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EARTHQUAKE SIGNATURE IN LATE HOLOCENE SEDIMENTS IN SAANICH INLET, BRITISH COLUMBIA

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Abstract

Short hydraulic piston cores collected in Saanich Inlet in 1989 and 1991, combined with longer piston cores collected in the same area in 1996 during Ocean Drilling Program Leg 169S, record a sequence of large earthquakes in southwestern British Columbia during the late Holocene. The sediment cores consist of rhythmically laminated (varved) marine mud with intercalated massive beds, interpreted to be debris flow deposits. Some of the extensive (>1 km) debris flow deposits are linked to past earthquakes, including the 1946 Vancouver Island earthquake (M7.3), a great (M~9) plate-boundary earthquake at the Cascadia subduction zone in January 1700, and a large crustal or plate-boundary earthquake about 1000 years ago. Earthquakes may also be responsible for debris flows in about AD 1600, 1500, 1250, 1150, *1000*, 850, 800, *450*, 350, 100, and BC 200, 220, *500*, 900, 2000, and 2020. We estimated the average recurrence interval for crustal and subcrustal earthquakes by excluding known plate boundary events (shown in italics). The calculated recurrence interval, 268 years, corresponds to a peak acceleration of 0.24 g, derived from a recurrence relationship generated from earthquake statistics. A peak acceleration of about 0.24 g translates into seismic shaking of MM (Modified Mercalli) Intensity VII, a level of shaking that can produce submarine landslides. We conclude that most or all of the extensive debris flow deposits in Saanich Inlet were triggered by moderate to large earthquakes rather than by non-seismic processes.

Résumé

Des sédiments prélevés par carottier à piston dans l'Anse Saanich en 1989, 1991 et lors de l'excursion "Ocean Drilling Program Leg 169S" en 1996 ont enregistré de gros tremblements de terre au sud-ouest de la Colombie-Britannique durant l'Holocène. Les carottes sont composées principalement de sédiments varvés à grain fin, mais elles incluent des couches massives déposées par des coulées de débris sous-aquatiques. Certaines coulées de débris extensives (>1km) sont liées à des séismes antérieurs tels que le séisme enregistré en 1946 sur l'Île de Vancouver (M7.3) et deux séismes à la limite des plaques au long de la zone de subduction Cascadia, datant de janvier 1700 (M~9) et d'il y a 1000 ans. D'autres coulées de débris extensives sont liées à des tremblements de terre, celles-ci sont datées de 1600, 1500, 1250, 1150, *1000*, 850, 800, *450*, 350, 100, après J.-C. et 200, 220, *500*, 900, 2000, et 2020 avant J.-C. Pour la période s'échelonnant sur les derniers 4020 ans, nous avons calculé la périodicité des tremblements de terre en excluant les séismes à la limite des plaques documentés (indiqués en italliques). Celle-ci correspond à 268 ans. Selon les statistiques des tremblements de terre pour la région de l'Anse Saanich, une périodicité de 268 ans correspond au sommet d'accélération de 0,24 de gravité. Ce qui révèle une intensité de tremblement de terre à l'échelle locale modifiée de Mercalli VII, soit une assez grande intensité pour produire des glissements de terrain. Bref, les tremblements de terre moyens à grands sont probablemnent à l'origine des coulées de débris extensives dans l'Anse Saanich.

1. INTRODUCTION

Southwestern British Columbia is one of the most seismically active areas in Canada (Rogers, 1994). Assessments of hazard are based the relatively short (ca. 100 year) record of instrumentally recorded earthquakes, but scientists have begun to extend this historic record using geological and geophysical data. We have investigated a possible earthquake proxy record at Saanich Inlet, a fiord on southeastern Vancouver Island (Fig. 1). The fiord contains a sequence of late Holocene varved sediments, with annual resolution. Interlayered with the varves are coarser sediments deposited by earthquake-triggered subaqueous landslides. This stratigraphy thus may contain information on times of past earthquakes.

In this paper, we will report results obtained from sediment cores collected in 1989 and 1991, and during ODP Leg169S in 1996. The objectives of this paper are to 1) provide a chronology of large earthquake-triggered debris flows over the past 4000 years, 2) establish the average recurrence interval for moderate to large earthquakes, and 3) compare the recurrence interval calculated from the sediment record with an empirical estimate of recurrence for the region.

