Late Holocene sedimentation in Saanich Inlet, British Columbia, and its paleoseismic implications[1]

A. Blais-Stevens, J.J. Clague, P.T. Bobrowsky, and R.T. Patterson

Abstract: Eight piston cores of sediment spanning the last 1500 years were collected from Saanich Inlet, an anoxic fiord on southern Vancouver Island, to obtain information on sedimentation and prehistoric earthquake activity. The cores consist mainly of fine-grained varved sediments, but include massive layers deposited by subaqueous debris flows. The debris flows may have been triggered by earthquakes or by the buildup of fine sediment on the walls of the inlet. Cesium-137 and ^{210}Pb data, ^{14}C ages, and varve counts were used to date and correlate massive layers in the eight cores. The uppermost massive layer in two cores may record a magnitude 7.2 earthquake that occurred in 1946 near Comox, British Columbia, 200 km north-northwest of Saanich Inlet. Seven older layers are found in two or more cores and are about 200, 440, 550, 800–850, 1050–1100, 1100–1150, and 1450–1500 years old. Two of these older layers may correlate with previously documented earthquakes in the region. There is an average of one massive layer per 116 varves in the core with the greatest number of such layers, which is broadly consistent with the expected periodicity of moderate to large earthquakes in the region, on average, one earthquake producing local Modified Mercalli Intensity VII or VIII per century. Saanich Inlet may contain a proxy record of all moderate and large earthquakes that have affected southwestern British Columbia during Holocene time, but some of the massive layers do not appear to correlate from core to core and undoubtedly are nonseismically generated deposits.

Résumé : Huit échantillons de sédiment prélevés par carottier à piston, s'échelonnant sur les derniers 1500 ans, ont été collectés dans le bras de mer Saanich, un fjord anoxique de l'île de Vancouver, pour obtenir des données sur la sédimentation et l'activité de tremblements de terre préhistoriques. 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. Ces coulées de débris ont pu être provoquées par des tremblements de terre ou par une accumulation excessive de sédiment fin sur les versants du bras de mer. Les données de ^{137}Ce et ^{210}Pb, les âges au ^{14}C et le comptage de varves ont été utilisés pour dater et la mise en corrélation des couches massives dans les huit carottes. La couche massive sommitale dans deux carottes correspond probablement au tremblement de terre de magnitude 7,2 survenu en 1946 près de Comox, en Colombie-Britannique, à 200 km au nord-nord-ouest du bras de mer Saanich. Sept couches plus anciennes apparaissent dans deux carottes ou plus, et leurs âges sont estimés à 200, 440, 550, 800–850, 1050–1100, 1100–1150 et 1450–1500 ans. Deux de ces anciennes couches peuvent être corrélées avec d'anciens tremblements de terre documentés pour cette région. Dans la carotte possédant le plus grand nombre de telles couches, on observe en moyenne une couche massive par 116 varves, ce qui concorde grossièrement avec la périodicité estimée des tremblements de terre de magnitude forte ou modérée dans la région—il y a en moyenne un tremblement de terre d'intensité VII ou VIII à l'échelle locale modifiée de Mercalli par siècle. Il est possible que les sédiments du bras de mer Saanich aient pu enregistrer tous les tremblements de terre, forts et modérés, qui ont affecté le sud-ouest de la Colombie-Britannique durant l'Holocène, mais pour certaines couches la corrélation de carotte à carotte n'est pas évidente, et incontestablement ces couches représentent des dépôts qui ont été engendrés par un processus autre que sismique.
[Traduit par la rédaction]

Received October 16, 1996. Accepted May 7, 1997.

A. Blais-Stevens.[2] Geological Survey of Canada, 601 Booth Street, Ottawa, ON K1A 0E8, Canada.
J.J. Clague. Geological Survey of Canada, 101 – 605 Robson Street, Vancouver, BC V6B 5J3, Canada, and Department of Earth Sciences, Simon Fraser University, Burnaby, BC V5A 1S6, Canada.
P.T. Bobrowsky. Geological Survey Branch, P.O. Box 9320, Victoria, BC V8W 9N3, Canada.
R.T. Patterson. Ottawa–Carleton Geoscience Centre and Department of Earth Sciences, Carleton University, Ottawa, ON K1S 5B6, Canada.

[1] Geological Survey of Canada Contribution 1996249; British Columbia Geological Survey Contribution 0059.
[2] Corresponding author (e-mail: ablais@gsc.nrcan.gc.ca).

Introduction

Southwestern British Columbia is one of the most tectonically active areas in Canada, and there is concern that a moderate to large earthquake may damage the cities and economic infrastructure of the region. Seismic activity is related to subduction of the oceanic Juan de Fuca plate beneath North America along the Cascadia subduction zone (Riddihough and Hyndman 1976) (Fig. 1). Rare, great (magnitude (M) $\geq$ 8) earthquakes occur at the boundary between the Juan de Fuca and North America plates (Rogers 1988; Atwater et al. 1995; Hyndman 1995), and smaller, more frequent earthquakes are centred within the two plates (Shedlock and Weaver 1991; Rogers 1994). Four large earthquakes have struck the region in historical time, in 1918 (M = 7) and 1946 (M = 7.2) on Vancouver Island, in 1872 (M = 7.4)

Fig. 1. Schematic diagram showing subduction of the oceanic Juan de Fuca plate beneath North America and epicentres of large ($M > 5$) historical earthquakes that have affected southwestern British Columbia and northwestern Washington. Star size is proportional to earthquake magnitude. Saanich Inlet and Victoria are located in the rectangle (see Fig. 2).

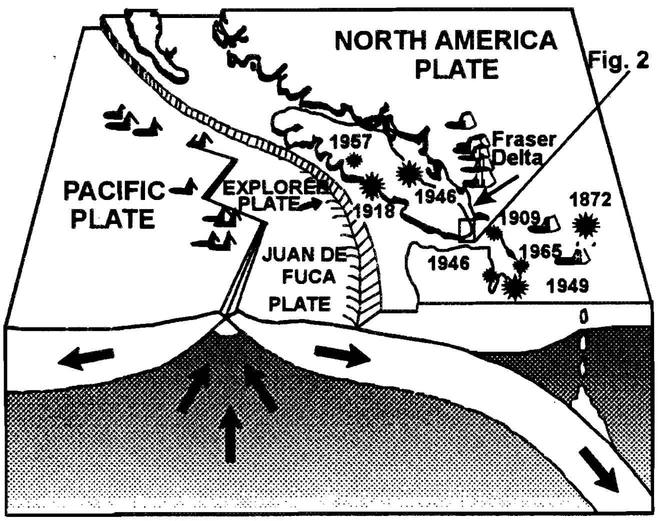
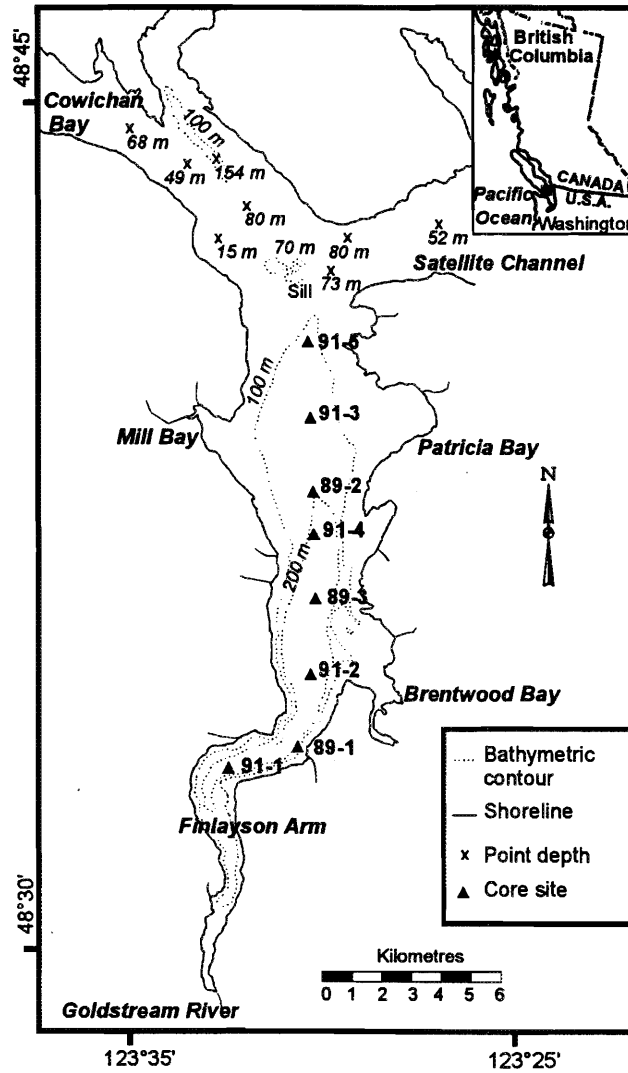


Fig. 2. Map of Saanich Inlet showing core sites. Solid square in inset indicates the location of the study area.



probably near Lake Chelan in northern Washington, and in 1949 near Tacoma, Washington ($M \approx 7.0$). Three of the four earthquakes occurred away from the southern Strait of Georgia – Puget Sound area, where most small earthquakes are concentrated (Rogers 1994).

