Modern to Late Holocene deposition in an anoxic fjord on the west coast of Canada: Implications for regional oceanography, climate and paleoseismic history

Audrey Dallimore, Richard E. Thomson, Miriam A. Bertram

Abstract

Laminated sediments preserved in the anoxic inner basin of Effingham Inlet on the Pacific coast of Vancouver Island, British Columbia, Canada, yield a high-resolution sediment deposition record spanning about 6000 yr. The varying thickness of diatom/terrigenous mud varves in sediment cores from the basin can be interpreted in terms of annual changes in surface productivity and freshwater input within the inlet. Similarly, the occurrence of un laminated mud units (homogenites) intercalated amongst the laminated sediments can be interpreted in terms of oceanic and climatic changes. These units appear to be associated with coastal upwelling events that result infrequently in highly oxygenated oceanic water penetrating to the bottom of the inner and outer basins of the inlet. The sedimentary record also contains massive and graded mud units considered to arise from debris flows and turbidity currents, some of which were probably initiated by seismic events, including a major event about 4500 14C yr BP which may be earthquake related. A total of seventeen oceanographic surveys of the inlet beginning in 1995 characterize the modern seasonal coastal upwelling regime and a unique bottom water oxygenation event which was recorded in January 1999, following a rapid transition from the strong El Niño event of 1997–98 to the moderate La Niña event of 1998–99. Circum-Pacific evidence suggests that a “regime shift” from warm to cold conditions occurred in the central northeast Pacific in the late 1990s, indicating that the coastal ocean processes influencing Effingham Inlet sedimentation are likely modified by climate-scale ocean variability.

Keywords: laminated sediments; anoxic fjords; Pacific climate; regime shift

1. Introduction

Annually laminated marine sediment records can extend our knowledge of atmospheric and oceanographic conditions beyond historic and instrumental...
records, once sediment proxies for climatic and oceanographic conditions are identified (Kennett and Ingram, 1995; Pike and Kemp, 1996a; Sancetta, 1996; Kemp, 1996, 2003; Ware and Thomson, 2000). In the last decade studies of laminated marine sediment records from around the world increasingly indicate that the variability in the preservation and deposition of the annual winter laminae, which

Fig. 1. Location map of Effingham Inlet study area showing coring sites and location of moorings, sediment traps and oceanography stations. Aerial photograph inset shows drainage courses and recent logging activity.
records variations in precipitation, and the spring/summer diatomaceous laminae, which are indicative of annual productivity in the coastal ocean, archive the abrupt crossing of depositional thresholds that are related to global climate changes (Kennett et al., 1995; Bull and Kemp, 1996; Hughen et al., 1996; Pike and Kemp, 1996a; Schimmelmann and Lange, 1996; Schimmelmann et al., 1998; Schultz et al., 1998; Lückge et al., 2001; Kemp, 2003). Studies of laminated marine sediments in Saanich Inlet, an anoxic British Columbia fjord located on the southwest coast of Vancouver Island (Fig. 1) (Gross et al., 1963; Gucluer and Gross, 1964) have revealed a high-resolution sediment record of the entire Holocene as a result of ODP Leg 169S (Bornhold et al., 1998; Blais-Stevens et al., 1997, 2001; Blais-Stevens and Clague, 2001). However, Saanich Inlet is restricted from full open ocean processes due to its location along the inner coast of Vancouver Island.

This study is located in anoxic Effingham Inlet, British Columbia which is directly connected to the open ocean (Fig. 1) and contains an annually laminated sediment record spanning about 6000 yr (Patterson et al., 2000; Dallimore, 2001; Hay et al., 2003; Chang et al., 2003). We have monitored an oceanographic transect in Effingham Inlet for the past 9 yr to establish the modern oceanographic and climatic regime, enabling us to infer sedimentological proxies for climate-scale variability throughout the late Holocene. Paleoseismic events are also recorded in the Effingham Inlet sediment record (Dallimore et al., 2001) since periodic tectonic processes affect sediment stability in the inlet due to close proximity to the zone of subduction of the oceanic Juan de Fuca Plate beneath the continental North America plate (Rogers, 1988; Atwater et al., 1995a,b; Hyndman, 1995).

