liquefaction calculated in PROLIQ2 (Levson *et al*., 1996a, b, 1998). PLS is defined by:

Equation 3
$$PLS = \frac{\sum\left(W_i H_i Pl_i\right)}{\sum\left(W_i H_i\right)}$$

Where Pl_i is the probability of liquefaction at depth i (calculated from 0 to 20 metres), H_i is the layer thickness, and W_i is the weighting function that decreases linearly from 0.1 at the surface to 0 at a depth of 20 metres. Hazard ratings are assigned to specific PLS ranges (Table 5; Levson *et al*., 1996b).

TABLE 5
LIQUEFACTION HAZARD RATINGS

PLS (in 50 years)	Hazard Rating
>25%	very high
15-25%	high
5-15%	moderate
2-5%	low
0-2%	very low

Thirty-one PLS analyses were conducted, with sand density estimated primarily on the basis of dynamic cone penetration tests (DCPTs; Table 6). DCPT blowcounts are approximately equivalent to standard penetration test (SPT) blowcounts at shallow depths, and have been used in this way here. Cone penetration test (CPT) tip resistance

TABLE 6
PLS SUMMARY

Stratigraphic Unit	Most Common Map units	Number of Boreholes	PLS %
Holocene beach sand	S4, O5	2	22+7
Victoria clay; sand facies	R2, C1-C5, O1, O5	6	4.5+3
Colwood delta plain	G1	11	2+2
Colwood delta distal and lateral foreset	G2	5	6+4
Colwood delta late stage channel	G3	1	5.6
Anthropogenic fill	F*	6	16+11

* including F2, FT, FG, FC1 and FC2

and shear-wave velocity data are also used to estimate liquefaction susceptibility, using the relationships defined by Robertson and Fear (1996) and Robertson *et al*. (1992), respectively (*see* also Boulanger *et al*., 1997).

The principal stratigraphic units susceptible to liquefaction are the sand facies of the Victoria clay, the Colwood sand and gravel, Holocene sands and modern anthropogenic fills (Tables 1 and 6). Older Pleistocene sands are generally too dense to liquefy; SPT blowcounts in the Quadra sand exceed 70, and shear-wave velocities generally exceed 500 m/sec in the older Pleistocene deposits (Monahan and Levson, 1997).

The sand facies of the Victoria clay varies from clean medium sand, up to 4 metres thick, to sand beds less than 1 metre thick interbedded with clay and silt (Figure 2). The sand facies changes over very short distances, so that its thickness and distribution cannot be mapped with the data available. Furthermore, it occurs near the top of the Victoria clay and is generally subject to seasonal variations in saturation. PLS values, based on fully saturated sands, average 4.5±3% (Table 6). Consequently, map unit O1, in which the sand is usually saturated, is assigned a very low to moderate hazard. However, those map units in which the sand is saturated seasonally are assigned a very low liquefaction hazard in upland areas (map units R2 and C3), where the sands are likely to be saturated infrequently, and a very low to low liquefaction hazard elsewhere (map units C1, C2, C4, C4a, C4b and C5). The liquefaction hazard estimate is conservative, because well developed sands occur only locally in the Victoria clay.

The Colwood sand and gravel is commonly too dense to be susceptible to liquefaction (average shear-wave velocity is 335 m/sec; Figure 3; Table 4; Monahan and Levson, 1997) and the water table is commonly deep (*i.e.* greater than a few metres). In map unit G1 on the delta plain, PLS averages 2 ± 2% (Table 6). Consequently, this map unit is assigned a very low to low liquefaction hazard. However, in the parts of the Colwood delta and outwash plain that are sand-rich and/or where the water table tends to be shallow, the liquefaction hazard ranges from low to moderate: on the distal and lateral foresets (map unit G2, Figure 4), where PLS averages 6±4%; in the late stage channel facies (map unit G3), where PLS is 5.6% at one site; and where peat overlies the Colwood sand and gravel (map units O3 and O3a; Table 6).

Capilano-age sands occur in other map units and are interpreted to have similar characteristics as sands in the Victoria clay and the Colwood sand and gravel. The liquefaction hazard is interpreted to be very low to low where the sands are thin (map unit O2) or the water table is deep (map unit G4), and low to moderate where the sands are thicker and the water table is shallow (map unit O4).

Of the Holocene deposits susceptible to liquefaction, quantitative data to assess liquefaction susceptibility are available only for the beach sands (representative of map units O5 and S4). At Cadboro Bay, PLS is estimated to be 27% based on DCPT data. Other data from the site are equivocal: a PLS value of 16% is estimated in the same sand from shear-wave velocity data in a nearby SCPT, although the CPT tip resistance in much of the sand is very high indicating a lower PLS (Figure 6; Monahan and Levson, 1997). However, the latter may be a grain-size effect, with coarser or gravelly sands showing a higher tip resistance (Lunne *et al*., 1997; Monahan *et al.* 1995; Monahan, 1999). The sand unit on which the PLS calculation was performed is overlain by peat, which is in turn overlain by the modern beach sand in seaward parts of the site. The modern beach sand is locally 5 metres thick. Although no quantitative geotechnical data are available in this sand, it is probably more susceptible to liquefaction than the sand evaluated because it is younger. Consequently, areas underlain by Holocene beach sand (map units O5 and S4) are assigned a high to very high liquefaction hazard. Consistent with this assignment, many sandy shoreline deposits on the east coast of Vancouver Island liquefied during the 1946 Vancouver Island Earthquake (Hodgson, 1946; Rogers, 1980). Although borehole data are not available in other Holocene sandy deposits, these sediments are probably also highly susceptible to liquefaction. They are assigned a high to very high liquefaction hazard, where the water table is shallow (i.e. within a few metres of surface; map units S2 and S3), and moderate to very high where the depth to water table may be locally deeper (map unit S1).

Modern anthropogenic fills consist of a variety of materials varying from silt and clay to sands. The principal areas of fill are in shoreline settings, commonly associated with port facilities, and reclaimed gravel pits. The thickness of fill can exceed 10 metres. The properties of fills vary from dense engineered fills with a very low liquefaction hazard to loose fills with a very high liquefaction hazard. Insufficient data were available to distinguish these regionally, so that all fills mapped were assigned a high to very high hazard, to indicate that such a hazard *could* be present. PLS estimates for 6 fills analysed average 16±11% (Table 6). Historically, non-engineered fills perform very poorly in earthquakes.

QUALIFICATIONS AND LIMITATIONS OF THESE MAPS

1. **These maps are intended for regional purposes only, such as land use and emergency response planning, and should not be used for site-specific evaluations.**
2. These maps are based on interpretations of borehole records, the *approximate* locations of which are shown. Where borehole data are scarce, subsurface conditions had to be *inferred* from topographic and geomorphic evidence.
3. T he boundaries of most map units are gradational, particularly in the Victoria area due to the extreme irregularity of the bedrock surface. For these reasons, map unit boundaries are *approximate*, may enclose smaller occurrences of other map units, and are subject to revision as more borehole data become available. Furthermore, geological materials are variable,

and deposits of a map unit locally may have unusual properties. **Consequently, the hazard *at a specific site* could be either higher or lower than that shown on these maps.**

4. This map does not fully address man-made alterations to ground conditions, whether the changes lower or increase the hazard at a site. Poor soil sites may have been improved during construction, which will change the hazard rating from that shown on the maps.
5. Only the larger anthropogenic fills of which the authors were aware are shown on the maps. Other areas of fill may be present, and new areas of fill will be developed in the future. As noted above, the properties of fills vary widely, from dense engineered fills suitable for foundations to loose fills potentially with very to very high amplification and liquefaction hazards. Because these could not be distinguished on a regional basis with the data available, all fill units were assigned a high to very high hazard to indicate that such a hazard *could* be present. Non-engineered fills historically perform very poorly in earthquakes.
6. The stability of dams under earthquake shaking, and hazards due to the failures of dams or other man-made structures have not been addressed.
7. These maps show the variation in the earthquake hazard due to amplification of ground motion and liquefaction. However, a low hazard on these maps does not mean freedom from earthquake hazards, because all areas could be subjected to significant ground shaking during an earthquake. Furthermore, the degree of amplification on soft soils diminishes as the intensity of ground shaking on firm ground increases, so that in the case of a strong earthquake close to the city, little variation in ground shaking may occur due to local soil conditions at short period ground motions. However, the city will be affected more often by more distant earthquakes that generate moderate shaking on firm ground, so that areas shown with a high amplification hazard here (Geoscience Map 2000-3b) will be subjected to potentially damaging ground motions more often than sites with a low amplification hazard. The variation in ground motions predicted using the amplification factors shown here does not exceed the seismic design criteria of the current building code (National Research Council of Canada, 1995), but could be significant for structures not governed by the seismic provisions of the code as well as older structures. See the section on amplification of ground motion for more details.
8. The amplification of ground motion hazard has been estimated on the basis of the National Earthquake Hazard Reduction Program (NEHRP) site classes for susceptibility to amplification of ground motion (Building Seismic Safety Council, 1994), which are based on the average response of various types of soils. **Thus, variation in amplification factors within a site class is to be expected. In addition, the amplification hazard map does not address:**
    - amplification of ground motion due to resonance, which can be particularly destructive to structures whose natural periods match those of the site (Reiter, 1990; Rial *et al*., 1992);
    - amplification of ground motion due to topography, by which ground motions can be amplified on hills, ridges and the tops of cliffs (Geli *et al*., 1988; Finn, 1994; Somerville 1998); and
    - amplification due to three-dimensional effects, such as the focusing of energy by buried bedrock structures (Somerville 1998).
9. Hazards due to earthquake-induced landslides are addressed on a companion map (McQuarrie and Bean, 1998). However, other earthquake hazards, such as tsunamis, land subsidence and ground rupture are not addressed on this or any companion maps published as part of this investigation.
10. Furthermore, these maps can not be used to ***directly*** **predict the amount of damage that will occur at any one site because many other factors, such as building design and construction details, must be considered.** The maps in no way shows how different types of buildings or other man-made structures will perform during earthquakes. They can be used to estimate the relative natural hazard due to the susceptibility to soil amplification and liquefaction alone.

EXPANDED LEGEND

In this section, each map unit is described in detail and the amplification and liquefaction hazards are summarized. For details regarding the estimation of these hazards, the reader should refer to the relevant sections above (see also Table 1).

AREAS WITH BEDROCK AT OR NEAR SURFACE

Unit R1; Bedrock

This unit consists of nearly continuous outcrop and generally occurs in hilly and mountainous areas. This map unit is assigned to NEHRP site classes A and B, and a very low amplification hazard. However, high topographic amplification can occur on hills, ridges and the tops of cliffs (Geli *et al*., 1988; Finn, 1994), so that the very low hazard rating may not apply on such topographic features. This unit is assigned a very low liquefaction hazard, due to the general absence of liquefiable soils.

Unit R1/2; Outcrop and Thin Soil Cover Undifferentiated

This unit includes sparsely developed, mainly rocky, upland areas with little or no subsurface data, and where units R1 (bedrock) and R2 (thin soil cover) could not be readily differentiated on air photos due to extensive tree cover. This unit may include small unmapped upland peat bogs and areas of older Pleistocene deposits. Like units R1 and R2, this unit is assigned a very low to low amplification hazard, although high topographic amplification may occur on hills, ridges and the tops of cliffs (Geli *et al*., 1988; Finn, 1994), and a very low liquefaction hazard.

Unit R2; Thin Soil Cover with Scattered Bedrock Outcrop

This unit generally consists of shallow soils over bedrock. In much of Greater Victoria, this unit includes areas with less than 5 metres of Victoria Clay, mainly the brown clay facies, overlying thin older Pleistocene deposits or bedrock. Scattered outcrops occur throughout the unit, and bedrock is commonly found in the upper few metres (*e.g.* in utility line excavations). The thickness of older Pleistocene deposits in most places is less than a few metres, but may locally be up to 10 metres. In areas adjoining the Colwood delta and outwash plain, this unit is assigned to areas where borehole data show that less than 5 metres of the Colwood sand and gravel overlies bedrock. In upland regions above 60 metres elevation, the unit is assigned to areas where bedrock is generally overlain by less than a few metres of sediment, commonly older Pleistocene deposits with some colluvium, although locally sediment thicknesses are up to 10. This map unit generally occurs in hilly areas, where the topography is clearly controlled by the irregular bedrock surface. Due to the irregularity of the bedrock surface, the thickness of the sedimentary cover over bedrock can vary by several metres across short distances, such as the length of a building lot.

This map unit is assigned to NEHRP site classes A and B, where the soil thickness is less than 3 metres thick, and site class C where the soil thickness exceeds 3 metres. Consequently, this unit is assigned a very low to low amplification hazard. However, high topographic amplification can occur on hills, ridges and the tops of cliffs (Geli *et al*., 1988; Finn, 1994), so that these hazard ratings may not apply on such topographic features.

This unit is assigned a very low liquefaction hazard. Sands in the upper part of the Victoria clay are not widespread and where sands are present they are likely to be above the water table at most times of the year, particularly in this unit which generally occurs in upland areas. However, the liquefaction hazard may locally be higher, such as where depressions occur on the bedrock surface. Where Colwood sands and gravels occur in this unit, they are generally dense and above the water table most times of the year.