A major problem in assessing seismic risk in southwestern British Columbia is that the historical period during which earthquakes have been instrumentally recorded is very short (approx. 100 years). Geologic studies can be useful in extending this short record and thus may provide better estimates of earthquake recurrence and magnitude. Several different types of geologic evidence have been found for past large earthquakes in southwestern British Columbia and northern Washington. These include (1) stratigraphy indicative of sudden land-level changes and tsunamis, i.e., buried marsh soils capped, in some cases, by sheets of sand and gravel (Atwater 1987, 1992; Darienzo and Peterson 1990; Clague and Bobrowsky 1994*a*, 1994*b*; Mathewes and Clague 1994); (2) sand dykes and sand blows produced by coseismic liquefaction (Clague et al. 1992; Obermeier 1995); and (3) seismically triggered landslides (Adams 1990; Jacoby et al. 1992; Karlin and Abella 1992, 1996; Schuster et al. 1992).

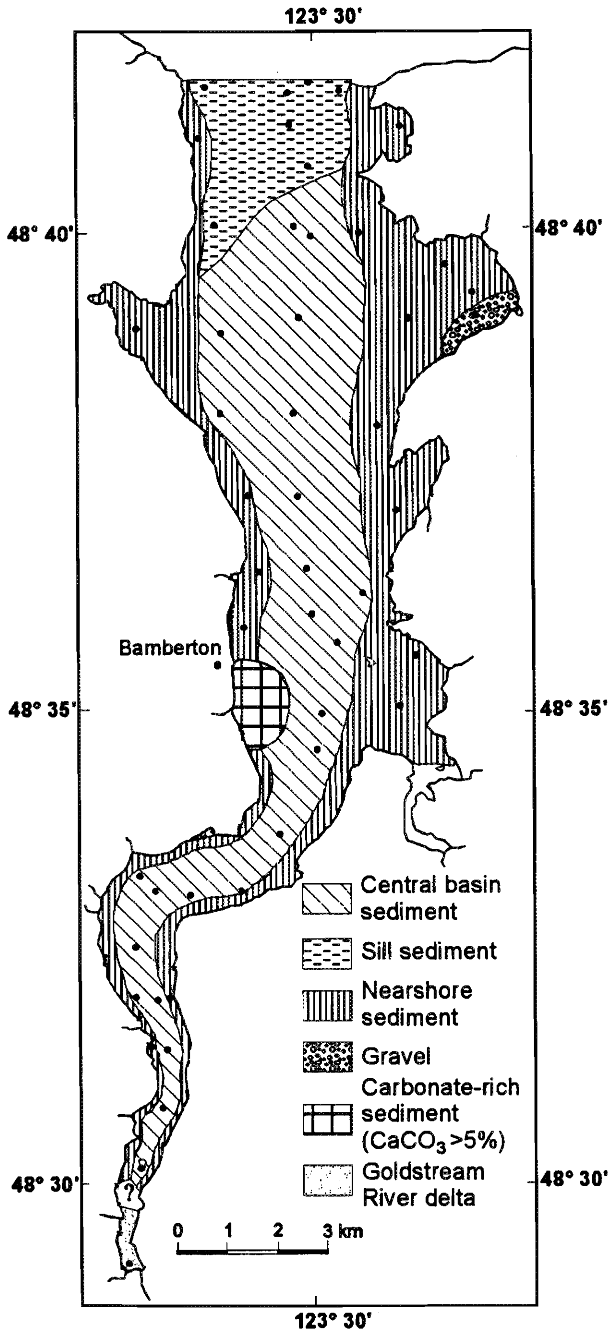
A limitation of most paleoseismological studies is that times of events cannot be precisely established because of reliance on radiocarbon dating: most radiocarbon ages have uncertainties of more than 100 years. In some cases, however, sediments with high temporal resolution, such as varves, can be used to more precisely date past events, including earthquakes.

Saanich Inlet on southern Vancouver Island (Fig. 2) was chosen as a site for paleoseismicity study because thick Holocene sediments in the central part of the fiord are varved and thus potentially can provide annual resolution for past events such as earthquakes. In addition, massive silty clay layers, which may have been emplaced by earthquake-triggered, sediment gravity flows, are present within the varved sequence (Bobrowsky and Clague 1990; Blais 1992). The objectives of this study were (1) to determine the source and age of sediments in the central part of Saanich Inlet, (2) to ascertain whether the massive silty clay layers are indeed sediment gravity flow deposits, (3) to determine whether the massive layers are products of earthquakes, and (4) to use varves to date past events more precisely than is possible with the radiocarbon method.

Study area

Saanich Inlet (Fig. 2) is 26 km long, up to 8 km wide, and has average and maximum depths of 120 and 236 m, respectively. The only significant stream flowing into Saanich Inlet is Goldstream River, and it contributes only a small percentage of the 9×10^4 t of sediment that accumulates in the inlet each year (Gross et al. 1963). In this respect, Saanich Inlet differs from most other fiords in British Columbia which have large inputs of freshwater and sediment at their heads (Herlinveaux 1962).

Fig. 3. Distribution of sediments in Saanich Inlet (dots are surface sediment samples). Central basin sediment = silt and clay with abundant diatom frustules; sill sediment = silt; nearshore sediment = fine sand and minor mud and gravel; carbonate-rich sediment = near limestone quarry at Bamberton. Modified from Gucluer and Gross (1964, their Fig. 3).



Plumes of clay- and silt-size sediment from Cowichan River enter Saanich Inlet from the northwest (Fig. 2) during periods of high discharge, commonly in the fall and winter (Herlinveaux 1962). Another possible source of terrigenous sediment is Fraser River, which flows into the Strait of Georgia, 50 km north of Saanich Inlet (Fig. 1).

A bedrock sill at 70 m depth at the mouth of Saanich Inlet (Figs. 2, 3) restricts water circulation, creating anoxic conditions below depths of 70–150 m (Carter 1934; Gross et al. 1963). In late summer or fall, dense cold water flows into the inlet from Satellite Channel and flushes the upper part of the anoxic zone; this increases the amount of dissolved oxygen in the inlet (Herlinveaux 1962; Anderson and Devol 1973; Stucchi and Giovando 1984). The amount of flushing differs from year to year, and, as a result, the anoxic layer varies considerably in thickness (Anderson and Devol 1973), although it rarely disappears completely (Stucchi and Giovando 1984).

Table 1. Location, depth, and length of piston cores.

Core	Lat. N	Long. W	Water depth (m)	Core length (cm)
89-1	48°33.73′	123°30.45′	227	885
89-2	48°38.41′	123°30.17′	198	1178
89-3	48°36.10′	123°30.00′	227	1180
91-1	48°33.21′	123°32.07′	220	1191
91-2	48°34.94′	123°30.23′	228	1155
91-3	48°39.63′	123°30.19′	176	1161
91-4	48°37.21′	123°30.11′	214	1030
91-5	48°40.74′	123°30.22′	168	945

There are three main types of sediment in Saanich Inlet (Fig. 3) (Gucluer and Gross 1964): (1) silt on the sill at the north end of the inlet, (2) fine sand and minor mud and gravel in nearshore environments, and (3) diatomaceous silty clay in deep water. The last group of sediments, which is the focus of this study, consists of alternating laminae of terrigenous silty clay deposited during the fall and spring freshets and diatoms deposited during spring and summer. Individual couplets have been shown to be annual deposits and thus may be termed varves (Gross et al. 1963; Sancetta and Calvert 1988; Sancetta 1989). Because anoxic conditions exist at the sediment–water interface in deep water in the central part of the inlet, epifauna and infauna are absent, and there is no bioturbation that would otherwise destroy stratification.

The sill not only inhibits water circulation but also prevents the entry into the inlet of turbidity currents flowing down Satellite Channel from Cowichan River (Gucluer and Gross 1964), as is demonstrated later. Suspension, therefore, is the main mode of sediment transport in the inlet. This explains why sediments along the axis of the inlet are finer than those on the sill (Fig. 3) (Gucluer and Gross 1964).

Methods and materials

Eight 0.1 m diameter cores, ranging in length from 8.85 to 11.91 m, were collected with a piston corer from the deepest part of Saanich Inlet in 1989 and 1991 (Fig. 2; Table 1). The amount of free fall of the trigger (pilot) core was reduced during the 1991 coring operation in an effort to recover the uppermost water-rich sediments, which appear to have been lost during the 1989 coring operation.

Each core was cut into approximately 1.5 m lengths and later split and stored in a cold room at the Pacific Geoscience Centre. The split cores were photographed and described in detail (colour, unit thicknesses, contacts, structures, fossils).

Samples were taken from the cores and analyzed for

Fig. 4. Typical varved sediments from Saanich Inlet (core 89-2). Each couplet comprises a dark lamina of fine terrigenous sediment (t) and a light, diatom-rich lamina (d).