2. Study area

Effingham Inlet is 17 km long multiple-silled glacial fjord located on the southwestern coast of Vancouver Island, which opens to the Pacific Ocean through Barkley Sound. The fjord has an inner and outer basin, each more progressively restricted from the open ocean waters by shallow bedrock sills (Fig. 1). The Effingham River, with a drainage basin of about 79 km², discharges into the northern end of the inner basin. Run-off also enters the inlet directly from the steep bedrock basin walls during the frequent heavy rainfalls of fall and winter, depositing significant amounts of terrigenous detritus into the inlet (Dallimore, 2001). Water property distributions in the inlet (Fig. 2) are characteristic of a weakly mixed estuary (Thomson, 1981; Patterson et al., 2000) with small (<2 m) tidal variation and negligible

![Fig. 2. 3.5 kHz sub-bottom survey profile of the surficial sediments of Effingham Inlet and Barkley Sound, showing Holocene sediments draped over glacially-carved bedrock substrate. Vertical exaggeration of profile about 50 X. Water property structure shows a weakly mixed characteristic estuarine stratified water column and the anoxic character of the inner basin bottom waters.](image-url)
currents, except in the southern oceanward portion of the inlet and in constricted narrows in the vicinity of the shallow sills.

As part of the Coastal Upwelling Domain along the west coast of North America, the ocean and climate dynamics of the study region are strongly seasonally dependent (Thomson, 1981; Thomson and Gower, 1998; Ware and Thomson, 2000), and influenced by the relative positions of the Aleutian Low and the North Pacific High atmospheric pressure systems, the Jet Stream and El Niño/La Niña events (Roden, 1989; Patterson et al., 2000). Paleoceanographic signals recorded in the sediment record are therefore indicative of past seasonality and climate. Annual summer (May through August) upwelling of deep (>200 m) slope waters onto the Vancouver Island continental shelf deliver nutrient-rich waters to the upper ocean, with particularly strong upwelling-driven nutrient flux occurring through the numerous submarine canyons that cut across the continental margin in this region (Allen et al., 2001). Increased nutrients in the photic zone subsequently support a dramatic increase in surface primary productivity (Thomson, 1981), leading to the diatom blooms that are commonly observed in spring and summer in this region, and which are ultimately deposited as the diatomaceous laminae of the Effingham Inlet sediments (Grimm et al., 1996, 1997; Kemp, 1996; Sancetta, 1996; Chang et al., 1998, 2003; Patterson et al., 2000; McQuoid and Hobson, 2001). Upwelling of deep shelf waters also occurs in the winter months but because of low light levels and cool water temperatures, conditions are not conducive to diatom blooms.

The normal pattern of seasonal upwelling off Vancouver Island can be interrupted in some years by climatic events, such as El Niño–Southern Oscillation (ENSO) events (Philander, 1990; Diaz and Markgraf, 1992). The effects of El Niño events are felt on average every 3 to 7 yr in the equatorial ocean. However, it is only major El Niño events, that occur on average every 10 to 25 yr, that impact mid-latitude oceanic regions, such as the B.C. shelf (Thomson, 1981; Subbotina et al., 2001). A particularly strong El Niño event in the equatorial Pacific Ocean, which characteristically weakens or halts upwelling along the North American eastern boundary regions as far north as California, leads to anomalously warm, low-nutrient waters and reduced or altered populations of phytoplankton and fish (Barber and Chavez, 1983; Wilkerson et al., 1987; Lange et al., 2000; Mackas et al., 2001). The expressions of a strong El Niño event in B.C. coastal waters are warm nearshore waters, and a reduced upwelling tendency along the B.C. shelf (Ware and Thomson, 2000). At times, a marked “transition” to moderate to strong La Niñas (or cold phases) of the ENSO cycle, follows a major El Niño event. La Niña conditions appear to be linked to colder than normal B.C. coastal waters and enhanced upwelling tendency (Chavez et al., 2002; Castro et al., 2002).