Unit R2a consists of those areas of unit R2 where thicknesses of older Pleistocene deposits between 5 and 10 metres can be mapped. This unit is assigned to NEHRP site class C, and a low amplification hazard. Like unit R2, this unit is assigned a very low liquefaction hazard.

AREAS WITH OLDER PLEISTOCENE DEPOSITS AT SURFACE

Unit T; Thick Older Pleistocene Deposits

This unit occurs where older Pleistocene deposits are greater than 10 metres thick and are exposed at the surface. These deposits are commonly thicker than 30 metres and locally exceed 60 metres, such as along the sea cliffs at Cowichan Head. They occur principally as drumlinoid ridges, several kilometres in length, and as shorter ridges south of prominent bedrock hills (crag-and-tail features). Hilly areas underlain by unit T are typically characterized by smooth topography, in contrast to the irregular topography of areas underlain by shallow bedrock (unit R2). Locally, bedrock knobs reach almost to the surface within this map unit but are rarely detectable with the borehole data available. The surficial deposits are commonly the Vashon till or the Quadra sand but, where the drumlinoid ridges have been subjected to Holocene erosion, older deposits are exposed.

Based on the average shear-wave velocity of older Pleistocene units of 499 m/sec (Table 4), this map unit is assigned to NEHRP site class C and a low amplification hazard. However, the limited results of the SHAKE analyses and survey of the effects of recent minor earthquakes indicate that greater amplification than anticipated for site class C can sometimes occur above thick older Pleistocene deposits. Furthermore, high topographic amplification can occur locally on hills, ridges and the tops of cliffs (Geli *et al*., 1988; Finn, 1994), so that this hazard rating may not apply on such topographic features.

The unit is assigned a very low liquefaction hazard, because the older Pleistocene sands are very dense. However, due to near surface reworking by colluvial and fluvial processes, the liquefaction hazard in older Pleistocene sands may locally be greater.

Unit Ta is assigned to areas that have smooth surface topography, comparable to areas with thick older Pleistocene deposits (unit T), but where borehole data indicate that bedrock is locally shallow (<10 metres). Like unit T, this unit is assigned a low amplification hazard and a very low liquefaction hazard.

Unit T/C3 is applied to those areas intermediate between units T and C3, typically areas with a discontinuous cover of Victoria clay over older Pleistocene deposits. Like units T and C3, this unit is assigned a low amplification hazard and a very low liquefaction hazard.

AREAS WITH CAPILANO DEPOSITS (LATEST FRASER GLACIATION) AT SURFACE

Colwood Sand And Gravel

Unit G1; Sand and Gravel of the Colwood Delta and Outwash Plain

This unit consists of interbedded sand and gravel of the raised Late Pleistocene delta and outwash plain centred on the City of Colwood and the District of Langford (Figure 3). The delta and outwash plain have a terraced surface between 60 and 90 metres elevation. Few boreholes penetrate the entire thickness of these deposits, and these are all located in the eastern part of the delta and outwash plain. The maximum known thickness of these deposits is 30 metres, and the thickness is probably greater in much of Colwood and the eastern part of Langford. Silts occur locally in the delta topset in abandoned channel deposits. In the vicinity of Happy Valley Road, outwash sand and gravel are overlain by 1 to 2 metres of silt interpreted to be a late-stage glaciolacustrine deposit marginal to the delta. Deposits of silt up to several metres thick also occur interbedded with sand in lateral and distal parts of the delta foreset. Where these are exposed at the surface they are distinguished as unit G2, but they are likely also present beneath parts of the delta and outwash plain in unit G1. On the margins of the delta, the Colwood sand and gravel overlies bedrock (see unit R2), but in the gravel pits south of Esquimalt Lagoon they overlie older Pleistocene deposits that are locally over 50 metres thick.

The average shear-wave velocity of the Colwood sands and gravels is 335 m/sec (Table 4). However, average shear wave velocity of the deltaic deposits may be locally less, because distal and lateral foreset deposits (average shear-wave velocity of 199 m/sec) may locally underlie the higher velocity sands and gravels observed at surface. On the basis of these data, this unit generally meets the criteria for NEHRP site class D, and is assigned a moderate amplification hazard.

In this map unit, these deposits are generally dense and the water table is commonly deep, so that the unit is assigned a very low to low liquefaction hazard (PLS= 2 $\pm$ 2%, Table 6). However, the liquefaction hazard may locally range up to moderate in areas of perched and shallow water table, such as in the vicinity of Happy Valley Road.

Unit G2; Distal and Lateral Foreset Sand and Silt of the Colwood Delta

This unit consists primarily of interbedded silt and sand that are interpreted to be distal and lateral foreset deposits of the Colwood delta, overlain by a few metres of the brown clay facies of the Victoria clay (Figure 4). In most areas it forms a regularly sloping surface that descends from the surface of the Colwood delta and outwash plain and represents the final delta slope. Locally it has been assigned to areas where the delta and outwash plain are incised by Holocene stream erosion, exposing older delta foreset deposits. These deposits are commonly 10 to 30 metres thick.

The average shear-wave velocity of distal and lateral foreset beds at one site where no gravel was present is 199 m/sec (Table 4), so that this unit is assigned to NEHRP site class D and a moderate amplification hazard. The unit is assigned a very low to moderate liquefaction hazard (PLS = 6$\pm$4%). Compared to unit G1, this map unit includes more sand and the water table is typically shallower.

Unit G3; Late Stage Glaciofluvial Channel

This map unit consists of late-stage channels and associated point bars. These are incised into the upper part of the Colwood delta and outwash plain in the vicinity of Colwood Creek. Where borehole data are available, sediments consist of fine sand and silt a few metres thick, and elsewhere the deposits are interpreted to be finer than adjacent parts of the delta and outwash plain. Parts of the channels are filled with peat and are assigned to map unit O3.

Like units G1 and G2, this map unit is assigned to NEHRP site class D and a moderate amplification hazard. This map unit is assigned a low to moderate liquefaction hazard based on the inferred presence of finer sands more susceptible to liquefaction than in unit G1, and a relatively shallow water table due to the proximity of Colwood Creek. One PLS calculation (5.6%) is consistent with this assignment.

Unit G4; Glaciolacustrine Deposits Marginal to the Colwood Delta

This unit occurs in small valleys adjacent to the Colwood Delta and outwash plain. Borehole control in these areas is poor. Where Highway 1 crosses Millstream Creek, a borehole encountered 14 metres of stiff silt and clay with interbedded compact to dense sand, overlying 3 metres of very dense gravelly till. Downstream, thinly bedded to laminated fine sand and silt were observed in a small exposure. The surface expression of this unit is flat or gently sloping, as in Millstream Creek valley. These areas are interpreted to represent glaciolacustrine deposits marginal to the Colwood delta and outwash plain, and may include glaciofluvial and fluvial sediments.

Estimated V_{S30} at the site described above is ~360 m/sec, so that this map unit is assigned to NEHRP site classes C and D and a low to moderate amplification hazard. The liquefaction hazard is interpreted to be very low to low, similar to the other units with sands of Capilano age and low water table - the Victoria Clay and the Colwood delta. The sand present in the borehole at Millstream Creek is consistent with this rating.

Victoria Clay

Unit C1; Intermediate between Units R2 and C2, Including Undifferentiated Areas

This unit mainly consists of areas where soil profiles typical of units R2 and C2 occur together on a scale that is not 'mappable' with the data available. This unit also includes areas where there is greater than 5 metres of Victoria clay, but where the thickness of the lower grey clay facies is less than 3 metres. In regions of poor subsurface control, the unit is commonly assigned to areas of sloping ground between units R2 and C2, and to small low-lying areas that cannot be confidently mapped as unit C2. In such cases, use of this map unit indicates uncertainty. However, where borehole data are present, they commonly demonstrate that the subsurface conditions are truly a complex mixture of units R2 and C2. In some areas of sloping ground mapped as unit C1, the absence of reported bedrock may indicate that older Pleistocene deposits underlie the Victoria clay. As additional data become available, much of unit C1 could be reassigned to units R2, C2, and possibly C3, C4, C4a, C4b, and C5.

This unit is assigned to NEHRP site classes C, D and E, reflecting the range in conditions from units R2 to C2 and sediment thicknesses generally greater than 3 metres in this map units. Consequently, this map unit is assigned a low to high amplification hazard. As in units R2 and C2, the liquefaction hazard is estimated to vary from very low to low.

Unit C2; Thick Soft Clay

This unit is assigned to areas with more than 3 metres of the grey clay facies of the Victoria clay (Figure 2). The thickness of the grey clay facies is commonly greater than 10 metres and locally exceeds 20 metres. In this unit, the grey clay facies is overlain by the brown clay facies of the Victoria clay, which is generally 2 to 5 metres thick. The thickness of older Pleistocene deposits underlying the Victoria clay is generally less than a few metres, but may be greater adjacent to drumlinoid ridges. The unit occupies low-lying and gently sloping ground, and where borehole data are not available, this unit is assigned to such areas below 60 metres elevation.

Estimated V_{S30} in this map unit is generally between 155 and 360 m/sec, so that this unit is assigned to NEHRP site classes D and E, and a moderate to high amplification hazard. Because the grey clay facies commonly meets the criteria for soft clay, much of this unit can be assigned to NEHRP Site Class E on the basis of soft clay thickness greater than 3 metres (Table 2). However, not all of the grey clay facies is soft. In deeper occurrences, the shear strength exceeds 25 kPa due to the normal increase of shear strength with depth. Furthermore, the upper part of the grey clay facies is commonly slightly overconsolidated where overlain by the brown clay facies; and in occurrences of unit C2 that are a few tens of metres wide, the grey clay is commonly sandy. In these cases the grey clay facies may not meet the criteria for soft clay.

The liquefaction hazard is estimated to be very low to low in this unit, because sands in the upper part of the Victoria clay are not widespread, and where sands are present they are likely to be above the water table at most times of the year.

Unit C2a is assigned to areas where the lower slopes of the Colwood delta are overlain by the Victoria clay. Little is known about the thickness or geotechnical properties of the Victoria clay in these areas. However, the land is low-lying and organic soils locally occur at surface (unit O1), indicating that thicknesses of soft clay greater than 3 metres could be present. The hazards are interpreted to be the same as unit C2.

Unit C3; Thin Clay Over Thick Older Pleistocene Deposits

This unit occurs in areas with less than 5 metres of Victoria clay overlying older Pleistocene deposits greater than 10 metres thick. It generally occurs on the upper flanks of drumlinoid ridges.

Based on estimated V_{S30} between 400 and 660 m/sec, this map unit is assigned to NEHRP site class C and a low amplification hazard. However, the limited results of the SHAKE analyses and the survey of the effects of recent minor earthquakes indicate that greater amplification than anticipated for site class C can sometimes occur above thick older Pleistocene deposits.

This unit is assigned a very low liquefaction hazard, because the older Pleistocene sands are very dense. Furthermore, sands in the upper part of the Victoria clay are not widespread and are likely to be above the water table at most times of the year, particularly in this unit which generally occurs in upland areas.

Unit C4; Intermediate between Units C3 and C5, Including Undifferentiated Areas

This map unit includes areas with more than 5 metres of Victoria clay but less than 3 metres of the grey clay facies, underlain by more than 10 metres of older Pleistocene deposits, as well as areas of poor subsurface control on gently sloping ground that may include profiles typical of both units C3 and C5. The brown clay facies tends to be thicker (up to 10 metres) where the Victoria clay overlies thick older Pleistocene deposits than where it overlies bedrock, probably because of better drainage through the Quadra sand.

This unit is assigned to NEHRP site classes C, D and E, reflecting the range in conditions from units C3 to C5 and sediment thicknesses generally greater than 3 metres in this map units. Consequently, this map unit is assigned a low to high amplification hazard. As in units C3 and C5, the liquefaction hazard is estimated to vary from very low to low.

Unit C4a is assigned to the part of unit C4 where subsurface control is sufficient to show that it consists of more than 5 metres of Victoria clay but less than 3 metres of the grey clay facies. The only area assigned to this unit is located in a gentle depression on the top of a Pleistocene drumlinoid ridge in the vicinity of the University of Victoria.

Based on estimated V_{S30} between 345 and 580 m/sec, this map unit is assigned to NEHRP site classes C and D and a low to moderate amplification hazard. This unit is assigned a very low to low liquefaction hazard, because the older Pleistocene sands are very dense, and sands in the upper part of the Victoria clay are not widespread and are likely to be above the water table at most times of the year.

Unit C4b is assigned to areas of sloping ground with poor subsurface control between units C3 and C4. In this map unit, the Victoria clay overlies thick older Pleistocene deposits and may be greater than 5 metres, but the thickness of the grey clay facies is interpreted to be less than 3 metres.

Based on estimated V_{S30} between 345 and 580 m/sec, this map unit is assigned to NEHRP site classes C and D and a low to moderate amplification hazard. This unit is assigned a very low to low liquefaction hazard, because the older Pleistocene sands are very dense, and sands in the upper part of the Victoria clay are not widespread and are likely to be above the water table at most times of the year.