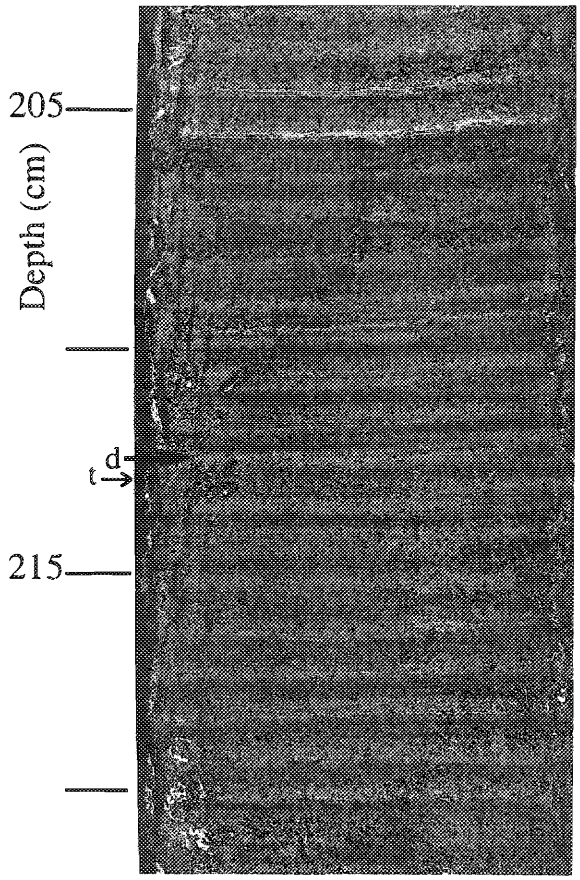
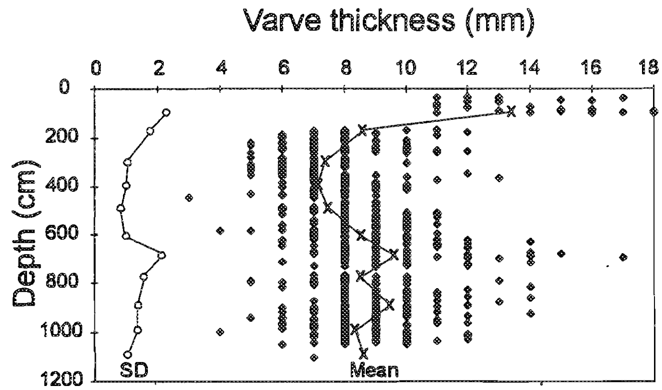


Fig. 5. Scattergram of varve thickness vs. core depth for core 91-4. The upper metre of sediment comprises slightly thicker varves because of the high concentration of interstitial water. In general, however, there are no trends in varve thickness with depth (coefficient of correlation = 0.017). SD, standard deviation.



texture and foraminiferal content. Grain-size analyses were done with a Micromeritic SediGraph 5100. Foraminferal samples were washed on a 63 μm screen, and residues were transferred to vials, immersed in a formalin solution, and examined with a binocular microscope. All foraminifera in each sample were counted.

Shells, wood fragments, and other plant material were extracted from the cores and radiocarbon dated at IsoTrace Laboratory (University of Toronto). Approximate calendric ages were calculated from the radiocarbon ages using the calibration method of Stuiver and Reimer (1993). A reservoir age correction of 801 $\pm$ 23 years was applied to marine shell age determinations (Robinson and Thomson 1981; Stuiver and Braziunas 1993).

The uppermost sediments in each core were analyzed for ^{137}Cs and ^{210}Pb to provide additional chronological control. Cesium-137 samples were freeze-dried, weighed, and analyzed using an APTEC gamma ray spectrometer with a solid-state Ge(Li) detector. This detector allows the 662 keV gamma ray of ^{137}Cs to be separated from interfering isotopes such as ^{208}Tl and ^{214}Bi. Counting and spectral reduction were done according to the method of Lewis (1974). Lead-210 samples were analyzed using a 4000-channel Canberra Model 8180 multichannel analyzer connected to a 300 mm^2 surface barrier detector following the method outlined by Eakins and Morrison (1978).

Stratigraphy and sedimentology

Varved sediments

The varved sediments consist of alternating, light-coloured (olive to olive brown; 5Y 4/3, 2.5Y 4/3), diatom-rich laminae and darker (dark olive grey to very dark greyish brown; 5Y 3/2, 2.5Y 3/2), mineral-rich silt and clay laminae (Fig. 4). Most laminae are horizontal and undisturbed, but laminae in the upper 0.5 – 1 m of cores are commonly contorted, probably due to disturbance during coring. The terrigenous laminae of many couplets consist of a lower, lighter, clay-rich zone and an upper, darker, more silty zone.

Couplets range from 1 to 25 mm thick, generally with gradational contacts between light- and dark-coloured laminae. The uppermost metre of cored sediment contains high concentrations of interstitial water, resulting in slightly thicker varves; otherwise, there are no obvious variations in varve thickness (Fig. 5), and therefore no change in the sedimentation rate, during the period spanned by the cored sediments. In addition, we found no exceptionally thick or thin couplets or groups of couplets that could be used as marker strata.

To estimate sedimentation rates at core sites, average varve thickness was calculated in two ways. The first method ignores compaction caused by brief upright storage of the cores prior to splitting. However, all the cores were handled in the same fashion, therefore data should be comparable between cores. The second method compensates for compaction of the varves. In both cases, sedimentation rates decrease from north to south, with the exception of core 89-3 (Table 2).

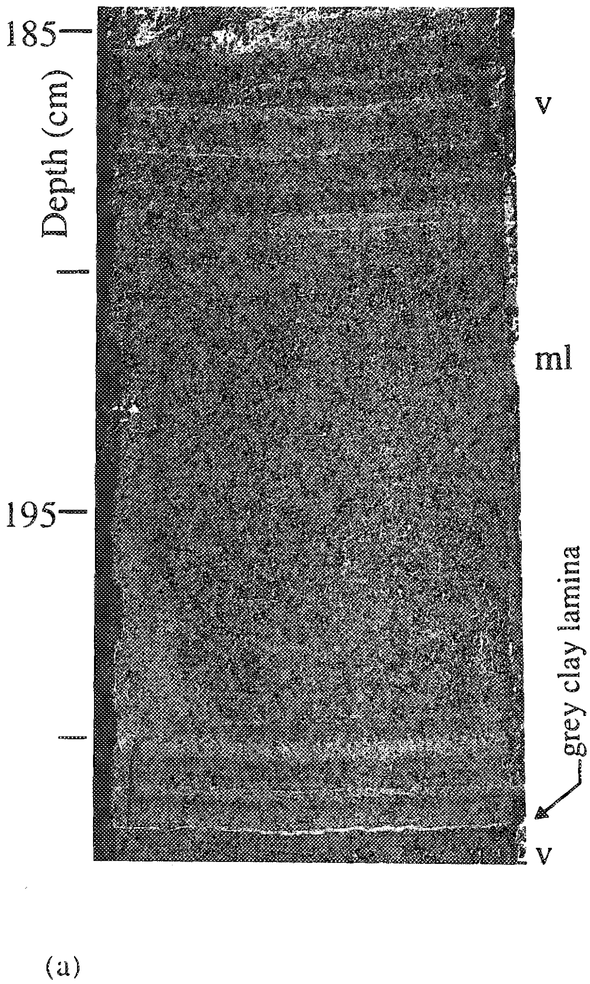
Massive layers

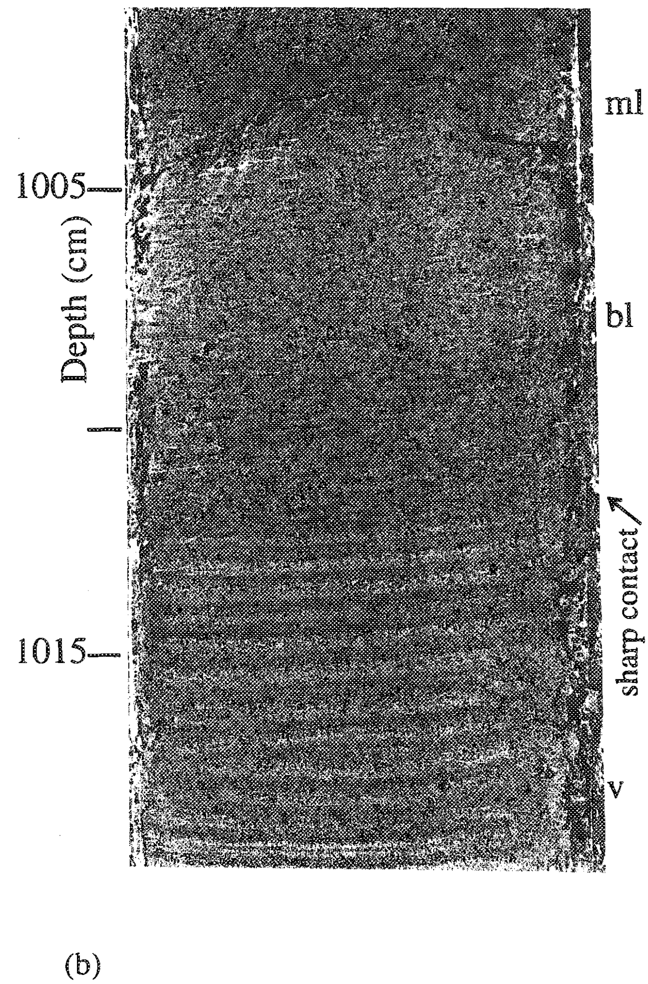
Massive layers comprise dark olive grey (5Y 3/2), homogeneous silty clay (Fig. 6*a*). Commonly, these layers erosively overlie varved sediments. Above about half of the basal contacts, there is a 0.02 – 1.1 m zone of diffuse, brecciated fine laminae (Fig. 6*b*). Varve intraclasts with no apparent fabric are present in the lower parts of some massive beds, indicating that varved sediments were eroded and incorporated into some of the massive layers. In places, varves are overturned, truncated, and erosionally overlain by massive layers (Fig. 7).