2. SAANICH INLET

Saanich Inlet is 26 km long and up to about 8 km wide. Its average and maximum depths are 120 m and 238 m, respectively. The main source of freshwater and sediment is Cowichan River, which is located north of the inlet (Fig. 1). During periods of high discharge, generally in the fall and winter, clay- and silt-size sediment is carried in suspension from Cowichan River into Saanich Inlet via Satellite Channel (Herlinveaux, 1962).

Saanich Inlet is separated from Satellite Channel by a bedrock sill at 70 m depth (Fig. 1). The sill restricts deep-water circulation in Saanich Inlet, and, as a result, the lower part of the water column is anoxic (Carter, 1934; Gross et al., 1963). Consequently, deep-water sediments are not bioturbated and laminated sediments can accumulate without disturbance. The varved laminae form distinctive couplets, each consisting of a terrigenous mud layer deposited during fall and winter, and a diatom-rich layer deposited during spring and summer (Gross et al., 1963; Sancetta and Calvert, 1988; Sancetta, 1989). Deposition of varves is occasionally interrupted by erosive debris flows with sources on the sidewalls of the inlet (Blais, 1995; Blais-Stevens et al., 1997).

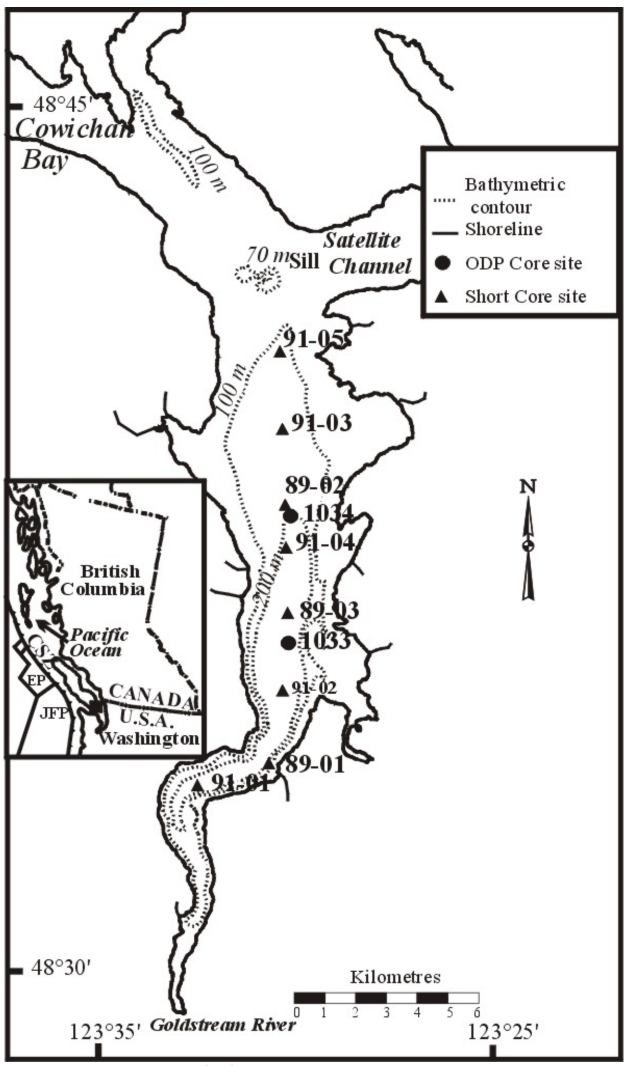

Figure 1. Map of Saanich Inlet showing cores sites. Inset: CSZ = Cascadia subduction zone; EP Explorer plate; and JFP= Juan de Fuca Plate.

3. METHODS

We collected short piston cores up to 20 m long were in 1989 and 1991. Longer, continuous cores were collected at two sites in Saanich Inlet in 1996 during ODP Leg 169S (Fig. 1) using a hydraulic piston coring system. Four holes with lateral offsets of 10 m were drilled to a maximum depth of 105.1 m below the seafloor at ODP site 1033 (48°35.438'N, 123°30.201'W; 238 m water depth). Five holes with lateral offsets of 10 m were drilled to a maximum depth of 118.2 m below the seafloor at ODP site 1034, 4 km north of site 1033 (48°38.000' N, 123°30.000'W; 200 m water depth). Core handling procedures are described in the ODP Initial Reports volume (Bornhold et al., 1998).

Seventy one samples of shell, fish bone, wood, and charcoal were AMS radiocarbon dated at the Center for Accelerator Mass Spectroscopy at Lawrence Livermore National Laboratory. Approximate calendric ages were calculated from the radiocarbon ages using the calibration program of Stuiver and Reimer (1993).