Unit C5; Thick Soft Clay Over Thick Older Pleistocene Deposits

This unit consists of Victoria clay with more than 3 metres of the grey clay facies overlying older Pleistocene deposits thicker than 10 metres. It occupies small low-lying areas on the crest and flanks of the drumlinoid ridge at the University of Victoria. In these areas, 5 metres of the grey clay facies has been observed

This map unit is assigned to NEHRP site classes D and E, because estimated is V_{S30} between 300 and 340 m/sec and the grey clay facies commonly meets the criteria for soft clay (Table 2), and is assigned a moderate to high amplification hazard.

This unit is assigned a very low to low liquefaction hazard, because the older Pleistocene sands are very dense, and sands in the upper part of the Victoria clay are not widespread and are likely to be above the water table at most times of the year.

AREAS WITH HOLOCENE DEPOSITS AT SURFACE

Holocene Peats

Unit O1; Peat Over Soft Clay

This map unit is defined as Holocene peat and organic soil overlying the Victoria clay (Figure 2). The thickness of peat varies from less than 1 metre to a maximum known thickness of 8 metres immediately northwest of the Saanich Public Works Yard at McKenzie Avenue and Quadra Street. The brown clay facies is not present in this map unit, and the grey clay facies is generally normally consolidated. The thickness of the underlying grey clay facies commonly exceeds 10 metres and has a maximum known thickness of 30 metres. In the absence of borehole data, this map unit is applied to swamps and closed depressions that occur in areas below 60 metres elevation.

This map unit is assigned to NEHRP site classes E and F, because the grey clay facies is normally consolidated so that the thickness of soft clay generally exceeds 3 metres and the thickness of peat locally exceeds 3 metres, respectively. The map unit is assigned a high to very high amplification hazard.

The liquefaction hazard is estimated to be very low to moderate. Compact to dense sands occur at the top of the Victoria clay. These sands are only well developed locally and are not mappable with the data available, but they are probably saturated at most times of the year.

Unit O2; Upland Peat

This unit consists of upland peat deposits above 60 metres elevation. The peats in this unit are commonly less than a few metres thick, but locally exceed 5 metres. In boreholes, these deposits have been observed to overlie up to 3 metres of soft clayey silts and sands, that in turn overlie older Pleistocene deposits or bedrock. However, they may also overlie other sediment types, such as colluvial deposits, outwash sand and gravel, and glaciolacustrine sediments.

Where peat thickness exceeds 3 metres, this map unit can be assigned to NEHRP site class F. Although the estimated V_{S30} is between 300 and 340 m/sec, this map unit is poorly known in boreholes, and it is conservatively assigned a moderate to very high amplification hazard.

The liquefaction hazard is estimated to be very low to low, because sands are thin and have comparable age and density to Capilano age sand (sand facies of the Victoria clay and the Colwood sand and gravel). The sands are likely to be saturated most times of the year.

Unit O3; Peat Over Sand and Gravel of the Colwood Delta and Outwash Plain

This unit consists of peat deposits overlying sand and gravel of the Colwood delta and outwash plain. Peat deposits are generally less than 4 m thick, but locally reach 7 metres. These deposits occur in low-lying areas on the delta and outwash plain, such as late-stage abandoned channels and around the margins of modern lakes like Langford and Glen lakes.

As other map units associated with the Colwood delta and outwash plain (G1, G2 and G3), much of this unit can be assigned to NEHRP site class D, although where peat thickness exceeds 3 metres, it can be assigned to NEHRP site class F. Consequently, it is assigned a moderate to very high amplification hazard.

This map unit is assigned a low to moderate liquefaction hazard, as in other map units associated with the Colwood delta and outwash plain with a shallow water table (G2 and G3). Furthermore, finer sands more susceptible to liquefaction may occur in this unit than in than in map unit G1, particularly adjacent to Colwood Creek.

Unit O3a consists of closed depressions, mainly interpreted to be kettles, on the surface of the Colwood delta and outwash plain and in which peat *may* occur. The unit is assigned the same amplification and liquefaction hazard rating as unit O3.

Unit O4; Holocene Peat Over Glaciolacustrine Deposits

This unit consists of peat overlying glaciolacustrine deposits marginal to the Colwood delta and outwash plain (unit G4). The presence of peat is documented in soil surveys (Day *et al.*, 1959; Jungen, 1985), observed in the field, and inferred from the local presence of swamps.

This unit is in part assigned a NEHRP site class D, because the thickness of glaciolacustrine deposits is likely to be thicker and thus the V_{S30} lower than in adjoining parts of map unit G4 (assigned to site classes C and D). However, part of the map unit likely could be assigned to NEHRP site class F, if peat thicknesses exceed 3 metres. Consequently, this map unit is assigned a moderate to very high amplification hazard.

The liquefaction hazard is estimated to be low to moderate, as in other map units with Capilano age sand and shallow water table.

Unit O5; Peat Over Holocene Beach Sand

This unit is assigned to areas where peat overlies Holocene sand in a shoreline setting. At Cadboro Bay, where borehole data are available, the peat unit is 2 to 6 metres thick and the underlying sand is 3 to 9 metres thick (Figure 6). These deposits in turn overlie over 30 metres of Holocene marine mud and the grey clay facies of the Victoria clay.

This map unit is assigned to NEHRP site classes E and F, because V_{S30} in the SCPT at Cadboro Bay is 157 m/sec (Figure 6) and the thickness of peat locally exceeds 3 metres. Consequently, this map unit is assigned a moderate to very high amplification hazard. The liquefaction hazard is high to very high due to the presence of the Holocene beach sands and shallow water table. Two PLS calculations average 22 ± 7 (Table 6).

Holocene Sands

Unit S1; Alluvial Fan and Fan Delta Deposits

This unit consists of small alluvial fans and fan deltas. No borehole data are available in this unit, but the fans probably consist of sand and gravel, particularly where they occur along the lower flanks of sandy and gravelly drumlinoid ridges from which they have been derived.

The amplification hazard assigned to this map unit varies according to the deposits that the alluvial fans and fan deltas overlie: low to moderate (NEHRP site classes C to D) where they overlie bedrock and older Pleistocene deposits; and moderate to high (NEHRP site classes D to E) where they overlie thick accumulations of Victoria clay. This map unit is assigned a moderate to very high liquefaction based on the inferred presence of young sandy sediments, and a variable depth to the water table. Further investigations may reduce this hazard in some cases.

Unit S2; Goldstream Delta Deposits

The Goldstream River has built a small delta at the head of Saanich Inlet. The landward part of the delta plain consists of pebble to cobble gravel alluvial deposits, and the seaward part consists of predominantly sandy tidal flats. The gravel alluvium is interpreted to have prograded over finer deltaic deposits, including tidal flat deposits.

The amplification hazard is interpreted to be moderate, based on an inferred thick accumulation of deltaic deposits that probably have shear-wave velocities that would place it in site class D. The liquefaction hazard is interpreted to be high to very high because of the inferred presence of deltaic sands beneath the alluvial gravels and the shallow water table.

Unit S3; Stream Deposits

Sandy alluvial deposits have been mapped only where they are interpreted to be more than a few metres thick or are extensive enough to be mapped.

The amplification hazard assigned to this map unit varies according to the deposits that the stream deposits overlie: moderate (NEHRP site class D) where they overlie glaciolacustrine deposits; and moderate to high (NEHRP site classes D to E), where they overlie thick accumulations of Victoria clay.

This map unit is assigned a high to very high liquefaction hazard, based on the inferred presence of Holocene sands and the shallow water table. Observations along most streams indicate that they are generally downcutting or have a boulder and cobble gravel bed. In such cases, the liquefaction hazard appears to be negligible. However, the streams have not been investigated along their entire length. Furthermore, some of the most serious damage during many earthquakes occurs as a result of liquefaction adjacent to streams. Consequently, the streams are highlighted as a zone where a high to very high liquefaction hazard *may locally occur* and where caution should be exercised.

Unit S4; Beach Sands

This unit includes modern beach sands**.** These deposits are up to several metres thick at Ross Bay and the northern part of Cadboro Bay, but elsewhere thicknesses are unknown.

The amplification hazard assigned to this map unit varies according to the deposits that the beach sands overlie: low to moderate (NEHRP site classes C to D) where they overlie thin accumulations of Victoria clay; moderate (NEHRP site class D) where they overlie Colwood sands and gravels or intermediate thicknesses of Victoria clay; and moderate to high or very high (NEHRP site classes D to F) where they overlie thick accumulations of Victoria clay and/or Holocene peat.

This map unit is assigned a high to very high liquefaction hazard due to the presence of the young Holocene sands and a shallow water table. Consistent with this assignment, PLS calculations in slightly older shoreline sands (and probably slightly less susceptible to liquefaction) in map unit O5 adjacent to this map unit at Cadboro Bay indicate a high to very high liquefaction hazard (PLS = 22 ± 7, Table 6).

AREAS WITH ANTHROPOGENIC FILL AT SURFACE

Unit F; Fill

Only the larger and thicker deposits of anthropogenic fill of which the authors are aware are included in this map unit, the principal areas being in shoreline settings and in reclaimed gravel pits. The thickness of fill can exceed 10 metres. The properties of fill vary widely, from dense engineered fills that present little earthquake hazard, to loose fills that can contribute significantly to the amplification and liquefaction hazards. However, there are insufficient data to distinguish these on a regional basis. This map unit consists of fills in which the underlying natural deposits are not as well defined in borehole data as in the other fill map units described below (FR2, FT, FG, FC1 and FC2).

The amplification hazard assigned to this map unit varies according to the deposits that the fills are inferred to overlie: low to moderate (NEHRP site classes C to D) over bedrock and thin accumulations of Victoria clay; low to high (NEHRP site classes C to E) over unknown or variable accumulations of Victoria clay; and moderate to high (NEHRP site classes D to E) over thick accumulations of Victoria clay.

Because there are insufficient data to distinguish engineered fills from loose fills regionally, all fill units are assigned high to very high liquefaction to indicate that a high to very high hazard *could* be present. PLS calculations in 6 fills analysed average 16 ± 11 (Table 6). Non-engineered fills historically perform very poorly in earthquakes.

Unit FR2 is assigned to areas where fill overlies bedrock or thin native soils (unit R2).

This map unit is assigned to NEHRP site class C where fills are thin, to site class D, where thicker fills occur. The amplification hazard is estimated to be low to moderate. As in map unit F, this map unit is assigned a high to very high liquefaction hazard.

Unit FT is assigned to large areas of fill in reclaimed gravel pits in older Pleistocene deposits (Quadra sand and gravel; part of unit T). Fill thicknesses are between 10 and 20 metres, so that the estimated V_{S30} is between 170 and 270 m/sec. This map unit is assigned to NEHRP site classes D and E and a moderate to high amplification hazard. As in map unit F, this map unit is assigned a high to very high liquefaction hazard.

Unit FG is assigned to large areas of fill in reclaimed gravel pits in Colwood sand and gravel (unit G1). Generally, reported fill thicknesses are up to 9 metres, where the estimated V_{S30} is 210. Consequently, most of this map unit is assigned to NEHRP site class D like other parts of unit G1, and is assigned a moderate amplification hazard. However, one small area with up to 30 metres of clayey fill (E.J. McQuarrie, *pers. comm.*) is assigned to NEHRP site classes D and E and a moderate to high amplification hazard. As in map unit F, this map unit is assigned a high to very high liquefaction hazard.

Unit FC1 is assigned to areas where fill overlies unknown or variable thicknesses of Victoria clay (unit C1). Like map unit C1, this map unit is assigned to NEHRP site classes C to E, and a low to high amplification hazard. As in map unit F, this map unit is assigned a high to very high liquefaction hazard.

Unit FC2 is assigned to areas where fill overlies unit C2. In shoreline settings, fill may overlie soft Holocene marine mud that in turn overlies the Victoria clay, in which the brown and grey clay facies are both present (Figure 5). Like map unit C2, this map unit is assigned NEHRP site classes D to E, and a moderate to high amplification hazard. As in map unit F, this map unit is assigned a high to very high liquefaction hazard.