Table 2. Average thickness of varves from south (core 91-1) to north (core 91-3).

	91-1	89-1	91-2	89-3	91-4	89-2	91-3
Average thickness of uncompacted varves (mm)	4.65	6.51	6.92	5.7	9.57	10.39	12.71
Average thickness of compacted varves (mm)	4.44	—	4.68	—	8.35	—	9.08

Fig. 6. Massive layers. (*a*) Massive silty clay (ml) underlain and overlain by varved sediments (v; core 89-2). (*b*) Brecciated laminae (bl) at the base of a massive layer (ml; core 89-3).





A total of 53 massive layers was found in seven of the eight cores (Fig. 8; Table 3). The layers range in thickness from 0.02 to 1.10 m (average thickness = 0.165 m). There are no systematic variations in the thickness of massive layers within any core, but the layers are slightly thicker, and also more abundant, in southern Saanich Inlet than they are in the north (Fig. 8).

Particle-size analysis

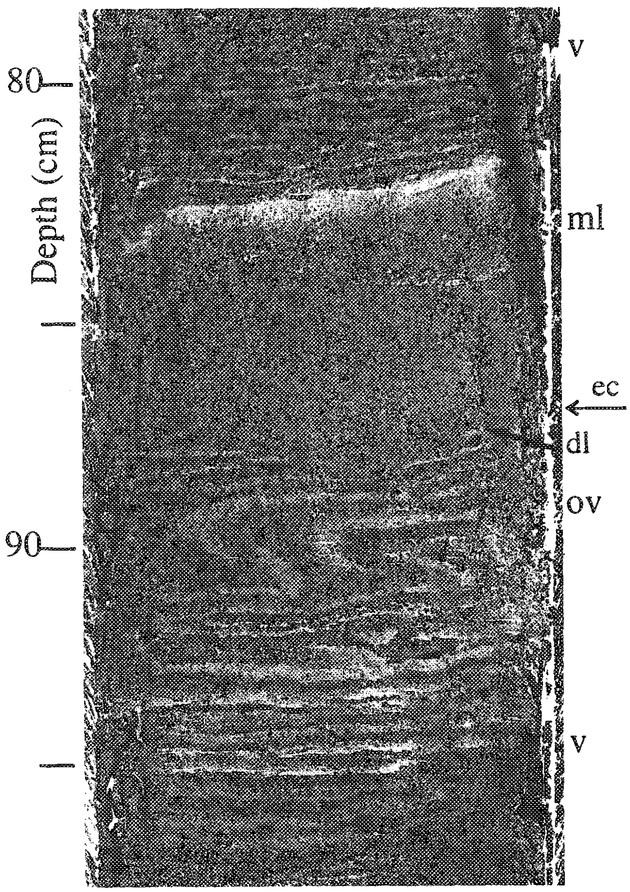
Most cored sediments are silty clay with less than 5% fine sand (Fig. 9); a notable exception is the gravelly base of a massive layer at a depth of 9.86–9.88 m in core 91-1. Many massive layers are slightly coarser than the varves directly above and below them (Bobrowsky and Clague 1990). A Student's *t* test, performed on the percent sand in varved and massive sediments, showed that there is only one chance in a thousand that the means are the same (Blais 1995).

There is no apparent southerly decrease in the particle size of varves related to the previously mentioned decrease in sedimentation rates in that direction. Similarly, there are no systematic areal trends in the particle size of the massive sediments.

Other sediments

The northernmost, shallowest core (91-5) lacks distinctive massive layers or varves. The entire core is composed of weakly stratified clayey silt with scattered shell fragments, whole shells, and foraminifera. Silty clay laminae similar

Fig. 7. Truncated discontinuous laminae (dl) and deformed varves (ov), overlain across an erosional contact (ec) by a massive layer (ml; core 89-1).



to those observed in the varves are randomly distributed throughout the core. The sediments are more silty than varved and massive sediments in the other seven cores. The average sedimentation rate, calculated from calibrated radiocarbon ages, is between 12 and 26 mm/a, higher than rates farther south (Table 2).

Foraminifera

The varved sediments contain diatoms (siliceous tests) but lack foraminifera. The absence of foraminifera in the varves is expected because calcareous tests dissolve in a reducing environment like the deep waters of Saanich Inlet.

The massive layers contain both diatoms and calcareous and agglutinated benthic foraminifera (Table 3) (Blais 1995). Most of the foraminifera found are *Trochammina* spp., *Spiroplectammina biformis*, and *Eggerella advena*. The latter two species form a shallow-water foraminiferal biofacies in Saanich Inlet (Blais 1995), whereas *Trochammina* occurs in a wide variety of marine environments. These observations imply that the foraminifera were transported from above the anoxic zone (<150 m depth), deposited, and buried rapidly before the tests could dissolve.

Chronology

Cesium-137

The uppermost sediments in one 1989 core (89-3) and in four of the five 1991 cores (91-1, 91-2, 91-3, and 91-4) contain

Table 3. Distribution of massive layers within the cores from south (91-1) to north (91-3).

91-1		89-1		91-2		89-3		91-4		89-2		91-3	
Forams.[a]	Depth of layer (cm)	Forams.[a]	Depth of layer (cm)	Forams.[a]	Depth of layer (cm)	Forams.[a]	Depth of layer (cm)	Forams.[a]	Depth of layer (cm)	Forams.[a]	Depth of layer (cm)	Forams.[a]	Depth of layer (cm)
F	63–78	NS	82–87	F	277–282	NS	46–53	NS	306–310	F	73–75	NS	350–356
F	223–247	NS	166–169	NS	356–374	NS	199–247	F	448–461	NS	185–196		
F	302–308	F	371–418	NS	482–486	NS	318–343	NS	547–552	F	656–660		
F	397–401	NF	476–479	F	610–639	F	365–367	F	810–814	NS	725–729		
F	428–439	F	559–562	NS	676–683	F	384–403			F	840–843		
F	462–468	NS	656–660	NS	777–782	F	556–619			F	1006–1008		
F	521–528	F	694–698	F	868–871	F	644–698						
F	607–612	F	848–850	NS	899–905	F	777–809						
F	638–651			NS	1058–1063	F	816–824						
F	831–841			F	1098–1170	NS	885–907						
F	877–987					NF	937–997						
F	1073–1082					NF	1149–1177						

[a]F, foraminifera present; NF, no foraminifera; NS, no sample collected for foraminiferal analysis.