Marker horizons, including distinctive varves, massive beds, a layer of volcanic ash, indistinctly laminated varves, and a massive gray clay unit, aided correlation of cores between the two coring sites. Varve counts and variations in varve thickness were also used for correlation. Precise varve counts were made for cores 1033B and 1034B. Varves in the other cores were not directly counted; but numbers of varves were estimated from average couplet thicknesses.

The uppermost deep-water sediments in Saanich Inlet have very low densities and high water contents. These sediments were not recovered during ODP coring. Most of the short cores collected in 1989 and 1991, however, did include surface sediment, or at least sediment very close to the seafloor. Comparison of the two sets of cores allowed us to tie the ODP core stratigraphy to a historical datum, a diatom marker dating to AD 1940 (McQuoid and Hobson, 1997).

4. RESULTS AND DISCUSSION

4.1 Stratigraphy

The cored sediments span the last 15,000 years. The major stratigraphic units, from youngest to oldest, are 1) distinctly laminated, olive gray, diatomaceous, marine mud intercalated with muddy debris flow deposits, 2) indistinctly laminated, bioturbated, olive gray mud, and 3) gray glaciomarine mud. Two stratigraphic markers are found within the indistinctly laminated marine mud – a layer of Mazama volcanic ash and a gray silty clay bed (Fig. 2). Unit 1, which is relevant to this paper, is described below (see also Blais-Stevens et al. 2001, and Blais-Stevens and Clague 2001).

4.1.1 Varves

The varves range in thickness from a few millimeters to as much as 20 mm in the upper parts of the cores (Fig. 3). They thin from north to south, due to a decrease in sedimentation rates in that direction. This trend shows that Cowichan River is the main source of terrigenous sediment in Saanich Inlet (Matsumoto and Wong, 1977; Blais, 1995; Blais-Stevens and Clague, 2001).

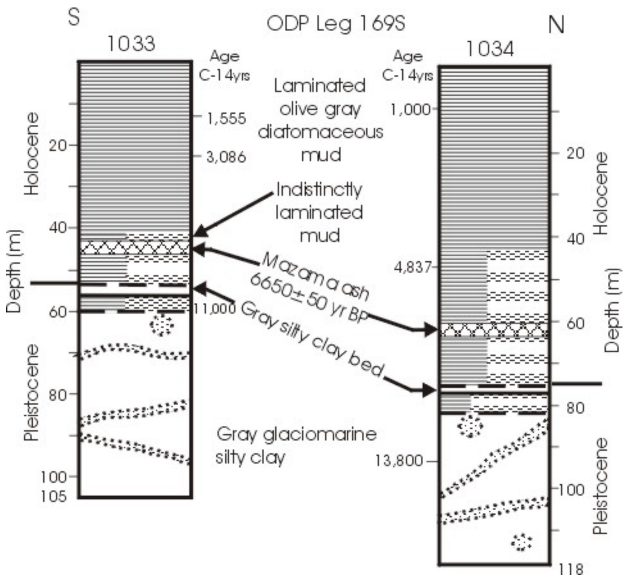

Figure 2. Schematic stratigraphic summary of ODP cores 1033 and 1034. Ages are in radiocarbon years BP.

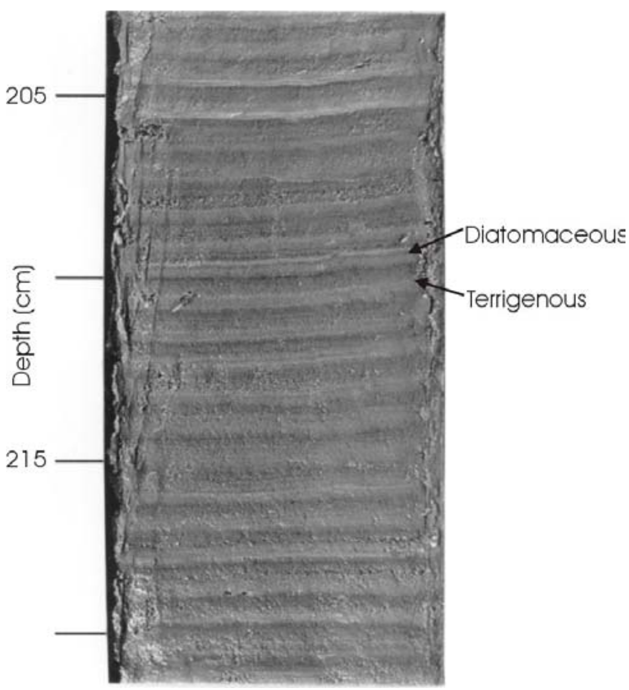

Figure 3. Typical varved sediments. Each couplet comprises a dark lamina of terrigenous sediment (winter layer) and one light, diatom-rich lamina (summer layer).