3. Methods

Sediment cores were obtained in October 1999 from the inner and outer basins of Effingham Inlet using a piston coring apparatus deployed from the CCGS John P. Tully. The piston cores are each 10 cm in diameter and approximately 11 m in length. To characterize the sediment–water interface, five freeze cores (Hughen et al., 1996; Kulbe and Niederreiter, 2003) of 0.5 to 1.5 m in length were also retrieved, three from the inner basin and two from the outer basin core sites (Fig. 1, Table 1). Sediment slabs (20 cm length, 4 cm width, 1 cm thickness) of the entire core from the center of one outer basin core half (TUL99B11) and one representative inner basin core half (TUL99B03) were X-rayed using conventional medical X-ray equipment and Kodak min-R 2000 single screen mammography film (Pike and Kemp, 1996b; Axelsson, 2002). Total organic carbon and grain-size analyses of the sediments were performed at the Geological Survey of Canada in Ottawa. Grain-size samples were dried, treated with H2O2 to remove organic materials and then dry-sieved using a particle analyzer (Klassen et al., 2000).

Twenty-three samples of wood and shell material were recovered from the piston cores for conventional and Accelerator Mass Spectrometry (AMS) radiocarbon dating which was performed at the IsoTrace Radiocarbon Laboratory of the University of Toronto. Results are reported in radiocarbon years before present (14C yr BP) and also as calibrated calendar years (cal yr BP), as calculated using the C14Cal program and the INTCAL98 database for terrestrial (wood)
Table 1
Results of radiocarbon dating performed at Isotrace Radiocarbon Laboratory of the University of Toronto, as calculated using the C14Cal program and the INTCAL98 database for terrestrial (wood) and the MARINE98 database for marine (shell) material (Stuiver et al., 1998a,b; Stuiver and Reimer, 1986, 1993)