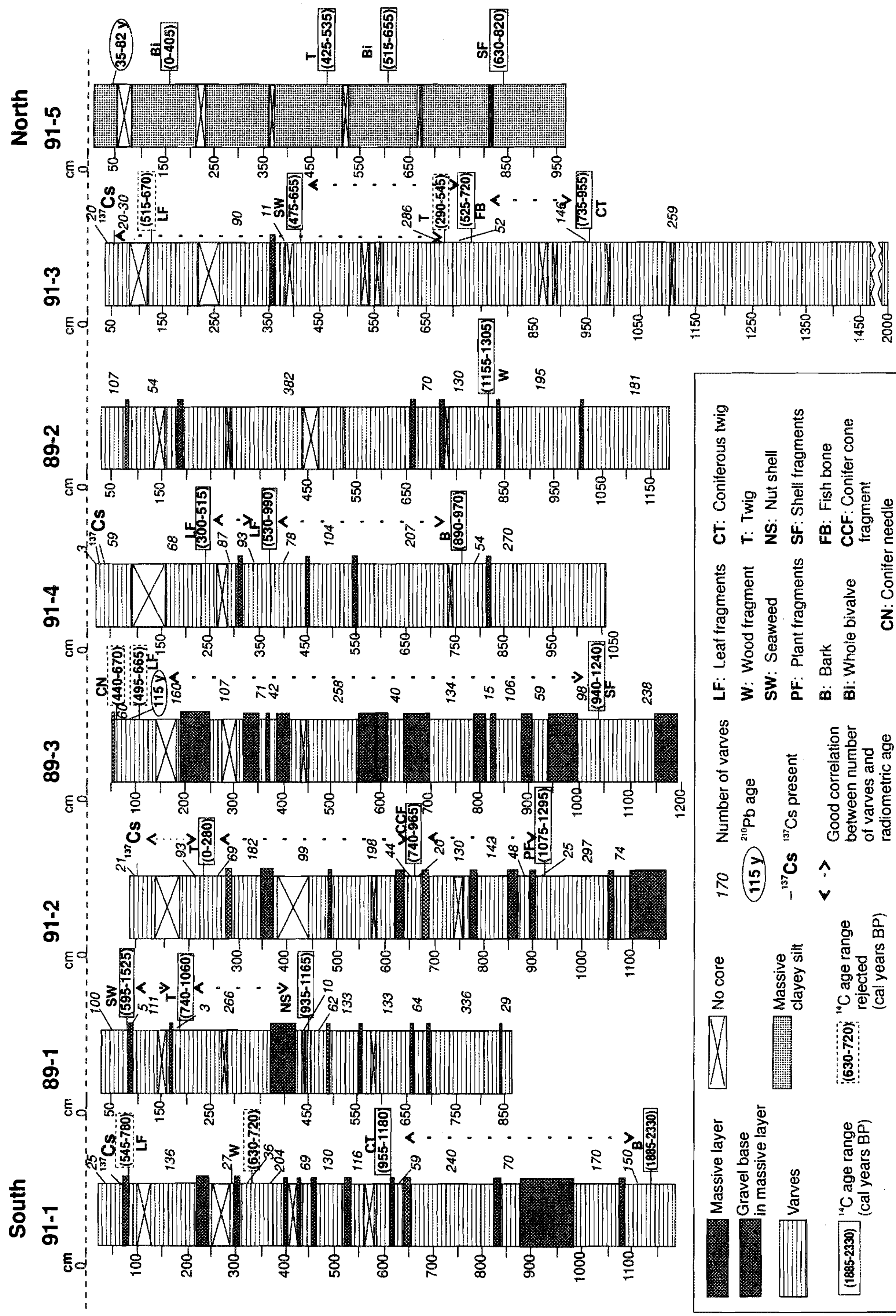
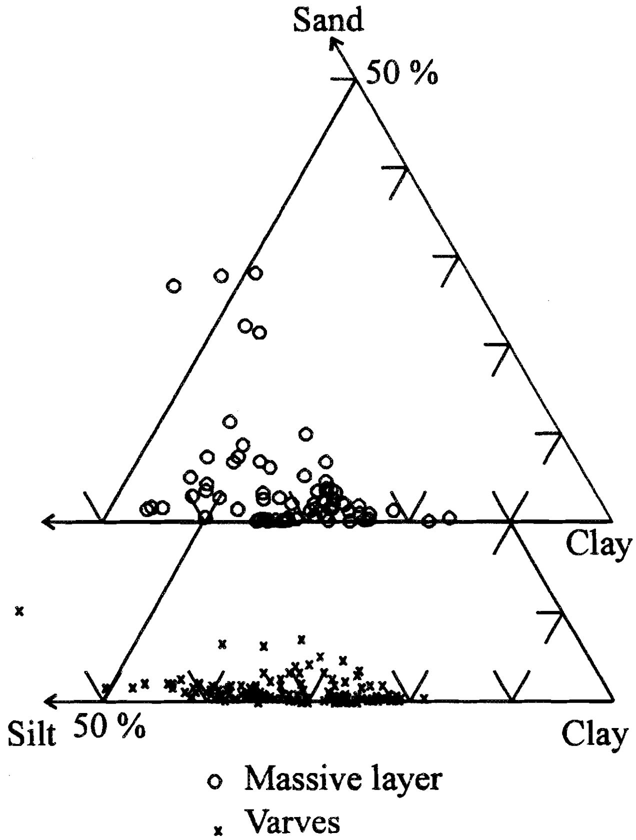


Fig. 8. Summary of core stratigraphy and radiometric age data.

Fig. 9. Particle-size distribution of samples of varves and massive sediments. Sand is finer than 0.25 mm. The five coarsest samples of massive layers are from core 91-1.



trace amounts of ^{137}Cs. Concentrations range from 0.9 to 1.3 pCi/g (1 Ci = 35 GBq); the lower limit of detection is 0.05 pCi/g. No ^{137}Cs was found in the other two 1989 cores, but this is not surprising, as sediments directly below the sea floor were not recovered during the earlier coring operation (Blais 1995). Cesium-137 concentrations are too low to identify the 1963 peak; consequently, the deepest sediments containing the radioisotope were assigned an age of 1954, the beginning of atmospheric nuclear testing.

The ^{137}Cs data and varve thickness suggest that roughly 0.07–0.35 m of sediment is missing from the tops of the 1991 cores. An unknown, but probably greater, amount of sediment is missing from the two 1989 cores that have no ^{137}Cs.

Lead-210

Atmospherically derived ^{210}Pb is present in two of the eight analyzed cores (89-3 and 91-5). It was not possible to estimate background concentrations of ^{210}Pb, which are required to accurately date the sediments, but age estimates were obtained using a least squares method with background ^{210}Pb as a variable (Blais 1995). Age estimates were made assuming a constant rate of sediment supply. A best-fit regression line was calculated by varying the background value, with the available data points providing constraints. The best-fit line was then used to estimate the accumulation rate and, hence, the age of the sediments at a specific depth. R^2 values of near 1, calculated with different backgrounds, indicate that age estimates are not sensitive to the background ^{210}Pb concentrations.

Sediments at 83–85 cm depth in core 89-3 are approximately 115 years old. Two age estimates were made for core 91-5, using different data points. Using all the data, sediments at 50–51 cm depth are estimated to be 35 years old. If only the lowest three data points are used (the uppermost sediments may be mixed), the calculated age at 50–51 cm depth is 82 years. Even with this uncertainty, the analyses show that sediment near the sea floor was recovered in both cores.

Radiocarbon ages

Calibrated radiocarbon ages on fossil plant detritus and shells range from 115 (0–155)[3] cal years BP (calendar years before AD 1950) to 2110 (1885–2330) cal years BP (Table 4; Fig. 8). Most of the 26 radiocarbon ages are consistent with their stratigraphic position, ^{137}Cs and ^{210}Pb data, and varve counts (Fig. 8). Five of the radiocarbon ages, however, seem anomalous; four of these five ages appear to be too old, and the dated material may have been reworked from older Holocene sediments. One radiocarbon age from core 91-3 may be too young, although it is consistent with an age determined from ^{137}Cs data and the estimated sedimentation rate. If this age is valid, two radiocarbon ages from the upper part of this core (TO-3536, TO-3705; Table 4) are too old.

Varve chronology

Varve counts were made for each of the cores except 91-5, which contains no varves (Fig. 8; Table 5). The total number of varves in each core ranges from 909 to 1461. The varve counts generally agree with the radiometric age data (see Discussion). The counts, however, may slightly underestimate the true age of sediment at any depth in the cores, because some erosion probably occurred during emplacement of the massive layers. Furthermore, no estimate was made of the number of varves in the uppermost, loose, water-saturated sediments in each core. Although some varves were destroyed when the cores were sectioned, the losses are minor. Finally, it should be pointed out that the "no core" zones (Fig. 8) are not missing varves; rather they are the result of slight compaction due to upright storage of cores before they were split.

Discussion

Style and pattern of sedimentation

The eight cores from Saanich Inlet provide a sediment record spanning 1500 years. During fall and winter, terrigenous sediment (clay, silt, and some fine sand) is deposited from suspension. During spring and summer, diatom-rich sediment rains out onto the floor of the inlet. Sedimentation rates decrease from north to south, demonstrating that the main source of sediment is Cowichan River. Seven of the eight cores show regular deposition of rhythmites under anoxic conditions, interrupted sporadically by high-energy debris flows (see below).

We considered the possibility that turbidity currents origi-

[3] Values in parentheses are 2σ age ranges.

Table 4. Radiocarbon ages from the study area.