4.1.2 Debris flow deposits

The debris flow deposits are silty clay beds with erosional basal contacts, thick diatom caps, and basal zones of deformed varves grading upward into massive mud. They generally have a greater amount of silt and sand than the varves and contain broken tests of shallow water foraminifera. The beds range in thickness from a few centimetres to a few decimetres (Fig. 4). These deposits were produced by sediment gravity flows from sidewall failures (Blais, 1995; Blais-Stevens and Clague, 2001; Calvert et al., 2001). The beds are thicker and more abundant at the south end of Saanich Inlet (44 at ODP site 1033), where the sidewalls are steep, than at the north end (22 at ODP site 1034) (Blais, 1995; Blais-Stevens and Clague, 2001).

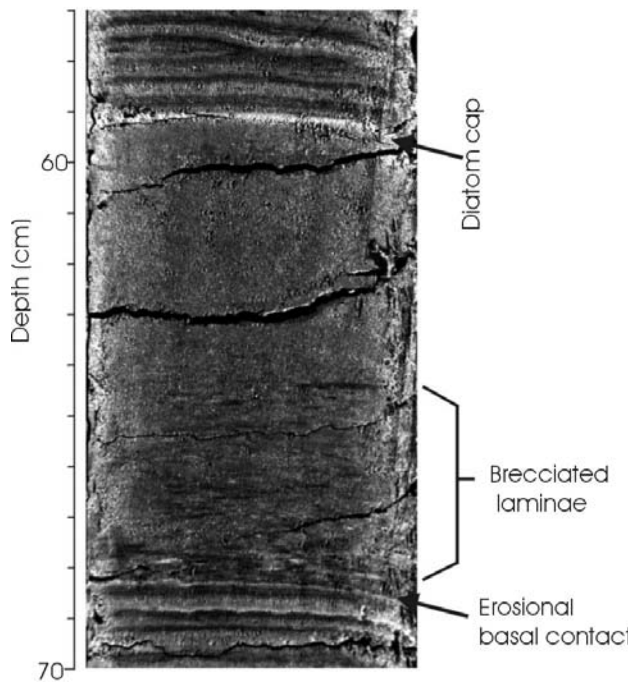

Figure 4. Debris flow deposit showing erosional basal contact, basal zone of brecciated laminae, and diatom cap.

4.3 Correlation of debris flow deposits

Debris flow deposits were correlated from core to core using radiocarbon, ^{137}Cs, and ^{210}Pb dates, varve counts, marker horizons, sedimentology, and bed thicknesses. Eighteen debris flow units, deposited over the last 4000 years, have extents of more than 1 km (Fig. 4).

4.4 Origin of debris flows

Debris flow deposits that are found in only one core, and thus not areally extensive, need not be triggered by earthquakes. They could result from failures of sediment off the mouths of small streams, discharge of submarine groundwater springs, or other phenomena.