ACKNOWLEDGMENTS

This project received funding from the Capital Regional District, the Geological Survey of Canada, the British Columbia Resources Inventory Committee, Corporate Resources Inventory Initiative, and the Joint Emergency Preparedness Program. The authors thank the following agencies for providing the geotechnical and geological data on which this map is based: Thurber Engineering Ltd., the Ministry of Transportation and Highways, B.C. Hydro, B.C. Buildings Corporation, B.C. Ferry Corporation, the Insurance Corporation of British Columbia, the Capital Regional District, the City of Victoria, the District of Saanich, the District of Oak Bay, the Township of Esquimalt, the Town of View Royal, the City of Colwood, the District of Langford, the Greater Victoria Water District, the Greater Victoria School Board, the Sooke School Board, the Saanich School Board, the National Research Council, Department of National Defence, Public Works and Government Services Canada, the University of Victoria, Camosun College, the Greater Victoria Hospital Society, the Juan de Fuca Hospital Society, Juan de Fuca Parks and Recreation Commission, Esquimalt Nation, Songhees Nation, BC Tel, Pacific Coast Savings, Foundex Explorations Ltd., Levelton Associates, and C.N. Ryzuk and Associates. These data were generated by the Ministry of Transportation and Highways, B.C. Hydro, Department of National Defense, Thurber Engineering Ltd., Levelton and Associates, C.N. Ryzuk and Associates, Payne Geological Engineering, AGRA Earth and Environmental, Golder and Associates, Cook, Pickering and Doyle, Klohn-Crippen Consultants, CBA Engineering, Wright-Parry Engineering, Ltd., Bullock Baur Associates, Morrow Environmental Consultants, Technology Resource Inc., CBR International, Duncan and Associates, UMA, Steele, Barber and Associates, McCarter, Nairne and Partners, and Thorson and Thorson. Water well data were provided by the Ministry of Environment, Lands and Parks. The SCPT and SASW data were generated by ConeTec Investigations and MOTH. GIS support was provided by G. Letham and C. Spicer at AXYS Environmental Consulting Ltd. Proprietary geological reports obtained during the geotechnical data search contain many useful insights, notably those by Thurber Engineering Ltd., Levelton and Associates and Payne Geological Engineering. This project has relied on the assistance and support of many individuals, but in particular, the authors thank G.C. Rogers, J. Cassidy, R. Lloyd, M. Williams, R. Gibbs, B. Harding, B. Kerr and J. Valeriote. The maps and reports associated with this project have received technical reviews by J.J. Clague, J.A. Hunter, G.C. Rogers, J. Cassidy, R.H. Lloyd, S. Pitt, B. Warman, E.J. McQuarrie and S.M. Bean, and editorial reviews by B. Grant, W.J. McMillan and D. Jakobsen.

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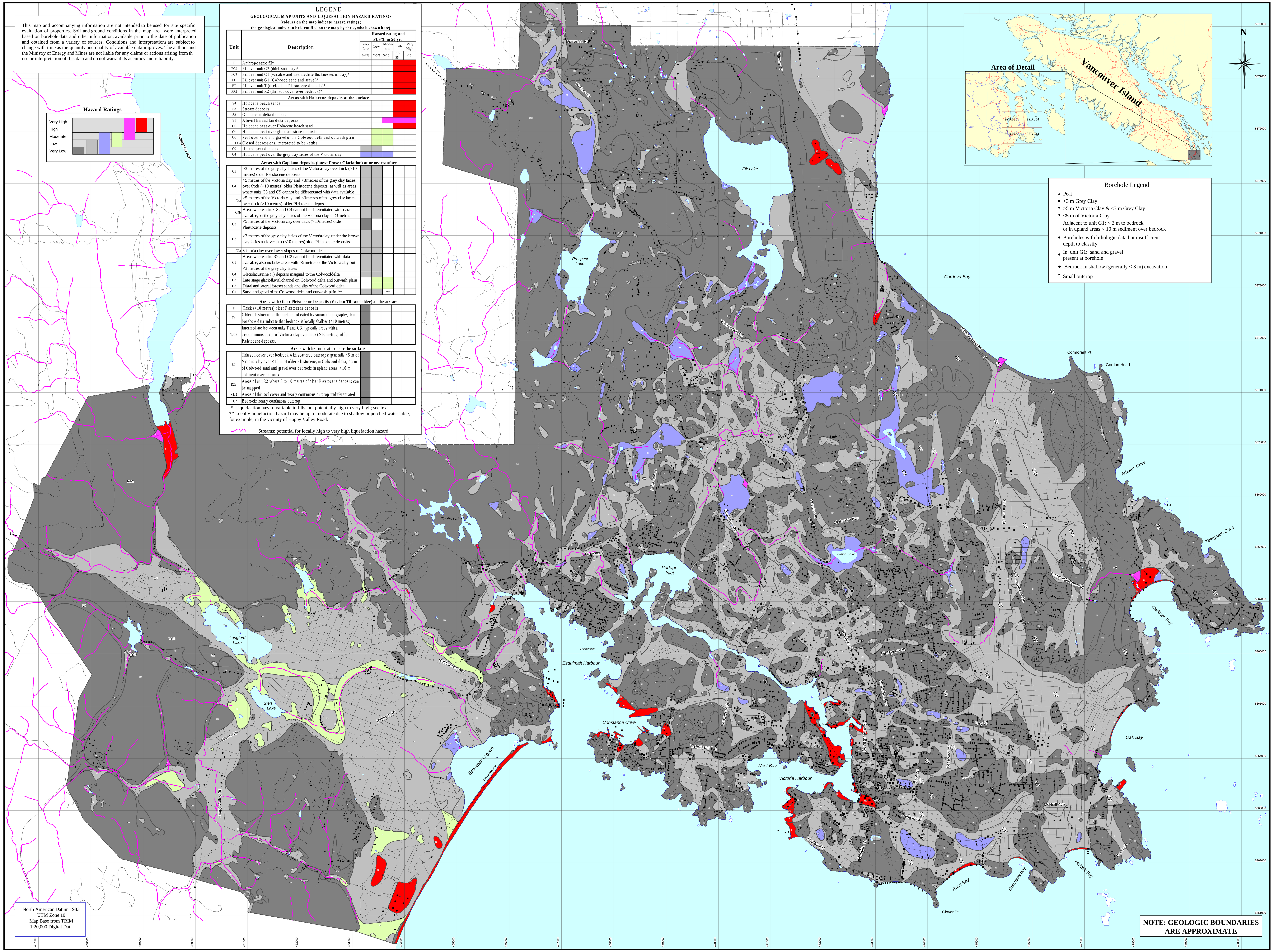

LEGEND

GEOLOGICAL MAP UNITS AND LIQUEFACTION HAZARD RATINGS

(colours on the map indicate hazard ratings; the geological units can be identified on the map by the symbols shown here)

Unit	Description	Hazard rating and PLS% in 50 yr. Very Low 0-2%	Low 2-5%	Moderate 5-15	High 15 25	Very High >25
F	Anthropogenic fill*					
FC2	Fill over unit C2 (thick soft clay)*					
FC1	Fill over unit C1 (variable and intermediate thicknesses of clay)*					
FG	Fill over unit G1 (Colwood sand and gravel)*					
FT	Fill over unit T (thick older Pleistocene deposits)*					
FR2	Fill over unit R2 (thin soil cover over bedrock)*					
	Areas with Holocene deposits at the surface					
S4	Holocene beach sands					
S3	Stream deposits					
S2	Goldstream delta deposits					
S1	Alluvial fan and fan delta deposits					
O5	Holocene peat over Holocene beach sand					
O4	Holocene peat over glaciolacustrine deposits					
O3	Peat over sand and gravel of the Colwood delta and outwash plain					
O3a	Closed depressions, interpreted to be kettles					
O2	Upland peat deposits					
O1	Holocene peat over the grey clay facies of the Victoria clay					
	Areas with Capilano deposits (latest Fraser Glaciation) at or near surface					
C5	>3 metres of the grey clay facies of the Victoria clay over thick (>10 metres) older Pleistocene deposits					
C4	>5 metres of the Victoria clay and <3metres of the grey clay facies, over thick (>10 metres) older Pleistocene deposits, as well as areas where units C3 and C5 cannot be differentiated with data available					
C4a	>5 metres of the Victoria clay and <3metres of the grey clay facies, over thick (>10 metres) older Pleistocene deposits					
C4b	Areas where units C3 and C4 cannot be differentiated with data available, but the grey clay facies of the Victoria clay is <3metres					
C3	<5 metres of the Victoria clay over thick (>10metres) olde Pleistocene deposits					
C2	>3 metres of the grey clay facies of the Victoria clay, under the brown clay facies and over thin (<10 metres) older Pleistocene deposits					
C2a	Victoria clay over lower slopes of Colwood delta					
C1	Areas where units R2 and C2 cannot be differentiated with data available; also includes areas with >5metres of the Victoria clay but <3 metres of the grey clay facies					
G4	Glaciolacustrine (?) deposits marginal to the Colwood delta					
G3	Late stage glaciofluvial channel on Colwood delta and outwash plain					
G2	Distal and lateral foreset sands and silts of the Colwood delta					
G1	Sand and gravel of the Colwood delta and outwash plain **			**		
	Areas with Older Pleistocene Deposits (Vashon Till and older) at the surface					
T	Thick (>10 metres) older Pleistocene deposits					
Ta	Older Pleistocene at the surface indicated by smooth topography, but borehole data indicate that bedrock is locally shallow (<10 metres)					
T/C3	Intermediate between units T and C3, typically areas with a discontinuous cover of Victoria clay over thick (>10 metres) older Pleistocene deposits.					
	Areas with bedrock at or near the surface					
R2	Thin soil cover over bedrock with scattered outcrops; generally <5 m of Victoria clay over <10 m of older Pleistocene; in Colwood delta, <5 m of Colwood sand and gravel over bedrock; in upland areas, <10 m sediment over bedrock.					
R2a	Areas of unit R2 where 5 to 10 metres of older Pleistocene deposits can be mapped					
R1/2	Areas of thin soil cover and nearly continuous outcrop undifferentiated					
R1/2	Bedrock; nearly continuous outcrop					

* Liquefaction hazard variable in fills, but potentially high to very high; see text.
** Locally liquefaction hazard may be up to moderate due to shallow or perched water table, for example, in the vicinity of Happy Valley Road.

Streams; potential for locally high to very high liquefaction hazard

Borehole Legend

- ▲ Peat
- ■ >3 m Grey Clay
- ▼ >5 m Victoria Clay & <3 m Grey Clay
- ◆ <5 m of Victoria Clay
  Adjacent to unit G1: < 3 m to bedrock
  or in upland areas < 10 m sediment over bedrock
- ● Boreholes with lithologic data but insufficient depth to classify
- ● In unit G1: sand and gravel present at borehole
- ✚ Bedrock in shallow (generally < 3 m) excavation
- ★ Small outcrop

BRITISH COLUMBIA
Ministry of Energy and Mines
Geological Survey Branch
Geoscience Map 2000-3a

RELATIVE LIQUEFACTION HAZARD MAP OF GREATER VICTORIA

(TRIM 92B.043, 044, 053, 054)

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Paul Henderson, P.Eng.[3] and Alex Sy, P.Eng.[3]

Scale 1:25,000 (approximate)

0.5 0 0.5 1 1.5 k

[1]Monahan Petroleum Consulting
[2] British Columbia Geological Survey
[3] Klohn-Crippen Consultants Ltd.

This map accompanies the "Relative Liquefaction and Amplification of Ground Motion Hazard Maps of Greater Victoria (Geoscience Maps 2000-3a and 3b): Report and Expanded Legend", by P.A. Monahan, V.M. Levson, P. Henderson and A. Sy.

Victoria is located in one of the most seismically active regions of Canada (Rogers, 1998; Clague, 1996). The effects of earthquakes are not only dependent upon the magnitude of the earthquake and the distance from the source, but they can vary considerably due to local geological conditions These conditions can be mapped with varying degrees of completeness using existing geological and geotechnical data. It is the objective of this map to show those areas of Greater Victoria in which the earthquake hazard is potentially *increased* due to the presence of soils susceptible to liquefaction. This map accompanies four other maps relevant to earthquake hazards in Greater Victoria: a map of the Quaternary geology, on which this hazard map is based (Geoscience Map 2000-2; Monahan and Levson, 2000); a map that shows areas susceptible to amplification of ground motion (Geoscience Map 2000-3b; Monahan *et al*., 2000b); a map that shows areas susceptible to earthquake-induced slope instability Geoscience Map 2000-3c; McQuarrie and Bean, 2000); and a composite map that shows areas susceptible to the amplification of ground motion, liquefaction, and earthquake-induced slope instability hazards (Geoscience Map 2000-1; Monahan *et al.*, 2000a). Results of this project are also discussed by Monahan *et al.* (1998).

For the proper use of this map, the accompanying report and expanded legend should be carefully read and understood. This map is intended for regional purposes only, such as land use and emergency response planning, and should not be used for site-specific evaluations. This map can be used with other criteria to help planners select potential areas for development, avoid geologically vulnerable areas, and prioritize seismic upgrading programs *However, this map does not replace the need for site-specific geotechnical evaluations* prior to new construction or upgrading of building and other facilities. The qualifications and limitations of this map are discussed in more detail below and in the accompanying report and expanded legend.

GEOLOGICAL MAPPING

The initial step in the evaluation of the liquefaction hazard in the Victoria area was the preparation of a geological map that shows the thickness and distribution of Quaternary stratigraphic units (Monahan and Levson, 2000). Subsurface geological data on which the geological map is based include over 5000 geotechnical borehole logs; several hundred water well logs; and nearly 3000 engineering drawings for municipal sewer and water lines. Geological map units were defined on the basis of these data, and in part coincide with the U.S. National Earthquake Hazard Reduction Program (NEHRP) soil classes for susceptibility to amplification of ground motion (Building Seismic Safety Council, 1994). Although the relative liquefaction hazard map is colour-coded as to the level of hazard, the geological map units are shown on the map and indicated by the appropriate label in each polygon (see legend). The geological map units are described in more detail in the accompanying report and expanded legend. Map unit boundaries were interpreted on the basis of the subsurface data airphotos, large-scale topographic maps, and published soil maps. In addition, limited field checking was conducted. In areas of poor subsurface control, the subsurface conditions are largely *inferred* from topographic and geomorphic evidence. To assist the user in determining the accuracy of the subsurface geological mapping, sites where subsurface geological data were available to us are shown on the maps.