Radiocarbon age (^{14}C years BP)[a]	Calibrated age range (cal years before AD 1950)[b]	Core	Laboratory No.[c]	Depth (cm)[d]	Dated material
110±50	Modern−280	91-2	TO-3535	229−230	Twig
370±50	300−515	91-4	TO-3539	248.5−249.5	Leaf fragments
400±80	290−545	91-3	TO-4050	680.5	Twig
430±50	425−535	91-5	TO-3687	478.5	Deciduous twig
560±100	440−670	89-3	TO-3533	53	Conifer needle
580±80	495−665	89-3	TO-3632	81	Leaf fragments
620±70	515−670	91-3	TO-3536	115	Plant remains
710±50	630−720	91-1	TO-3703	329.5−330	Wood fragments
720±80	545−780	91-1	TO-3534	66−68	Deciduous leaf
820±150	530−990	91-4	TO-3686	365	Leaf fragments
960±50	735−955	91-3	TO-3685	952.5	Conifer twig
970±50	740−965	91-2	TO-3684	662	Conifer cone
970±80	Modern−405	91-5	TO-2904	158	Bivalve shell
1000±40	890−970	91-4	TO-2903	759.5	Bark
1010±70	740−1060	89-1	TO-3531	172	Conifer twig
1130±50	935−1165	89-1	TO-3530	448	Nut shell
1170±50	955−1180	91-1	TO-2900	606.5	Conifer twig
1300±50	1075−1295	91-2	TO-2901	921	Plant fragments
1320±50	1155−1305	89-2	TO-3537	826	Wood fragments
1370±60	475−655	91-3	TO-3705	411.5	Seaweed
1410±40	515−655	91-5	TO-2905	602.5	Bivalve shell
1460±60	525−720	91-3	TO-2902	738	Fish bones
1560±50	630−820	91-5	TO-2906	846	Shell fragments
1880±240	595−1525	89-1	TO-3532	76	Seaweed
1940±60	940−1240	89-3	TO-1553	1041	Shell fragments
2120±80	1885−2330	91-1	TO-3683	1138	Bark

[a]Laboratory-reported error terms are 1σ. Ages corrected to $\delta^{13}C = -25.0‰$ P_{DB}.
[b]Determined from dendrocalibrated data of Stuiver and Brazuinas (1993) and Stuiver and Pearson (1993). The range represents the 95% confidence interval ($\pm 2\sigma$) calculated with an error multiplier of 1.
[c]TO, IsoTrace Laboratory (University of Toronto).
[d]Depth below sediment−water interface.

nating on the Cowichan River delta sporadically carried sediment into Saanich Inlet, but this is unlikely because (1) such turbidity currents would probably have to be large to start at Cowichan Bay, 10 km from the north end of the inlet, follow the sea floor down to 154 m depth, turn right, rise over the sill at 70 m depth, and travel the 20 km length of Saanich Inlet; (2) the density of a sediment-laden Cowichan River would have to be 10 times greater than it is presently, during a spring flood, to produce a hyperpycnal flow; (3) there are no Bouma-sequence turbidites in the cores, including 91-5, which is nearest the sill; (4) the massive layers do not show grading or imbrication of clasts typical of turbidites; and (5) if south-flowing turbidity currents deposited the massive layers, proximal facies would be present in the north and distal facies in the south, which is not the case.

The northernmost core (91-5) is more silty than, and lacks the rhythmic lamination of, the other seven cores. The sediments in this core were deposited from suspension, like the varves, but closer to the main source of terrigenous sediment (Cowichan River). There are at least two possible explanations for the absence of rhythmic lamination in this northernmost core. The core site is adjacent to the sill at the north end of the inlet, nearest the Cowichan River. As a consequence, the high influx of terrigenous sediment throughout the year may overwhelm the seasonal diatom blooms that produce the light-coloured laminae farther south (Sancetta 1989). A second possible explanation is that bottom waters at this site may be oxygenated. This would allow bivalves and other infauna to bioturbate the sediments, obscuring or destroying stratification. The presence of calcareous foraminifera within the sediments indicates that there is some oxygen at the sediment−water interface at this site.

Origin of massive layers

When the massive layers in Saanich Inlet were first studied by Bobrowsky and Clague (1990), it was not clear whether they were products of in situ liquefaction of varves, oxygenation of bottom waters and resultant bioturbation of sediments, or sediment gravity flows. Particle-size data presented in this study (Fig. 9) and in Bobrowsky and Clague (1990) show that many massive layers are coarser than the bounding varves, supporting an allogenic origin. There is other evidence that the massive layers are products of sediment gravity flows: (1) basal contacts of massive layers are sharp, and some are clearly erosional (Figs. 6*b*, 7); (2) one massive layer in core 91-1 has a gravelly base that truncates under-

Table 5. Cumulative number of varves from top of core to successive massives layers from south (core 91-1) to north (core 91-3).

	91-1[a]	89-1	91-2[a]	89-3[a]	91-4[a]	89-2	91-3[a]
	40	105	202	59	254	107	155
	176	216	384	334	425	161	
	203	485	483	441	529	543	
	443	557	681	512	790	613	
	512	690	745	554		743	
	642	823	875	810		938	
	758	887	1017	850			
	828	1223	1065	921			
	1057		1387	936			
	1127		1461	1042			
	1297			1101			
				1435			
Total	1447	1252	1461	1435	1060	1119	909

[a] ^{137}Cs or ^{210}Pb present.

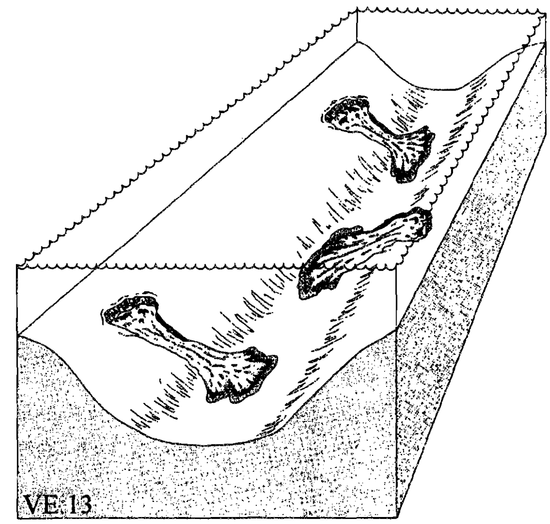
Table 6. Summary of correlations based on scenarios 1−3 (1997 datum).

Scenario 1		Scenario 2		Scenario 3	
Correlation No.	Age (years)	Correlation No.	Age (years)	Correlation No.	Age (years)
		I	62	I	43
I	206	II	205	II	206
II	446	III	444	III	446
III	517			IV	517
IV	559	IV	548	V	559
				VI	763
		V	809		
V	833			VII	833
VI	879	VI	889		
VII	1071	VII	1078	VIII	1083
VIII	1141			IX	1153
IX	1475	VIII	1474	X	1479

lying varves (Blais 1992); (3) some massive layers contain varve intraclasts; (4) a zone of brecciated varves marks the base of many massive layers; and (5) most massive layers contain benthic foraminifera, which implies that the sediment was transported downslope from above the anoxic zone (<150 m depth).

These characteristics are consistent with deposition by localized submarine sediment gravity flows, and not with large turbidity currents that flow the length of the inlet (Fig. 10). Some massive layers could represent the E unit (pelagic mud) of the Bouma sequence and may thus be turbidity current deposits. This is unlikely, however, because no other elements of the Bouma sequence are present in the cores. The massive layers are ascribed to debris flows because (1) none of the layers exhibits sedimentary structures and textures typical of a classic turbidite, (2) there is no normal or inverse grading, (3) about half the layers contain a basal zone of brecciated varves, which probably formed by shearing at the base of a debris flow (Middleton and Hampton 1976; Johnson and Rodine 1984), and (4) varve intraclasts show no apparent fabric (Arnott and Hand 1989). The debris flows were probably localized and relatively small because the massive layers are thin (maximum thickness = 110 cm).

Fig. 10. Schematic diagram showing the inferred origin of massive layers in Saanich Inlet.



Correlation and ages of massive layers

An attempt was made to correlate cores on the basis of stratigraphy, ^{137}Cs and ^{210}Pb data, radiocarbon ages, and varve counts. Cesium-137 and ^{210}Pb provide a datum for correlating the uppermost sediments in six of the eight cores. Radiocarbon ages and varve counts help correlate the two cores that lack ^{137}Cs and ^{210}Pb (89-1 and 89-2), and varve counts provide cross-checks on radiocarbon and ^{210}Pb ages.

There is good correlation between the varve counts and radiocarbon ages (vertical arrows in Fig. 8). For example, the calibrated mean age of shell fragments at 10.4 m depth in core 89-3 is 1080 cal years BP (2σ range = 940−1240 cal years BP). Lead-210 data and varve counts give an age of 1205 years (1994 datum) at the same depth. Comparison of these two data sets suggests that there are unlikely to be more than 79 missing and uncounted varves to this depth in core 89-3. The age estimates for the massive layers in this core, based on varve counts, are thus considered to be accurate to within 6%.

It is difficult to positively correlate massive layers between the cores because of the lack of unique markers, inherent imprecision of radiocarbon ages, and the possibility of sediment loss due to stripping of varves by debris flows. However, some massive layers in two or more cores appear to correlate, based on varve counts below a datum established using ^{137}Cs and ^{210}Pb data (Fig. 8; Table 5). Correlations become less certain with depth because of the increasing likelihood that varves have been lost due to erosion by debris flows.

Inspection of Table 5 indicates possible correlations of massive layers dating about 200, 400−500, 750−850, 1000−1150, and 1450 years ago. We attempted to refine the correlations by adjusting the ages of successively older massive layers to account for missing varves, in the following manner (see Blais 1995 for additional details). The youngest massive layers (cores 91-1 and 89-3) of approximately the same age were assumed to correlate; of the two or more correlated layers, that with the fewest number of varves above it was then assigned the same age as the layer with the largest number of varves (the rationale for this is there could be missing varves). When the age of a massive layer was increased, all the other massive layers below it in that core were similarly adjusted. Correlations and related age adjustments were carried out in a stepwise fashion down the cores until there were no further matches. Three scenarios were considered, assuming different initial correlations of the uppermost massive layers and slightly different ages for these layers: (1) the two youngest massive layers in cores 89-3 and 91-1 are not the same age, (2) the two layers are 62 years old, and (3) the two layers are 43 years old (Table 6). All three scenarios yield similar correlations in the upper parts of the cores, i.e., massive layers that are 205–206, 444–446, and 548–559 years old. In the lower parts of the cores, the correlations are less certain, although there appear to be correlative layers with ages of approximately 800–850, 1050–1100, 1100–1150, and 1450–1500 years (Table 6). We estimate age uncertainties of about 10–20 years for massive layers younger than 500 years and 20–100 years for older massive layers.