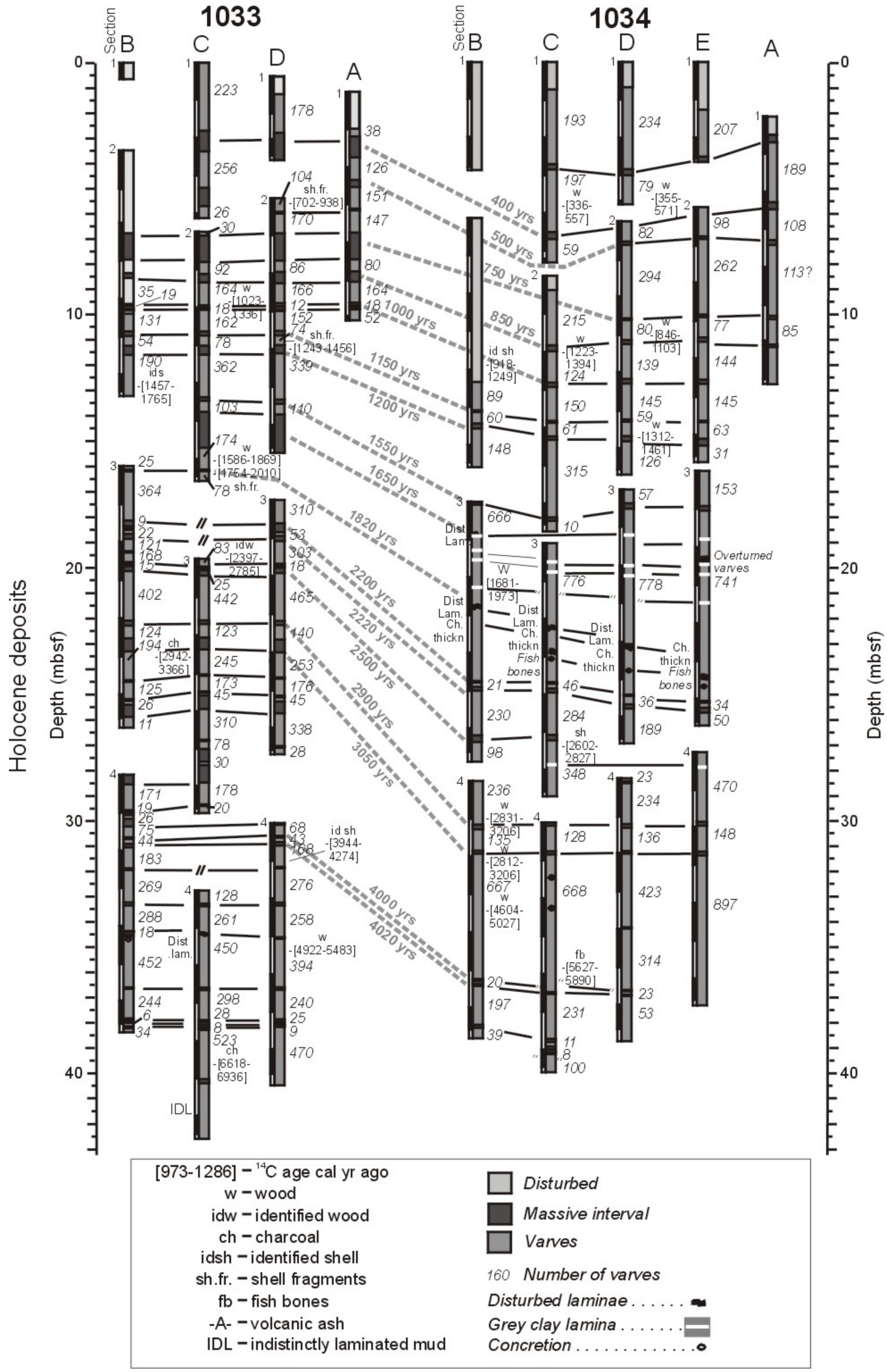

Figure 5. Correlation of debris flow beds in ODP cores (Blais-Stevens and Clague, 2001).

Saanich Inlet, however, is an ideal environment for earthquake-triggered slope failures. Most of the terrigenous sediment deposited in the inlet is derived from an external source (Cowichan River) and settles from suspension on the walls and floor of the fiord. Mud that has accumulated on the fiord walls is vulnerable to failure when shaken during earthquakes. We interpret large, extensive debris flows or groups of synchronous debris flows found over a large area (> 1 km) in two or more cores to be the result of earthquake shaking.

4.5 Debris flow deposits linked to known earthquakes

4.5.1 1946 Vancouver Island earthquake

A magnitude 7.3 earthquake, the largest in southwestern British Columbia in the twentieth century, struck Vancouver Island on June 23, 1946 (Hodgson, 1946; Rogers and Hasegawa, 1978). The epicentre of the earthquake was on central Vancouver Island, about 200 km north of Saanich Inlet. Shaking was strong with a maximum Modified Mercalli Intensity (MMI) of VI at Victoria and Vancouver, and some buildings in Victoria were damaged. Subaqueous landslides, triggered by shaking and by seismic liquefaction, occurred widely on Vancouver Island, to within at least 40 km of Saanich Inlet (Rogers, 1980). The uppermost massive bed in short core 89-3 dates to about 1946. Core 89-3, however, is the only core that has a massive bed of this age, and it is likely that the 1946 earthquake produced only small failures in Saanich Inlet.

4.5.2 1700 earthquake

A magnitude 9 earthquake occurred at the Cascadia plate boundary off the coasts of Vancouver Island, Washington, and Oregon on January 26, 1700 (Satake et al., 1996; Jacoby et al., 1997; Yamaguchi et al., 1997). The earthquake shook southern Vancouver Island and probably triggered subaqueous slope failures in Saanich Inlet.