<table>
<thead>
<tr>
<th>Core location and water depth (°N, °W)</th>
<th>Depth in core (m)</th>
<th>Material</th>
<th>Sample number</th>
<th>14C age (yr BP)</th>
<th>Calibrated age and age range at 2σ (cal yr BP)</th>
<th>Ave. sed. rate (mm/yr)</th>
<th>Core top missing (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner basin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TUL97A02</td>
<td>14</td>
<td>Wood</td>
<td>TO-8130*</td>
<td>940 ± 50</td>
<td>894 (784–1004)</td>
<td>?*</td>
<td>?</td>
</tr>
<tr>
<td>49° 04.360 125° 09.540</td>
<td>285</td>
<td>Fish bones</td>
<td>TO-8131†</td>
<td>3410 ± 50</td>
<td>3689 (3599–3779)</td>
<td></td>
<td></td>
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<td>100 m water depth</td>
<td>551</td>
<td>Wood</td>
<td>TO-8132</td>
<td>4050 ± 50</td>
<td>4582 (4464–4699)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TUL99B03</td>
<td>97</td>
<td>Wood</td>
<td>TO-8671</td>
<td>160 ± 40</td>
<td>195 (45–345)</td>
<td>2.3</td>
<td>102 cm</td>
</tr>
<tr>
<td>49° 04.275 125° 09.359</td>
<td>169</td>
<td>Shell</td>
<td>TO-8672</td>
<td>1770 ± 60</td>
<td>970 (835–1105)</td>
<td>r² = .95</td>
<td>(~437 yr)</td>
</tr>
<tr>
<td>120 m water depth</td>
<td>286</td>
<td>Wood</td>
<td>TO-8673</td>
<td>2050 ± 70</td>
<td>1858 (1795–1920)</td>
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<td></td>
</tr>
<tr>
<td>TUL99B04</td>
<td>553</td>
<td>Wood</td>
<td>TO-8674</td>
<td>2830 ± 80</td>
<td>2980 (2830–3130)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>49° 04.188 125° 09.337</td>
<td>822</td>
<td>Shell</td>
<td>TO-8675</td>
<td>3890 ± 80</td>
<td>3435 (3250–3620)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>121 m water depth</td>
<td>937</td>
<td>Wood</td>
<td>TO-8676</td>
<td>4190 ± 80</td>
<td>4745 (4570–4920)</td>
<td></td>
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<tr>
<td>TUL99B06</td>
<td>252</td>
<td>Wood</td>
<td>TO-8677</td>
<td>1080 ± 50</td>
<td>1048 (975–1120)</td>
<td>2.8</td>
<td>33 cm</td>
</tr>
<tr>
<td>49° 04.188 125° 09.337</td>
<td>276</td>
<td>Wood</td>
<td>TO-8678</td>
<td>1340 ± 50</td>
<td>1295 (1225–1365)</td>
<td>r² = .96</td>
<td>(~118 yr)</td>
</tr>
<tr>
<td>121 m water depth</td>
<td>629</td>
<td>Wood</td>
<td>TO-8679</td>
<td>2050 ± 80</td>
<td>2060 (1910–2210)</td>
<td></td>
<td></td>
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<tr>
<td>TUL99B07</td>
<td>1006</td>
<td>Wood</td>
<td>TO-8680</td>
<td>3590 ± 50</td>
<td>3950 (3860–4040)</td>
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<td></td>
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<tr>
<td>49° 04.173 125° 09.279</td>
<td>340</td>
<td>Wood</td>
<td>TO-8681</td>
<td>1890 ± 50</td>
<td>1870 (1760–1980)</td>
<td>2.6</td>
<td>156 cm</td>
</tr>
<tr>
<td>122 m water depth</td>
<td>821</td>
<td>Shell</td>
<td>TO-8682</td>
<td>4100 ± 60</td>
<td>3683 (3505–3860)</td>
<td>r² = 1</td>
<td>(600 yr)</td>
</tr>
<tr>
<td>TUL99B11</td>
<td>377</td>
<td>Wood</td>
<td>TO-8687</td>
<td>1080 ± 60</td>
<td>1060 (970–1150)</td>
<td>?**</td>
<td>?</td>
</tr>
<tr>
<td>49° 04.173 125° 09.401</td>
<td>620</td>
<td>Wood</td>
<td>TO-8688</td>
<td>2140 ± 60</td>
<td>2205 (2035–2375)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>122 m depth</td>
<td>779</td>
<td>Wood</td>
<td>TO-8689</td>
<td>3170 ± 50</td>
<td>3595 (3370–3520)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TUL99B12</td>
<td>842</td>
<td>Wood</td>
<td>TO-8690</td>
<td>3640 ± 50</td>
<td>4010 (3880–4140)</td>
<td></td>
<td></td>
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<tr>
<td>Outer basin</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>TUL99B11</td>
<td>531</td>
<td>Shell</td>
<td>TO-8683</td>
<td>2460 ± 90</td>
<td>1695 (1470–1920)</td>
<td>6.4</td>
<td>~515 cm</td>
</tr>
<tr>
<td>49° 02.632 125°09.23</td>
<td>898</td>
<td>Shell</td>
<td>TO-8684</td>
<td>2830 ± 60</td>
<td>1818 (1665–1970)</td>
<td>r² = .45</td>
<td>(~1180 yr)</td>
</tr>
<tr>
<td>205 m water depth</td>
<td>939</td>
<td>Wood</td>
<td>TO-8685</td>
<td>2570 ± 100</td>
<td>2660 (2400–2920)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TUL99B12</td>
<td>969</td>
<td>Shell</td>
<td>TO-8686</td>
<td>1820 ± 60</td>
<td>1048 (920–1175)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• The least squares method does not give reliable estimates for sedimentation rate or core top loss for TUL97A02. In particular, the youngest date, TO-8130 appears anomalously young and TO-8131† is from fish bones which have an uncertain reservoir correction, leaving only one remaining reliable date for a least squares linear regression.