Causes of debris flows

There are two main mechanisms for triggering debris flows in Saanich Inlet. First, as sediments build up on submarine slopes, they may exceed the critical angle of repose and slide or flow into deeper water. Second, sediments may fail when shaken during earthquakes. Whether an earthquake would trigger debris flows in Saanich Inlet depends on many factors, including the amount of sediment on the walls of the inlet, the strength of the sediments, the acceleration and period of seismic waves, and the duration of shaking. It is not possible to assess these factors from the core data, but three general scenarios can be proposed.

Scenario 1: none of the debris flows was triggered by an earthquake

Many of the massive layers do not appear to correlate from one core to the next, and it is possible that the debris flows were independently triggered at different times. The apparent lack of correlation of many of the massive layers could be explained by random failure of slopes on which sediment is gradually accumulating. However, a nonseismic triggering mechanism is less likely for massive layers that can be correlated over large areas. Separate simultaneous debris flows (Fig. 10) are harder to explain in a setting where slope failure occurs due to gradual buildup of sediment than in one where the trigger is earthquakes.

Scenario 2: all of the debris flows were triggered by earthquakes

Exposed sections of Pleistocene glaciolacustrine varves in the Puget Lowland of Washington, approximately 120 km southeast of Saanich Inlet, contain deformational structures similar to those produced by simulated seismic shaking (Sims 1975). Sims (1975) estimated that in a section of 1804 varves, 14 of 21 exposed deformed zones were the result of seismic shaking, giving an average of 129 years between each seismic event. Successive deformed zones were separated by 60–276 years. By including additional deformational structures that could potentially be products of earthquakes, the range becomes 23–276 years. Sims (1975) concluded from this study that varves could be used to determine the age of these deformational structures and, hence, seismic activity, assuming that a temporal datum could be established.

Sims' (1975) results coincide roughly with ours. The number of varves separating massive layers in Saanich Inlet ranges from 15 to >754, with an average of 116. This average is near Sims' estimate of the average number of years separating deformed zones that he attributed to seismic shaking.

The theoretical recurrence interval of earthquakes producing Modified Mercalli Intensity VII or VIII in the Victoria area is about one every 100 years (G.C. Rogers, written communication, 1994). Assuming that such an earthquake could trigger failures of sediments on the walls of Saanich Inlet, it is possible that all the massive layers in the cores are products of earthquakes. Core 89-3, for example, contains 10 massive layers that are younger than 1000 years (Table 5), and it is possible that each corresponds to an earthquake. If this is correct, cores from the southern part of Saanich Inlet contain a more complete record of earthquakes than cores farther north, probably because it requires less seismic energy to produce slope failures where the side walls are steeper.

Three massive layers in Saanich Inlet may record moderate to large earthquakes that have been documented elsewhere in southwestern British Columbia and Washington State. The uppermost massive layers in core 89-3 and, possibly, core 91-1 may be products of the 1946 Vancouver Island earthquake, centred near Comox, 200 km north-northwest of Saanich Inlet (Rogers and Hasewaga 1978; Rogers 1980). A massive layer dating to about 200 years ago may have been emplaced during an earthquake recorded by Spanish explorers wintering on the west coast of Vancouver Island in 1793 (Clague 1995). An even larger earthquake, centred near Seattle, Washington, approximately 140 km south-southeast of Saanich Inlet, occurred 1000–1100 years ago (Atwater and Moore 1992; Bucknam et al. 1992) and may be responsible for a widespread massive layer in Saanich Inlet that dates to 1050–1150 years ago. Although this earthquake was a considerable distance from Saanich Inlet, it apparently was very large, and ground motion on southern Vancouver Island may have been sufficient to trigger debris flows in the inlet. There is also evidence for a great Cascadia plate-boundary earthquake at about the same time (Atwater 1992; Atwater and Hemphill-Haley 1996).

The last great earthquake or series of closely spaced earthquakes on the Cascadia subduction zone occurred about 300 years ago. There is abundant evidence for this event in tidal marshes from northern California to central Vancouver Island (Atwater et al. 1995, and references therein). Although Saanich Inlet should have been shaken by this earthquake, only one massive layer, in core 89-3, was found that might coincide with this event, and this requires that the top of the core is a little younger than indicated in Table 5.

In summary, given that moderate to large earthquakes capable of generating debris flows in Saanich Inlet are fairly frequent and that at least two historic earthquakes (1946 and 1793) may have produced such failures, one might conclude that all of the massive layers record earthquakes. If this is correct, an earthquake strong enough to trigger failures in Saanich Inlet occurs, on average, once every 100 years. Intervals of earthquakes, however, are probably highly variable, a few tens to hundreds of years, judging by the record of massive layers in core 89-3 (Table 5).

On the basis of a recent geotechnical study, Banks (1997) suggests that the sediments are stable under gravity loads, which implies that the accumulation of sediment may not be a significant cause of debris flows in the basin. Banks (1997) further concluded that an earthquake causing slope failures would have to be larger than magnitude 4.5.

Scenario 3: some, but not all, of the debris flows were triggered by earthquakes

It is likely that the widespread massive layers that are about 200 and 1050–1150 years old are products of earthquakes. Several other massive layers are probably present in two or more cores, and they too may have been emplaced by earthquakes. For example, massive layers at about 440, 550, 800–850, and 1450–1500 years old may represent as yet unreported seismic events (Table 6). On the other hand, some massive layers appear to be present in only one core. The flows that deposited them were just as likely caused by slope failures triggered by the progressive buildup of sediment on the walls of the inlet as by earthquakes. Nevertheless, given the presence of potentially unstable accumulations of sediment on these slopes, it might be expected that every strong earthquake that has struck the area would trigger debris flows. Thus, Saanich Inlet probably contains a proxy record of all moderate to large earthquakes during Holocene time, but the set of massive layers includes nonseismically triggered debris flows in addition to those caused by earthquakes.

Conclusions

Deep-water sediments in Saanich Inlet consist mainly of silty clay varves and intercalated massive beds of silty clay. The varved sediments were deposited from suspension and consist of alternating laminae of terrigenous detritus, derived primarily from Cowichan River, and diatoms produced during spring and summer blooms. Sedimentation rates decrease from north to south, confirming Cowichan River as the main source of terrigenous sediment. Massive layers were deposited by localized debris flows. These layers are products of small failures of sediments from the side walls of the inlet, rather than large turbidity flows that travel the length of the fiord.

Most, but probably not all, of the massive layers were emplaced during earthquakes, including distant great plate-boundary events and smaller local crustal and subcrustal earthquakes. The average number of varves separating adjacent massive layers in the core with the greatest number of such layers is broadly consistent with the expected periodicity of moderate to large earthquakes in the region. Massive layers at the tops of two cores may have been deposited during the 1946 Vancouver Island earthquake ($M = 7.2$). A massive layer dating to about 200 years ago and found in two cores may have been emplaced during an earthquake in February 1793, reported by Spanish explorers wintering on the west coast of Vancouver Island. Another widespread massive layer, about 1050–1150 years old, may record a large crustal earthquake centred near Seattle, 140 km south-southeast of Saanich Inlet, or an even larger Cascadia plate-boundary earthquake. Some of the other massive layers probably record other prehistoric earthquakes, as yet undocumented elsewhere. Still other massive layers may be products of nonseismically triggered failures of metastable sediments that have gradually accumulated on the side slopes of the inlet.

Acknowledgments

Our study was funded by the Geological Survey of Canada and the Natural Sciences and Engineering Research Council of Canada (Research Grant OGP0041665 to R.T. Patterson). R. McDonald and G. Jewsbury helped collect the cores. T. Forbes analyzed samples for particle size and provided assistance in the laboratory. W. Bentkowski and T. Hamilton made the ^{137}Cs measurements, and R.J. Flett conducted ^{210}Pb analyses. Radiocarbon ages were provided by IsoTrace Laboratory. G. Bonham-Carter helped with statistical analyses. M. Taylor and E. Keane assisted in data processing, and W.R. Stevens provided technical assistance throughout the project. D. Everett drafted Fig. 10. Reviews by J.E. Adams, R.J. Cornett, R.W.C. Arnott, B.S. Hart, and R.J. Fulton greatly improved the manuscript.

References

Adams, J. 1990. Paleoseismicity of the Cascadia subduction zone — evidence from turbidites off the Oregon–Washington margin. Tectonics, **9**: 569–583.

Anderson, J.J., and Devol, A.H. 1973. Deep water renewal in Saanich Inlet, an intermittently anoxic basin. Estuarine and Coastal Marine Science, **1**: 1–10.