LIQUEFACTION HAZARD MAPPING

Liquefaction is the transformation that occurs when earthquake shaking (or other disturbance) causes a saturated granular soil (e.g. sand) to lose its strength and behave like a liquid. Liquefaction can be one of the major causes of damage during an earthquake. The susceptibility of a site to liquefaction is dependent upon the depth to water table and the density, grain size and age of the underlying deposits (*e.g.* Youd and Perkins, 1978).

This map was prepared by assigning a hazard rating or range of hazard ratings to each geological map unit based on these criteria and a suite of quantitative analyses using a modified version of PROLIQ2 and similar analyses (Monahan *et al*., 1998). PROLIQ2 (Atkins *et al*., 1986) estimates the probability that liquefaction will occur at a site by combining Seed's method of determining liquefaction susceptibility (Seed *et al*., 1985) with the probabilistic seismic model developed for the National Building Code of Canada (National Research Council of Canada, 1995). However, the severity of surface disruption caused by liquefaction is a function of the depth and thickness of the liquefiable units. Consequently, Klohn-Crippen Consultants introduced the term "probability of liquefaction severity" (PLS), in which a depth weighting function is applied to the layer by layer probabilities of liquefaction calculated in PROLIQ2 (Levson *et al*., 1996a, b, 1998). PLS is defined by:

$$PLS = \frac{\Sigma (W_i H_i PL_i)}{\Sigma (W_i H_i)}$$

where Pl_i is the probability of liquefaction at depth i (calculated from 0 to 20 metres), H_i is the layer thickness, and W_i is the weighting function that decreases linearly from 0.1 at the surface to 0 at 20 metres. Hazard ratings for specified PLS ranges are summarized in the following table.

Liquefaction Hazard Ratings

PLS (in 50 years)	Hazard Rating
>25%	very high
15-25%	high
5-15%	moderate
2-5%	low
0-2%	very low

Holocene sands (map units O5, S1, S2, S3 and S4) and modern anthropogenic fills (map units F, FR2, FT, FG, FC1 and FC2) are assigned high to very high hazard ratings. Consistent with these assignments, many sandy shoreline deposits on the east coast of Vancouver Island liquefied during the 1946 Vancouver Island Earthquake (Hodgson, 1946; Rogers, 1980), and non-engineered fills historically perform very poorly in earthquakes. The larger fills in the Victoria area are associated with port facilities and reclaimed gravel pits. For further details on the hazard assessment of fills, refer to section 5 of the qualifications and limitations of this map.

Map units wit Capilano age sands and a typically shallow water table (map units G2, G3, O1, O3, O3a and O4) are assigned hazard ranges up to the moderate level. The liquefaction hazard in the other map units is very low to low.

QUALIFICATIONS AND LIMITATIONS OF THIS MAP

1. **This map is intended for regional purposes only, such as land use and emergency response planning, and should not be used for site specific evaluations.**

2. The map is based on interpretations of borehole records, the *approximate* locations of which are shown on the map. Where borehole data are scarce, subsurface conditions had to be *inferred* from topographic and geomorphic evidence.

3. The boundaries of most map units are gradational, particularly in the Victoria area due to the extreme irregularity of the bedrock surface. For these reasons, map unit boundaries are *approximate*, may enclose smaller occurrences of other map units, and are subject to revision as more borehole data become available. Furthermore, geological materials are variable, and deposits of a map unit may locally have unusual properties. **Consequently, the hazard *at a specific site* may be higher or lower than shown on the map.**

4. This map does not fully address man-made alterations to ground conditions whether the changes decrease or increase the hazard at a site. Poor soil sites may have been improved during construction, which will change the hazard from that shown on the map.

5. Only the larger fills of which the authors were aware are shown on this map. Other areas of fill are present, and new areas of fill will be developed in the future. The properties of fills vary from dense engineered fills with a very low liquefaction hazard to loose fills with a very high liquefaction hazard. Because these could not be distinguished on a regional basis with the data available, all fill units were assigned a high to very high hazard, to indicate that such a hazard *could* be present. Non-engineered fills historically perform very poorly in earthquakes.

6. The stability of dams under earthquake shaking, and hazards due to the failures of dams or other man-made structures have not been addressed.

7. This map shows areas where the earthquake hazard is potentially increased due to liquefaction only. The amplification of ground motion and earthquake-induced landslide hazards are addressed on accompanying maps (Monahan et al., 2000b, and McQuarrie and Bean, 2000, respectively). *However, a low hazard on these maps does not mean freedom from earthquake hazards, because all areas could be subjected to significant ground shaking during an earthquake.* Furthermore, other earthquake hazards, such as tsunamis, land subsidence and ground rupture are not addressed on this or any companion maps published as part of this investigation.

8. **This map can not be used to *directly* predict the amount of damage that will occur at any one site because many other factors, such as building design and construction details, must be considered.** The map in no way shows how different types of buildings or other man-made structures will perform during earthquakes. This map can be used to estimate the relative natural hazard due to liquefaction susceptibility alone.

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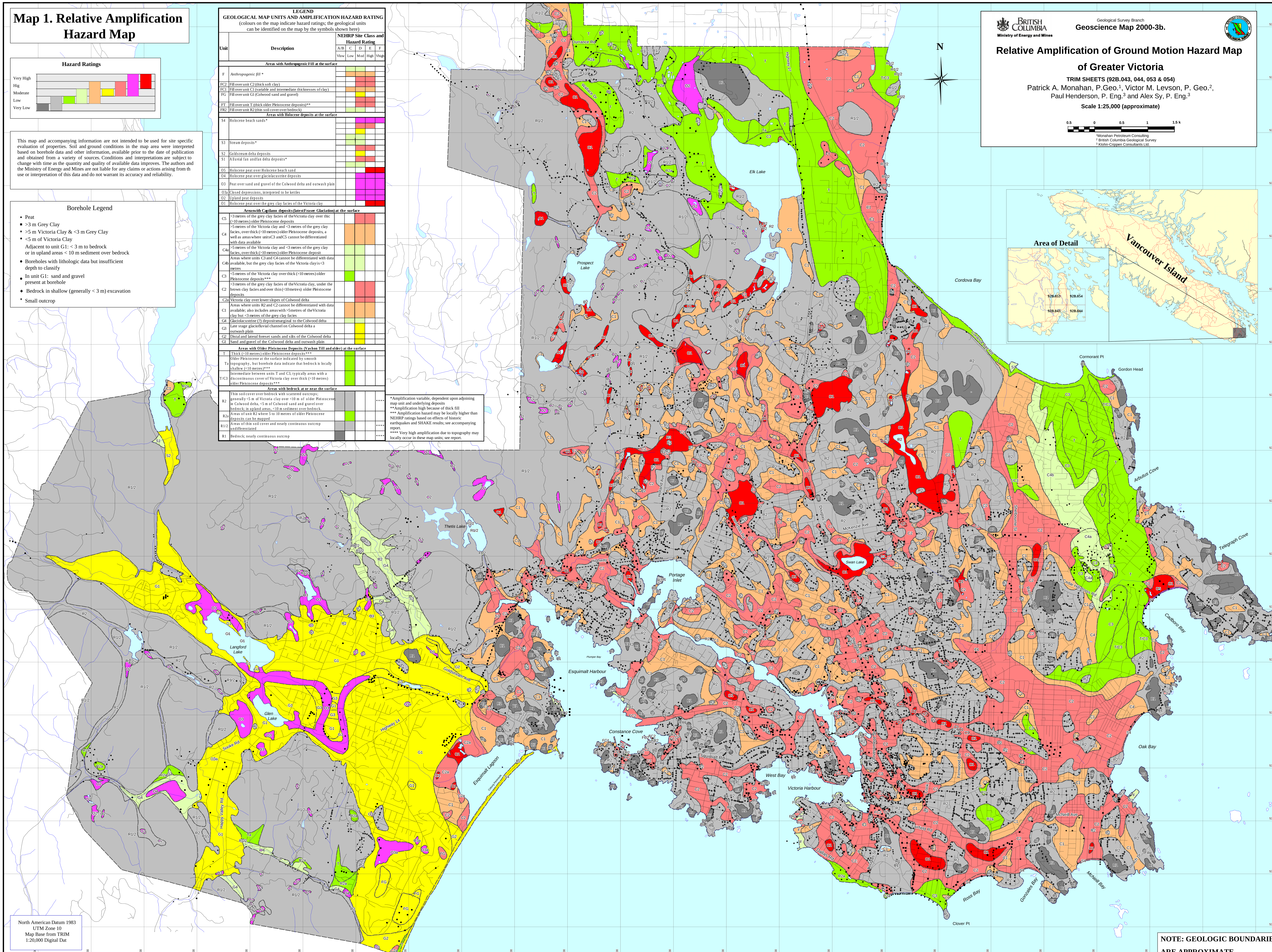
ACKNOWLEDGMENTS

This project received funding from the Capital Regional District, the Geological Survey of Canada, the British Columbia Resources Inventory Committee and Corporate Resources Inventory Initiative, and the Joint Emergency Preparedness Program. The authors also acknowledge the wealth of geological and geotechnical data and other assistance provided by numerous agencies and individuals, a complete listing of whom is provided in the accompanying report and expanded legend. In particular, the authors acknowledge the assistance of G. C. Rogers, J. Cassidy, R. Lloyd, M. Williams, R Gibbs, B. Harding, B. Kerr, and J. Valeriote. Cartography has been done by C. Spicer and G. Letham at AXYS Environmental Consulting Ltd.

Map 1. Relative Amplification Hazard Map



Hazard Ratings

Very High
Hig
Moderate
Low
Very Low

This map and accompanying information are not intended to be used for site specific evaluation of properties. Soil and ground conditions in the map area were interpreted based on borehole data and other information, available prior to the date of publication and obtained from a variety of sources. Conditions and interpretations are subject to change with time as the quantity and quality of available data improves. The authors and the Ministry of Energy and Mines are not liable for any claims or actions arising from th use or interpretation of this data and do not warrant its accuracy and reliability.

Borehole Legend

- ▲ Peat
- ■ >3 m Grey Clay
- ▼ >5 m Victoria Clay & <3 m Grey Clay
- ◆ <5 m of Victoria Clay
  Adjacent to unit G1: < 3 m to bedrock
  or in upland areas < 10 m sediment over bedrock
- ● Boreholes with lithologic data but insufficient depth to classify
- ● In unit G1: sand and gravel present at borehole
- ✚ Bedrock in shallow (generally < 3 m) excavation
- ★ Small outcrop

LEGEND
GEOLOGICAL MAP UNITS AND AMPLIFICATION HAZARD RATING

(colours on the map indicate hazard ratings; the geological units can be identified on the map by the symbols shown here)

Unit	Description	NEHRP Site Class and Hazard Rating				
		A/B	C	D	E	F
		Vlow	Low	Mod	High	Vhigh
Areas with Anthropogenic Fill at the surface						
F	*Anthropogenic fill* *					
FC2	Fill over unit C2 (thick soft clay)					
FC1	Fill over unit C1 (variable and intermediate thicknesses of clay)					
FG	Fill over unit G1 (Colwood sand and gravel)					
FT	Fill over unit T (thick older Pleistocene deposits)**					
FR2	Fill over unit R2 (thin soil cover over bedrock)					
Areas with Holocene deposits at the surface						
S4	Holocene beach sands*					
S3	Stream deposits*					
S2	Goldstream delta deposits					
S1	Alluvial fan andfan delta deposits*					
O5	Holocene peat over Holocene beach sand					
O4	Holocene peat over glaciolacustrine deposits					
O3	Peat over sand and gravel of the Colwood delta and outwash plain					
O3a	Closed depressions, interpreted to be kettles					
O2	Upland peat deposits					
O1	Holocene peat over the grey clay facies of the Victoria clay					
Areaswith Capilano deposits (latest Fraser Glaciation) at the surface						
C5	>3 metres of the grey clay facies of the Victoria clay over thic (>10 metres) older Pleistocene deposits					
C4	>5 metres of the Victoria clay and <3 metres of the grey clay facies, over thick (>10 metres) older Pleistocene deposits, a well as areas where units C3 and C5 cannot be differentiated with data available					
C4a	>5 metres of the Victoria clay and <3 metres of the grey clay facies, over thick (>10 metres) older Pleistocene deposit					
C4b	Areas where units C3 and C4 cannot be differentiated with data available, but the grey clay facies of the Victoria clay is <3 metres					
C3	<5 metres of the Victoria clay over thick (>10 metres) older Pleistocene deposits***					
C2	>3 metres of the grey clay facies of the Victoria clay, under the brown clay facies and over thin (<10 metres) older Pleistocene deposits					
C2a	Victoria clay over lower slopes of Colwood delta					
C1	Areas where units R2 and C2 cannot be differentiated with data available; also includes areas with >5 metres of the Victoria clay but <3 metres of the grey clay facies					
G4	Glaciolacustrine (?) deposits marginal to the Colwood delta					
G3	Late stage glaciofluvial channel on Colwood delta a outwash plain					
G2	Distal and lateral foreset sands and silts of the Colwood delta					
G1	Sand and gravel of the Colwood delta and outwash plain					
Areas with Older Pleistocene Deposits (Vashon Till and older) at the surface						
T	Thick (>10 metres) older Pleistocene deposits***					
Ta	Older Pleistocene at the surface indicated by smooth topography, but borehole data indicate that bedrock is locally shallow (<10 metres)***					
T/C3	Intermediate between units T and C3, typically areas with a discontinuous cover of Victoria clay over thick (>10 metres) older Pleistocene deposits***					
Areas with bedrock at or near the surface						
R2	Thin soil cover over bedrock with scattered outcrops; generally <5 m of Victoria clay over <10 m of older Pleistocene; in Colwood delta, <5 m of Colwood sand and gravel over bedrock; in upland areas, <10 m sediment over bedrock.					****
R2a	Areas of unit R2 where 5 to 10 metres of older Pleistocene deposits can be mapped					
R1/2	Areas of thin soil cover and nearly continuous outcrop undifferentiated					****
R1	Bedrock; nearly continuous outcrop					****

*Amplification variable, dependent upon adjoining map unit and underlying deposits
**Amplification high because of thick fill
*** Amplification hazard may be locally higher than NEHRP ratings based on effects of historic earthquakes and SHAKE results; see accompanying report.
**** Very high amplification due to topography may locally occur in these map units; see report.