Cores 89-3 and 91-3 contain a debris flow deposit dated at AD 1720 and 1725, respectively. These are minimum limiting ages for the event and we infer that they most likely result from simultaneous deposition during the 1700 earthquake (Blais-Stevens and Clague, 2001). Skinner (2002) has recently correlated debris flow deposits in three other short cores to these two units.

4.5.3 Other possible earthquakes

Other debris flow deposits in cores 89-3, 91-4, 1033, and 1034 date to about AD 1600, 1500, 1250, 1150, *1000*, 850, 800, *450*, 350, 100, and BC 200, 220, *500*, 900, 2000, and 2020 (Fig. 5). These cores span a distance of over 4 km, indicating that the deposits are widespread and are probably associated with earthquakes. Some of the debris flow deposits date to times of great earthquakes at the Cascadia subduction zone (italicized above; Atwater and Hemphill-Haley, 1997; Atwater et al., in press).

4.6 Debris flows and earthquake frequency

The average recurrence interval for the 18 extensive debris flows (and the less extensive debris flow dated to 1946) is 211 years. The events are separated from 20 to 950 years.

By excluding from the Saanich Inlet record four debris flows associated with plate boundary earthquakes, we can infer an average recurrence interval for moderate to large crustal and subcrustal earthquakes in the region (Rogers, 1994). The calculated recurrence interval is 268 years.

A recurrence interval of 268 years, when plotted on an acceleration diagram produced from historical earthquake data (Fig. 6), yields a peak ground acceleration of 0.24 g. This acceleration correponds to a level of shaking characteristic of a MMI VII earthquake. Earthquakes of this magnitude generally produce numerous landslides (Wald et al., 1999). Consequently, we infer that all of the extensive debris flow deposits in Saanich Inlet are likely the result of seismic shaking.

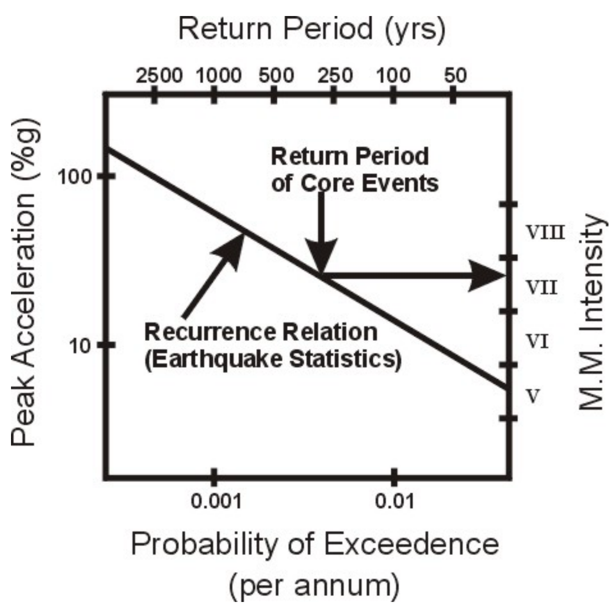

Figure 6. Relationship among peak acceleration, Modified Mercalli Intensity (MMI), and probability of exceedence for earthquakes on southern Vancouver Island, based on historical data. Widespread debris flows in Saanich Inlet recur, on average, once every 268 years. Earthquakes with this return period are of MMI intensity VII.

5 CONCLUSIONS

From a study of Saanich Inlet sediment cores, we have identified 18 extensive debris flows, as well as one less extensive debris flow related to the large AD 1946 Vancouver Island earthquake, over the last 4000 years.

Four of the extensive deposits correspond to documented plate boundary earthquakes. The average recurrence interval for the other widespread debris flow deposits is 268 years.

On southern Vancouver Island, earthquakes with a mean return period of 268 years have a peak ground acceleration of 0.24 g (MMI VII), which is high enough to trigger subaqueous landslides. Therefore, we conclude that the extensive debris flow deposits in Saanich Inlet are likely triggered by moderate to large earthquakes rather than by non-seismic processes.

ACKNOWLEDGEMENTS

We wish to thank Kim Conway for technical support and advice. Heidi Pass, Anastasia Ledwon, and Kevin Robertson assisted with laboratory analyses. Richard Franklin drafted some of the figures. Marten Geertsema helped with the formatting of the manuscript.

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