Arnott, R.W.C., and Hand, B.M. 1989. Bedforms, primary structures and grain fabric in the presence of suspended sediment rain. Journal of Sedimentary Petrology, **59**: 1062–1069.

Atwater, B.F. 1987. Evidence for great Holocene earthquakes along the outer coast of Washington State. Science (Washington, D.C.), **236**: 942–944.

Atwater, B.F. 1992. Geologic evidence for earthquakes during the past 2000 years along the Copalis River, southern coastal Washington. Journal of Geophysical Research, **97**: 1901–1919.

Atwater, B.F., and Hemphill-Haley, E. 1996. Preliminary estimates of recurrence intervals for great earthquakes of the past 3500 years at northeastern Willapa Bay, Washington. United States Geological Survey, Open-file Report 96-001.

Atwater, B.F., and Moore, A.L. 1992. A tsunami about 1000 years ago in Puget Sound, Washington. Science (Washington, D.C.), **258**: 1614–1616.

Atwater, B.F., Nelson, A.R., Clague, J.J., et al. 1995. Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone. Earthquake Spectra, **11**: 1–18.

Banks, S. 1997. Geotechnical analysis of two sites offshore Vancouver Island, British Columbia: establishing the frequency of major earthquakes since the last Ice Age through 100% borehole recovery. B.Sc. thesis, Technical University, Halifax, N.S.

Blais, A. 1992. Holocene sediments from Saanich Inlet, British Columbia and their neotectonic implications. *In* Current research, part A. Geological Survey of Canada, Paper 92-1A, pp. 195–198.

Blais, A. 1995. Foraminiferal biofacies and Holocene sediments from Saanich Inlet, British Columbia: implications for environmental and neotectonic research. Ph.D. thesis, Carleton University, Ottawa, Ont.

Bobrowsky, P.T., and Clague, J.J. 1990. Holocene sediments from Saanich Inlet, British Columbia, and their neotectonic implications. *In* Current research, part E. Geological Survey of Canada, Paper 90-1E, pp. 251–256.

Bucknam, R.C., Hemphill-Haley, E., and Leopold, E.B. 1992. Abrupt uplift within the past 1700 years at southern Puget Sound, Washington. Science (Washington, D.C.), **258**: 1611–1613.

Carter, N.M. 1934. Physiography and oceanography of some British Columbia fiords. Proceedings of the 5th Pacific Science Congress, Pacific Science Association, Vancouver, B.C., Vol. 1, pp. 721–733.

Clague, J.J. 1995. Early historical and ethnographical accounts of large earthquakes and tsunamis on western Vancouver Island, British Columbia. *In* Current research, part A. Geological Survey of Canada, Paper 95-1A, pp. 47–50.

Clague, J.J., and Bobrowsky, P.T. 1994*a*. Evidence for a large earthquake and tsunami 100–400 years ago on western Vancouver Island, British Columbia. Quaternary Research, **41**: 176–184.

Clague, J.J., and Bobrowsky, P.T. 1994*b*. Tsunami deposits beneath tidal marshes on Vancouver Island, British Columbia. Geological Society of America Bulletin, **106**: 1293–1303.

Clague, J.J., Naesgaard, E., and Sy, A. 1992. Liquefaction features on the Fraser delta: evidence for prehistoric earthquakes? Canadian Journal of Earth Sciences, **29**: 1734–1745.

Darienzo, M.E., and Peterson, C.D. 1990. Episodic tectonic subsidence of late Holocene salt marshes, northern Oregon, central Cascadia margin. Tectonics, **9**: 1–22.

Eakins, J.D., and Morrison, R.T. 1978. A new procedure for determination of ^{210}Pb in lake marine sediments. International Journal of Applied Radiation and Isotopes, **29**: 531–536.

Gross, M.G., Gucluer, S.M., Creager, J.S., and Dawson, W.A. 1963. Varved marine sediments in a stagnant fjord. Science (Washington, D.C.), **141**: 918–919.

Gucluer, S.M., and Gross, M.G. 1964. Recent marine sediments in Saanich Inlet, a stagnant marine basin. Limnology and Oceanography, **9**: 359–376.

Herlinveaux, R.H. 1962. Oceanography of Saanich Inlet in Vancouver Island, British Columbia. Journal of the Fisheries Research Board of Canada, **19**: 1–37.

Hyndman, R.D. 1995. Giant earthquakes of the Pacific Northwest. Scientific American, **273**(6): 68–75.

Jacoby, G.C., Williams, P.L., and Buckley, B.M. 1992. Tree ring correlation between prehistoric landslides and abrupt tectonic events in Seattle, Washington. Science (Washington, D.C.), **258**: 1621–1623.

Johnson, A.M., and Rodine, J.R. 1984. Debris flow. *In* Slope instability. *Edited by* D. Brunsden and D.B. Prior. John Wiley and Sons, New York, pp. 257–361.

Karlin, R.E., and Abella, S.E.B. 1992. Paleoearthquakes in the Puget Sound region recorded in sediments from Lake Washington, U.S.A. Science (Washington, D.C.), **258**: 1617–1619.

Karlin, R.E., and Abella, S.E.B. 1996. A history of Pacific Northwest earthquakes recorded in Holocene sediments from Lake Washington. Journal of Geophysical Research, **101**: 6137–6150.

Lewis, T. 1974. Heat production measurements in rocks using gamma ray spectrometer with a solid state detector. Canadian Journal of Earth Sciences, **11**: 526–532.

Mathewes, R.W., and Clague, J.J. 1994. Detection of large prehistoric earthquakes in the Pacific Northwest by microfossil analysis. Science (Washington, D.C.), **264**: 688–691.

Middleton, G.V., and Hampton, M.A. 1976. Subaqueous sediment transport and deposition of sediment gravity flows. *In* Marine transport and environmental management. *Edited by* D.J. Stanley and D.J.P. Swift. John Wiley and Sons, Toronto, pp. 197–218.

Obermeier, S.F. 1995. Preliminary estimates of the strength of prehistoric shaking in the Columbia River valley and the southern half of coastal Washington, with emphasis for a Cascadia subduction zone earthquake of about 300 years ago. United States Geological Survey, Open-file Report 94-589.

Riddihough, R.P., and Hyndman, R.W. 1976. Canada's active western margin — the case for subduction. Geoscience Canada, **3**: 269–278.

Robinson, S.W., and Thompson, G. 1981. Radiocarbon corrections for marine shell dates with application to southern Pacific Northwest Coast prehistory. Syesis, **14**: 45–57.

Rogers, G.C. 1980. A documentation of soil failure during the British Columbia earthquake of 23 June, 1946. Canadian Geotechnical Journal, **17**: 122–127.

Rogers, G.C. 1988. An assessment of the megathrust earthquake potential of the Cascadia subduction zone. Canadian Journal of Earth Sciences, **25**: 844–852.

Rogers, G.C. 1994. Earthquakes in Vancouver. *In* Geology and geological hazards of the Vancouver region, southwestern British Columbia. *Edited by* J.W.H. Monger. Geological Survey of Canada, Bulletin 481, pp. 221–229.

Rogers, G.C., and Hasewaga, H.S. 1978. A second look at the British Columbia earthquake of 23 June 1946. Bulletin of the Seismological Society of America, **68**: 653–675.

Sancetta, C. 1989. Spatial and temporal trends of diatom flux in British Columbian fjords. Journal of Plankton Research, **11**: 503–520.

Sancetta, C., and Calvert, S.E. 1988. The annual cycle of sedimentation in Saanich Inlet, British Columbia: implications for the interpretation of diatom fossil assemblages. Deep-Sea Research, **35**: 71–90.

Schuster, R.L., Logan, R.L., and Pringle, P.T. 1992. Prehistoric rock avalanches in the Olympic Mountains, Washington. Science (Washington, D.C.), **258**: 1620–1621.

Shedlock, K.M., and Weaver, C.S. 1991. Program for earthquake hazards assessment in the Pacific Northwest. United States Geological Survey, Circular 1067.

Sims, J.D. 1975. Determining earthquake recurrence intervals from deformational structures in young lacustrine sediments. Tectonophysics, **29**: 141–152.

Stucchi, D.J., and Giovando, L.F. 1984. Deep water renewal in Saanich Inlet, B.C. *In* Proceedings of a multidisciplinary symposium on Saanich Inlet, 2nd February, 1983. *Edited by* S.K. Juniper and R.O. Brinkhurst. Canadian Technical Report of Hydrography and Ocean Sciences, No. 38, pp. 7–15.

Stuiver, M., and Braziunas, T.F. 1993. Modelling atmospheric ^{14}C influences and ^{14}C ages of marine samples to 10,000 BC. Radiocarbon, **35**: 137–189.

Stuiver, M., and Pearson, G.W. 1993. High-precision bidecal calibration of the radiocarbon time scale, A.D. 1950 – 500 B.C. and 2500–6000 B.C. Radiocarbon, **35**: 1–23.

Stuiver, M., and Reimer, P.J. 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. Radiocarbon, **35**: 215–230.