British Columbia
Ministry of Energy and Mines
Geological Survey Branch
Geoscience Map 2000-3b.

Relative Amplification of Ground Motion Hazard Map of Greater Victoria

TRIM SHEETS (92B.043, 044, 053 & 054)

Patrick A. Monahan, P.Geo.[1], Victor M. Levson, P. Geo.[2], Paul Henderson, P. Eng.[3] and Alex Sy, P. Eng.[3]

Scale 1:25,000 (approximate)

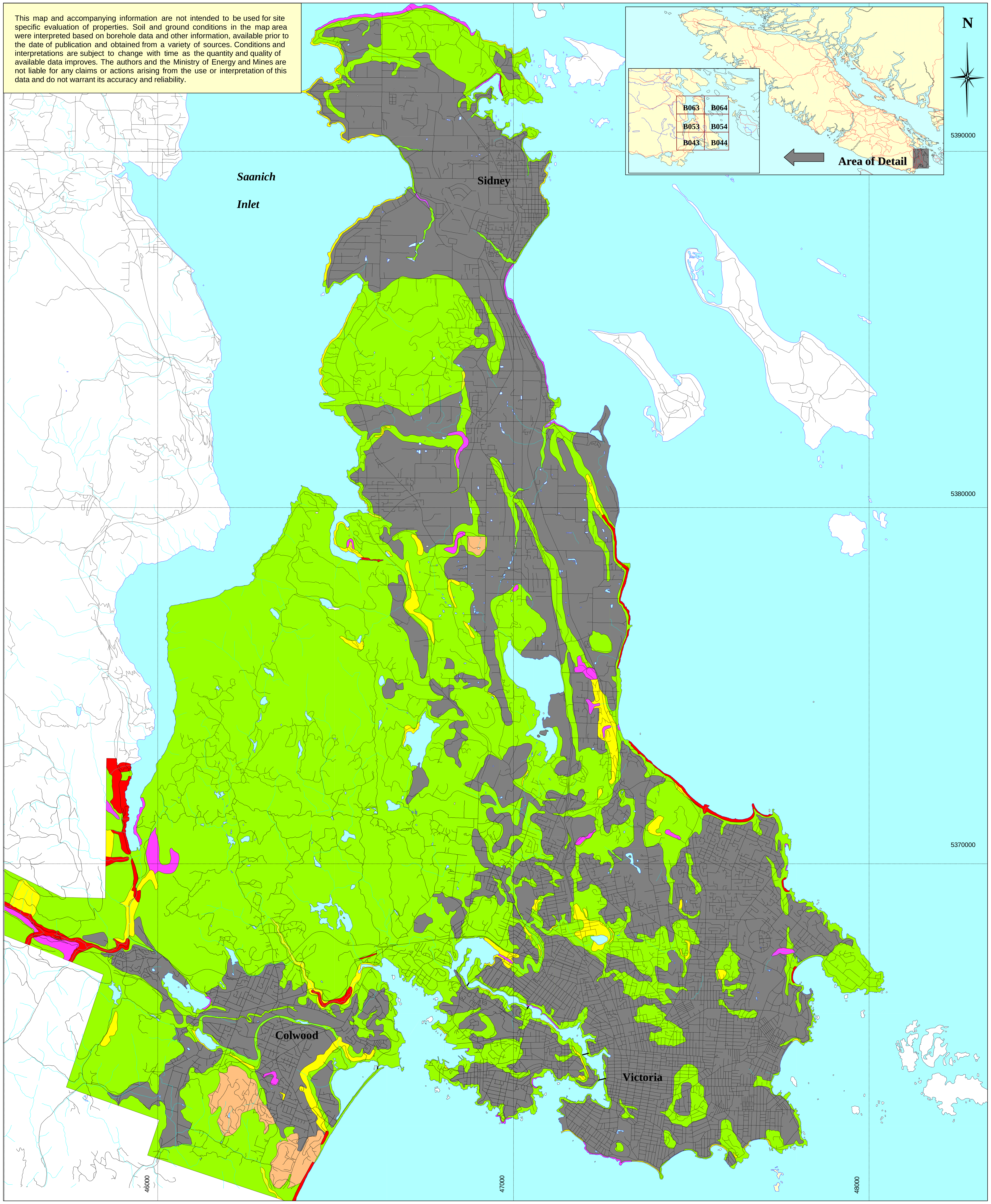
0.5 0 0.5 1 1.5 k

[1]Monahan Petroleum Consulting
[2] British Columbia Geological Survey
[3] Klohn-Crippen Consultants Ltd.

North American Datum 1983
UTM Zone 10
Map Base from TRIM
1:20,000 Digital Dat

NOTE: GEOLOGIC BOUNDARIES ARE APPROXIMATE

This map and accompanying information are not intended to be used for site specific evaluation of properties. Soil and ground conditions in the map area were interpreted based on borehole data and other information, available prior to the date of publication and obtained from a variety of sources. Conditions and interpretations are subject to change with time as the quantity and quality of available data improves. The authors and the Ministry of Energy and Mines are not liable for any claims or actions arising from the use or interpretation of this data and do not warrant its accuracy and reliability.



BRITISH COLUMBIA
Ministry of Energy and Mines

Geological Survey Branch
Geoscience Map 2000-3c

SEISMIC SLOPE STABILITY MAP OF GREATER VICTORIA

TRIM SHEETS 92B.043, 044, 053, 054, 063 & 064

By Eric J. McQuarrie, P. Eng., and Stephen M. Bean, P. Eng.,
Thurber Engineering Ltd.

INTRODUCTION

Seismic slope hazard mapping is intended to show relative susceptibility to earthquake-induced slope failures. This map is part of a larger earthquake hazard mapping project. Two companion earthquake hazard maps are published separately: an "Amplification of Ground Motion and Liquefaction Hazard Map" and a composite map showing all three hazards. Detailed descriptions of the methodology and the classification system used to prepare this seismic slope hazard map are provided in the Thurber Engineering Ltd. report entitled "Victoria Microzonation of Seismic Slope Hazards, Summary Report" to the Capital Regional District, dated January 23, 1998.

The maps are intended to provide basic regional data for land use planning, community planning and emergency response planning. Although this map can be used with other criteria to help planners select potential areas for development, avoid geologically vulnerable areas and to prioritize seismic upgrading programs, this map does not replace the need for site-specific geotechnical evaluations.

METHODOLOGY

The seismic slope hazard map is based on a compilation of existing subsurface data, previous slope stability assessments, bedrock geology and surficial geology maps, topographic data, and airphoto interpretation. Limited field observations were made at representative sites as well as sites flagged during airphoto interpretation as potentially unstable. Stability analyses were conducted on twelve different slope models including typical or simplified slopes found throughout the Victoria area as well as specific, complex slope models where more detailed information was available. The stability analyses determined both the static factor of safety and the yield acceleration (the intensity of seismic motions that would cause a slope failure).

SEISMIC SLOPE HAZARD CLASSIFICATION SYSTEM

The seismic slope hazard map uses a 5 class system (very low, low, moderate, high and very high) based primarily on the yield accelerations determined from the stability analyses. The general criteria for soil slopes using yield acceleration were as follows:

HAZARD RATING	YIELD ACCELERATION (g = acceleration due to gravity)	PROBABILITY OF SLOPE FAILURE (in 50 years)
Very Hig	less than 0.05g	greater than 62%
High	0.05g to 0.15 g	16 to 62%
Moderate	0.15g to 0.25g	8 to 16%
Low	greater than 0.25g	less than 8%
Very Low	n/a	n/a

Rock slopes were considered more qualitatively. The two most common rock types in Greater Victoria are relatively stable with relatively low relief, thus were generally given a low hazard rating. The potential for boulder ravelling or very small rock falls exists throughout much of these hilly areas, particularly during an earthquake, but overall such rock hazards are of relatively minor regional impact and can only be identified by site specific assessments. A low hazard rating is a reflection of the relative overall slope stability hazard and does not imply that a structure located at the base of a steep bedrock slope within such an area is safe since the map is not intended to identify hazards on a lot by lot basis.

The Mount Finlayson/Malahat/Goldstream River area consists of steeper terrain, greater relief, and much weaker bedrock creating steeply eroded valley terrain that poses considerably greater terrain hazards. Bedrock also has a direct influence on the slope stability at the north end of the Saanich Peninsula where northward dipping bedding in the sedimentary bedrock forms potential failure surfaces for the overlying colluvium.

The study, as a rule, does not consider stability hazards created by cuts or fills for roads or developments because such conditions are constantly changing and are usually at a scale that requires a detailed, site-specific assessment. Exceptions to this rule pertain primarily to areas where there has been large scale alterations to the natural terrain. In such cases, a natural hazard rating has been given along with a second rating pertaining to the areas altered by development (i.e. L(H*)) means a low seismic slope hazard naturally but several areas of anthropogenically-caused high hazard identified).

The slope hazard classes do not consider subaqueous failures that may occur along the coastline or the shores of lakes since slope conditions below the water cannot be assessed by airphotos and are not included on the T.R.I.M. maps. Polygons along the coastline refer to the seismic slope hazard above the high water level. A low rating does not necessary mean the slope should be safe during an earthquake since a subaqueous failure could impact the slope above the shoreline.

LIMITATIONS OF THIS MAP

The map is intended for regional purposes only, such as land use and emergency response planning and should not be used for site specific evaluations, property assessments or approving suitability for development. Responsibility for independent conclusions, interpretations or decisions by those using this map, lie with the user, including decisions to either purchase or sell land.

This map has been prepared in accordance with generally accepted hazard mapping practices. The map boundaries are based primarily on a slope map prepared from T.R.I.M. data, airphoto interpretation, regional surficial and bedrock geology maps and available site specific assessments or investigations. As such, the level of detail is not consistent across the entire map area or even within any given portion of the map area. Those areas where a site assessment has been conducted will have been mapped and analysed in much greater detail than other areas. The boundaries of each map polygon are approximate only, particularly where less detailed information was available. Also, each polygon has been given a rating that is considered representative of the relative seismic slope hazard but may often contain smaller areas with both higher and lower hazard ratings.

There is a practical limit to the size of potential slope failures that can be considered in a regional mapping study. Small failures caused by locally steeper terrain, not readily apparent on the slope map, or pockets of colluvium on a steep rock slope, cannot be identified at this scale. As a rule, the seismic slope hazard ratings do not consider hazards caused by cuts, fills, or other anthropogenic alterations to the natural terrain. Exceptions to this rule have been noted

Hazard Rating
(Probability of Seismically-induced Slope Failure in 50 yrs.)

- Very Hig (>62%)
- High (16-62%)
- Moderate (8-16%)
- L(H*) see text
- Low (<8%)
- Very Low (n/a)

UTM Projection NAD83
Compilation Scale 1:20,000

Cartography by
Axys Environmental Consulting Ltd., 1999.

1 0 1 2 3 km

This map accompanies the "Relative Liquefaction and Amplification of Ground Motion Hazard Maps of Greater Victoria (Geoscience Maps 2000-3a and 3b): Report and Expanded Legend", by P.A. Monahan, V.M. Levson, P. Henderson and A. Sy.

Victoria is located in one of the most seismically active regions of Canada (Rogers, 1998; Clague, 1996). The effects of earthquakes are not only dependent upon the magnitude of the earthquake and the distance from the source, but they can vary considerably due to local geological conditions. These conditions can be mapped with varying degrees of completeness using existing geological and geotechnical data. It is the objective of this map to show those areas of Greater Victoria in which the earthquake hazard is *increased* due to the presence of soils susceptible to amplification of ground motion. This map accompanies four other maps relevant to earthquake hazards in Greater Victoria: a map of the Quaternary geology, on which this hazard map is based (Geoscience Map 2000-2; Monahan and Levson, 2000); a map that shows areas susceptible to liquefaction (Geoscience Map 2000-3a; Monahan *et al.*, 2000b); a map that shows areas susceptible to earthquake-induced slope instability (Geoscience Map 2000-3c; McQuarrie and Bean, 2000); and a composite map that shows areas susceptible to the amplification of ground motion, liquefaction, and earthquake-induced slope instability hazards (Geoscience Map 2000-1; Monahan *et al.*, 2000a). Results of this project are also discussed by Monahan and Levson (1997) and Monahan *et al*. (1998).

For the proper use of this map, the accompanying report and expanded legend should be carefully read and understood. This map is intended for regional purposes only, such as land use and emergency response planning, and should not be used for site-specific evaluations. This map can be used with other criteria to help planners select potential areas for development, avoid geologically vulnerable areas, and prioritize seismic upgrading programs. *However, this map does not replace the need for site-specific geotechnical evaluation* prior to new construction or upgrading of buildings and other facilities. The qualifications and limitations of this map are discussed in more detail below and in the accompanying report and expanded legend.

GEOLOGICAL MAPPING

The initial step in the evaluation of the relative amplification of ground motion hazard in the Victoria area was the preparation of a geological map that shows the thickness and distribution of Quaternary stratigraphic units (Monahan and Levson, 2000). Subsurface geological data on which the geological map is based include: over 5000 geotechnical borehole logs; several hundred water well logs; and nearly 3000 engineering drawings for municipal sewer and water lines. Geological map units were defined on the basis of these data, and in part coincide with the U.S. National Earthquake Hazard Reduction Program (NEHRP) site classes for susceptibility to amplification of ground motion (Building Seismic Safety Council, 1994). Although the relative amplification of ground motion hazard map is colour-coded as to the level of hazard, the geological map units are shown on the map and indicated by the appropriate label in each polygon (see legend). The geological map units are described in more detail in the accompanying report and expanded legend. Map unit boundaries were interpreted on the basis of the subsurface data, airphotos, large-scale topographic maps, and published soil maps. In addition, limited field checking was conducted. In areas with little or no subsurface data, the subsurface conditions are largely *inferred* from topographic and geomorphic evidence. To assist the user in determining the accuracy of the subsurface geological mapping, sites where subsurface geological data were available to us are shown on the maps.

AMPLIFICATION OF GROUND MOTION HAZARD MAPPING

Amplification of ground motion refers to the increase in the intensity of ground shaking that can occur due to local geological conditions, such as the presence of soft soils. In the Victoria area, the amplification hazard rating for each geological map unit is estimated primarily on the basis of the NEHRP site classes for susceptibility to amplification (see Table 1) and are shown on the legend of this map.

The NEHRP site classes are defined primarily on the basis of the average shear-wave velocity in the upper 30 metres (Building Seismic Safety Council, 1994). Shear-wave velocity data were derived from 15 seismic cone penetration tests (SCPTs) and 4 spectral analysis of surface wave tests (SASW) in the Victoria area. These techniques are described by Robertson *et al.*, 1992 and Stokoe *et al.*, 1994, respectively. The shear-wave velocity data were used to develop a shear-wave velocity model for the principal Quaternary geological units, so that the average shear-wave velocity in the upper 30 metres could be estimated at other sites where such data were not available (Monahan and Levson, 1997).

On the basis of these criteria, the amplification hazard varies from very low, where bedrock is exposed (unit R1*), to high where soft clay is present (units C2, C5, O1 and O5). The assigned hazard rating extends to very high in units where peat more than 3 metres thick occurs at the surface (Map 1 Monahan *et al.*, 1998). Consistent with these hazard ratings, most damage experienced in Victoria during the 1946 Vancouver Island earthquake was concentrated in areas underlain by soft soils, and damage was the least where bedrock is near or at the surface Wuorinen, 1974, 1976).

TABLE 1
Categories for Soil Susceptibility to Amplification (definitions from Building Seismic Safety Council (1994); descriptive susceptibility ratings from Klohn-Crippen Consultants Ltd., 1994)

Site Class	General Description	Definition (Vs_{30}=average shear-wave velocity in upper 30 m, m/sec)	Susceptibility Rating
A	Hard rock	$Vs_{30}>1500$	Nil*
B	Rock	$760<Vs_{30}<1500$	Very Low*
C	Very dense soil and soft rock	$360<Vs_{30}<760$; or $Vs_{30}>760$ m/sec where >3 m of soil over bedrock	Low
D	Stiff soils	$180<Vs_{30}<360$	Moderate
E	Soft soils	$Vs_{30}<180$; or >3 m silt and clay with plasticit index >20, moisture content >40%, and undrained shear strength <25 kPa	High
F	Peats or highly organic clays	Peat thickness > 3	Very High (?)

*** Amplification on rock sites due to topography can be significant, and can exceed amplification due to soils in some cases. See below.**

However, several important qualifiers must be added to these hazard ratings.

1. Variation in amplification levels

The intensity of amplification on soft soils diminishes as the strength of ground shaking (i.e. acceleration) increases (Building Seismic Safety Council, 1994). This decrease is more pronounced for short period ground motions, which typically affect short buildings, than for long period ground motions, which typically affect tall buildings such as high rises** (see Maps 2 to 5 and adjoining text, and the accompanying report and expanded legend for more details). For example, at ground shaking levels of 0.1 g on bedrock (0.1 g is acceleration equal to 10% of the force of gravity, and approximately the onset of damage in buildings not designed to be earthquake resistant; bedrock refers to NEHRP site class B), short period ground motions can be amplified by a factor of 2.5 on soft soils (i.e. 0.25 g; Map 2). However, at ground shaking levels of 0.4 g on bedrock (0.4 g is the current building code design acceleration for Victoria; National Research Council of Canada, 1995), amplification of short period ground motions due to soft soils is minimal, and all areas will be shaken strongly but more or less equally (i.e. ~0.4 g; Map 4). Consequently, amplification on soft soils in Victoria may be minimal for short period ground motions in the event of a large earthquake in close proximity to the city (i.e. *all* areas will be shaken strongly), but could be significant for a large earthquake tens of kilometres distant and generating moderate shaking on bedrock in the city. However, a moderate shaking event is *much more likely* to occur than a strong shaking event. For example in the Victoria area, shaking of 0.1 g on bedrock is more than ten times as likely to occur as shaking of 0.4 g on firm ground. Thus, areas assigned a high amplification hazard on Map 1 will be subjected to potentially damaging ground motions *much more often* than areas with a very low hazard. For long period ground motions, amplification due to soil conditions also diminishes as the strength of ground motions increase, but can still be significant at 0.4 g (Maps 3 and 5).

This map does not address amplification of ground motion due to resonance. The specific periods of ground motion that match the natural periods of a site can be greatly amplified, and can be particularly destructive to structures whose natural periods match those of the site** (Reiter, 1990; Rial, 1992).

2. Topographic effects

This map does not show areas susceptible to amplification due to topography, which can exceed amplification due to soil conditions in some cases. High amplification is commonly experienced on hills, ridges and the tops of cliffs (Finn, 1994; Sommerville, 1998), which are generally underlain in the Victoria area by thin and/or dense soils and bedrock (units R1, R1/2, R2, and T). Consequently, the very low and low hazard ratings assigned to these map units may not apply on such topographic features. Amplification due to topography is poorly understood and not readily quantified at this time.

3. Three-dimensional effects

This map does not consider amplification due to three-dimensional effects, such as the focussing of energy due to the structure of the earth's crust in the region, which can be as great as amplification due to soil conditions (Somerville, 1998).

This map reflects variations in earthquake hazard due to soil conditions, which are applicable to most earthquakes that will affect the region. Topographic and three-dimensional effects are more dependent on the earthquake locatior and direction of seismic energy.

**** The critical period of ground motion for a specific building or building type should be determined by a qualified structural engineer.**

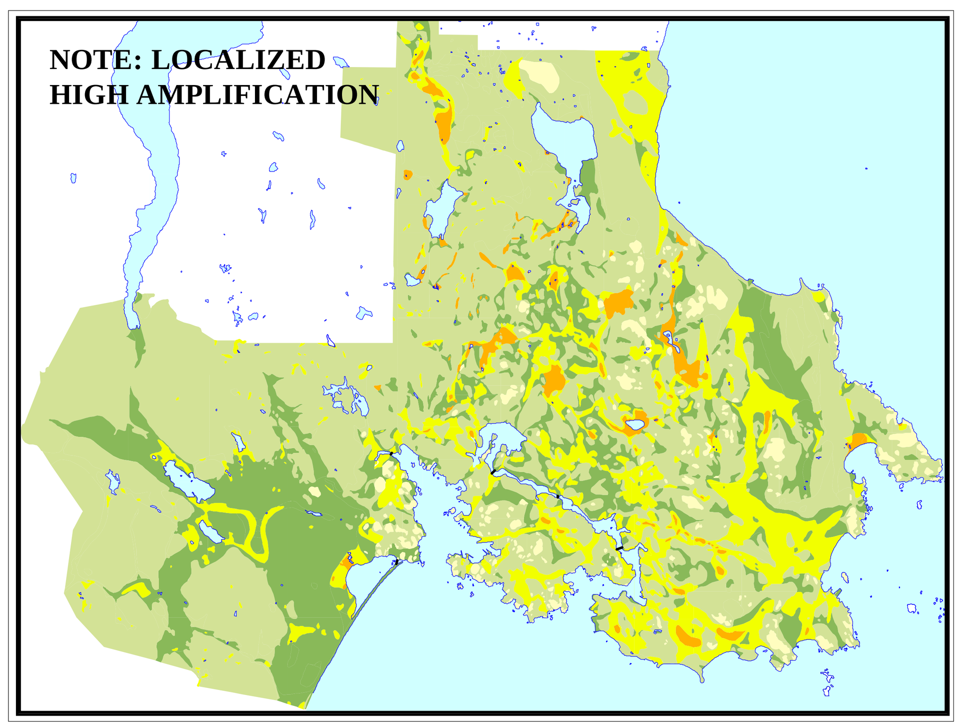
APPROXIMATE AMPLIFICATION FACTORS FOR DIFFERENT GROUND MOTIONS

***The relative amplification hazard ratings shown on Map 1 are generalized ratings and do not reflect the amplification hazard in all cases.* In particular, the amount of amplification due to soil conditions diminishes as the strength of ground shaking (i.e. acceleration) increases. Maps 2 to 5 show how *amplification factors* (not the actual amount of earthquake ground motion) can vary with different strengths and periods of ground motion. See below and see text under "Variation in amplification levels".**

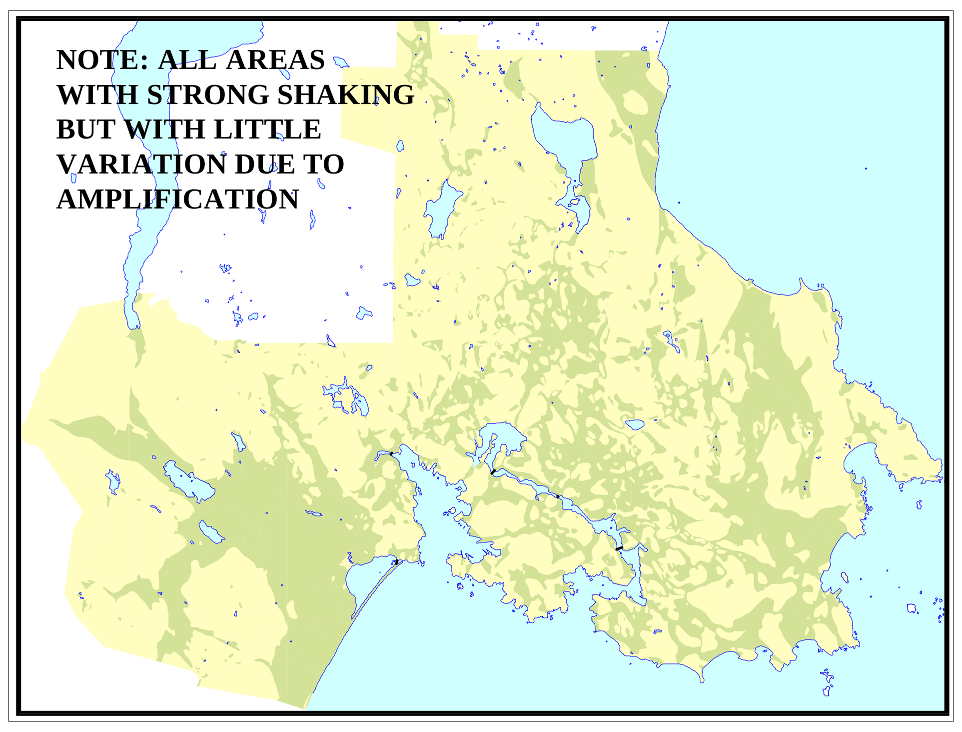
MODERATE EARTHQUAKE SHAKING
(0.1 g on bedrock - approximate onset of damage in buildings not designed to be earthquake resistant)

STRONG EARTHQUAKE SHAKING
(0.4 g on bedrock - current building code design acceleration for Victoria.)

SHORT PERIOD GROUND MOTIONS
(typically affecting short buildings)**



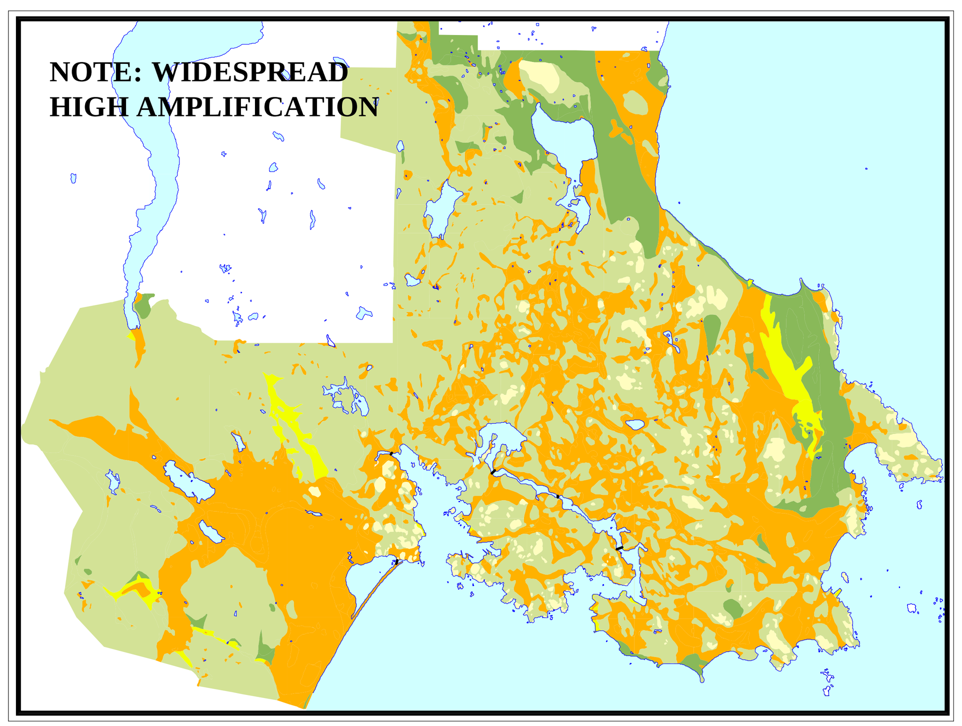
Map 2. amplification factors for short period ground motions at a moderate level of shaking on bedrock. Note that short period ground motions may be amplified 2.5 times (i.e. to 0.25 g) on soft soils. Note also that the high hazard areas shown on Map 1 also have high amplification on this map.



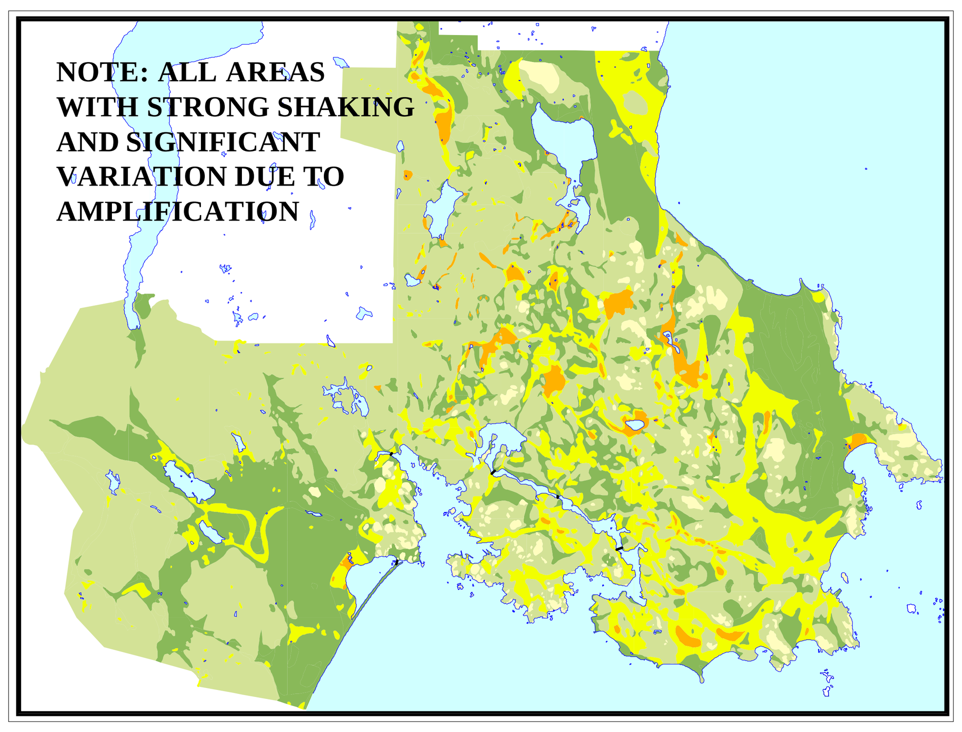
Map 4. amplification factors for short period ground motions at a strong level of shaking on bedrock. Note that in this case, there is little difference in amplification due to soil conditions across the area, and all areas will be shaken strongly but more or less equally (i.e.~0.4 g).

SHORT PERIOD GROUND MOTIONS

LONG PERIOD GROUND MOTIONS
(typically affecting tall buildings)**



Map 3. amplification factors for long period ground motions at a moderate level of shaking on bedrock. Note that long period ground motions may be amplified greater than 2.5 times or more on soft soils. Note also that the high hazard areas shown on Map 1 also have high amplification on this map.



Map 5. amplification factors for long period ground motions at a strong level of shaking on bedrock. Note that long period ground motions may be amplified 2.5 times on soft soils. Note also that the high hazard areas shown on Map 1 also have high amplification on this map.

LONG PERIOD GROUND MOTIONS

MODERATE EARTHQUAKE SHAKING

STRONG EARTHQUAKE SHAKING

Legend for Maps 2 to 5
Approximate Amplification Factors Relative to Rock, NEHRP Site class B)

Low — ~1
Moderate — ~1.5
High — >~2.5

Maps 2, 3, 4 and 5 show the approximate *amplification factors* for moderate and strong shaking (accelerations on bedrock of 0.1 g and 0.4 g, respectively), and for short and long period ground motions (typically affecting short and tall buildings, respectively**). The *amplification factor* is the amount by which ground motion on bedrock (i.e.NEHRP site class B) is multiplied due to soil conditions. Acceleration of 0.1 g represents the approximate onset of damage in buildings not designed to be earthquake resistant, and 0.4 g is the current building code design acceleration for Victoria (National Research Council of Canada, 1995). Both short and long period ground motions occur during an earthquake, but usually one type dominates depending on earthquake magnitude and distance from the source. These maps were prepared using the estimated average NEHRP site class for each geological map unit shown on Map 1 and the corresponding NEHRP amplification factors for short and long period structures (see Table 3 of the accompanying report).

Amplification factors decrease as the acceleration o bedrock increases, and this decrease is more pronounced for short period than long period ground motions. Short period ground motions can be amplified 2.5 times or more on soft soils during moderate shaking (Map 2; i.e. to 0.25 g, where acceleration on bedrock is 0.1 g). Conversely, relative amplification of short period ground motions due to the presence of soft soils during strong shaking is minimal, and all areas will be shaken strongly but more or less equally (Map 4; in this case ~0.4 g). Although little amplification of short period ground motions will occur during strong shaking (Map 4), *moderate shaking is much more likely to occur*, so that areas shown as high hazard on Map 1 will be subjected to potentially damaging short period ground motion *much more often* than low hazard areas. For example in the Victoria area, shaking of 0.1 g on bedrock is more than ten times as likely to occur as shaking of 0.4 g on bedrock. Although amplification of long period ground motions also diminishes as the intensity of ground shaking increases, it is still significant at 0.4 g (Maps 3 and 5). **Thus, in most cases (e.g. Maps 2, 3 and 5) and most often, the hazard ratings shown on Map 1 will reflect the intensity of amplification due to soil conditions (see also text under "Variation in amplification levels").**

The variation in ground motions predicted using the amplification factors shown here does not exceed the seismic design criteria of the current building code (National Research Council of Canada, 1995), but could be significant for structures not governed by the seismic provisions of the code as well as older structures. In the current building code amplification factors are expressed relative to "firm ground", typically NEHRP site class C, whereas NEHRP amplification factors are expressed relative to site class B.

***** The critical period of ground motion for a specific building or building type should be determined by a qualified structural engineer.***

Geological Survey Branch
Geoscience Map 2000-3b.

Relative Amplification of Ground Motion Hazard Map of Greater Victoria

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Scale 1:25,000 (approximate)

0.5 0 0.5 1 1.5 k

[1]Monahan Petroleum Consulting
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QUALIFICATIONS AND LIMITATIONS OF THIS MAP

1. **This map is intended for regional purposes only, such as land use and emergency response planning, and should not be used for site-specific evaluations.**
2. The map is based on interpretations of borehole records, th *approximate* locations of which are shown. Where borehole data are scarce, subsurface conditions had to be *inferred* from topographic and geomorphic evidence.
3. The boundaries of most map units ar gradational, particularly in the Victoria area due to the extreme irregularity of the bedrock surface For these reasons map unit boundaries ar *approximate*, may include smaller occurrences of other map units, and are subject to revision as more borehole data become available. Furthermore, geological materials are variable, and deposits of a map unit may locally have unusual properties. **Consequently, the hazard *at a specific site* may be higher or lower than shown on the map.**
4. This map does not fully address man-made alterations to ground conditions, whether the changes decrease or increase the hazard at a site. Poor soil sites may have been improved during construction, which will change the hazard from that shown on the map.
5. Only the larger fills of which the authors were aware are shown on the map. Other areas of fill are present, and new areas of fill will be developed in the future. The properties of fills vary from dense engineered fills to loose fills with a potentially high amplification hazard
6. The stability of dams under earthquake shaking, and hazards due to the failures of dams or other man-made structures have not been addressed.
7. This map shows areas where the earthquake hazard is *increased* due to amplification of ground motion. ***However, a low hazard on this map does not mean freedom from ground shaking due to earthquakes, because all areas could be subjected to significant ground shaking during an earthquake.*** Furthermore, the degree of amplification on soft soils diminishes as the intensity of ground shaking on bedrock increases, so that in the case of a strong earthquake close to the city, little *variation* in ground shaking (i.e. acceleration) may occur due to local soil conditions at short period ground motions. However, the city will be affected more often by more distant earthquakes that generate moderate shaking on bedrock, so that areas shown with a hig amplification hazard here will be subjected to potentially damaging ground motions *more often* than sites with a low amplification hazard. This subject is discussed in more detail above under "Variation in amplification levels" and illustrated in Maps 2 to 5.
8. The amplification of ground motion hazard has been estimated on the basis of the National Earthquake Hazard Reduction Progra (NEHRP) site classes for susceptibility to amplification of ground motion (Building Seismic Safety Council, 1994), which are based on the average response of various types of soils. Thus, variation in the amplification hazard should be expected within in an geological map unit. **This map does not address**:
   a) amplification of ground motion due to resonance, which can be particularly destructive to structures whose natural periods match those of the site (Reiter, 1990; Rial, 1992);
   b) amplification of ground motion due to topography, by which ground motions can be amplified on hills, ridges and the tops of cliffs (Finn, 1994; Somerville, 1998); an
   c) amplification due to three-dimensional effects, such as the focussing of energ due to the structure of the earth's crust in the region (Somerville, 1998).
9. This map addresses only the amplification of ground motion hazard. The liquefaction and earthquake-induced landslide hazards are addressed on accompanying maps (Monahan *et al*., 2000b, and McQuarrie and Bean, 2000, respectively). Other earthquake hazards, such as tsunamis, land subsidence and ground rupture are not addressed on this or any other maps published as part of this investigation.
10. **This map can not be used to *directly* predict the amount of damage that will occur at any one site because many other factors, such as building design and construction details, must be considered.** The map in no way shows how different types of building or other man-made structures will perform during earthquakes. This map can be used to estimate the relative natural hazard due to the susceptibility to soil amplification alone.

ACKNOWLEDGMENTS

This project received funding from the Capital Regional District, the Geological Survey of Canada, the British Columbia Resources Inventory Committee and Corporate Resources Inventory Initiative, and the Joint Emergency Preparedness Program. The authors also acknowledge the wealth of geological and geotechnical data and other assistance provided by numerous agencies and individuals, a complete listing of whom is provided in the accompanying report and expanded legend. In particular, the authors acknowledge the assistance of G. C. Rogers, J. Cassidy, R. Lloyd, M. Williams, R. Gibbs, B. Harding, B. Kerr, and J. Valeriote. Cartography by C.Spicer and G. Letham at AXYS Environmental Consulting Ltd.

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