• For these dates, the least squares method gives a negative age at the core top, therefore it is difficult to estimate an average sedimentation rate and sediment loss at the core top for core TUL99B13.

Material. The reservoir correction used for marine shell material ($R = 390 ± 25$ yr) is based on the MARINE98 database for this area (Robinson and Thompson, 1981; Stuiver and Braziunas, 1993; Stuiver and Reimer, 1986, 1993; Southen et al., 1990; Stuiver et al., 1998a,b) (Table 1). Additionally, one inner basin freeze core (TUL99B04) was dated by cesium-137 and lead-210 dating methods (Sorgente et al., 1999) and the 1963 Cesium peak was located at 23 cm depth in the core (cf. Chang et al., 2003).

A total of seventeen water properties surveys in Effingham Inlet and adjoining Barkley Sound were undertaken between October 1995 and August 2004, using a multi-sensor oceanographic profiling package consisting of a Conductivity–Temperature–Depth (CTD) probe, a 25-cm pathlength transmissometer, a fluorometer, and a 24-Niskin bottle rosette sampler for determining concentrations of oxygen, nutrients and other dissolved constituents. These shipboard profile data provide along-channel sections of temperature, salinity, density, dissolved oxygen, light attenuation (transmissivity) and chlorophyll. Mooring strings supporting current meters were deployed at the entrance and within the inner basin of the inlet and were
Fig. 3. Oxygen and density profiles superimposed on inlet bathymetry illustrating the strong oxygenation event of January 1999 and the weak oxygenation event of July 1999, with characteristic anoxic conditions in the inner basin returning within months. Although the oxygen profiles record these events, the stability of the density profiles indicate that density disturbance of the bottom waters probably occurred between sampling dates.
serviced every 6 mo. Two different sequentially sampling sediment traps were deployed on each mooring between May 1999 and September 2000; a Baker-type trap (Baker and Milburn, 1983) at approximately 40 meters above bottom (mab), and an OSU-type trap at approximately 30 mab. Water depths at the mooring sites were 116 m in the inner basin and 80 m at the inlet mouth (Fig. 1).

4. Results

4.1. Physical oceanography

The main anomalous features of the along-channel oceanographic survey were the occurrences of well-oxygenated (low oxic) bottom waters in the inner basin in January 1999, and again in July 1999 (Fig. 3). The typically anoxic/dysoxic conditions characteristic of the inlet were re-established sometime between the October 1999 (dysoxic conditions) and March 2000 (anoxic conditions) sampling dates. In the outer basin, higher oxygen levels were recorded periodically during our time series pointing to enhanced oceanic influences there which create dysoxic to oxic bottom water conditions. Throughout the rest of the time series waters of the inner and outer basins below sill depth have near-uniform temperature and salinity structure (Fig. 2) indicating that the bottom waters in the basins are normally highly stagnant and infrequently affected by intrusive renewal (oxygenation) events from the outer portion of the inlet. The oxygen profiles in the inner basin show a progressive decrease in oxygen with depth, creating a water column that is uniformly low oxic (>100 μm/kg) to dysoxic/suboxic (dissolved O$_2$<40 μm/kg) to anoxic (no oxygen) at the bottom. Anoxic and dysoxic conditions of the inner and outer basins also appear to be exacerbated by the oxygen-consuming decomposition of the high fluxes of organic material into the basin during the diatom blooms in spring and summer, and also by the input of terrestrial organic material in the fall and winter.

4.2. Conditions required for present day bottom water oxygenation events

Oceanographic profile data collected just prior to the oxygenation event of January 1999, highlight four "conditions" that appear to be necessary to allow oxygenated waters to penetrate to the bottom of the inner basin (Fig. 4). These are:

1) Strong northwest coastal winds: the major upwelling events of January and July 1999 were

![Diagram](image_url)

Fig. 4. Schematic representation of conditions required to allow oxygenated waters to enter the inner basin after a transition from a strong El Niño to a moderate La Niña event; strong and persistent northwest coastal winds, a stratified water column more pronounced by heavy rainfall, weak (neap) tidal currents and “pre-conditioning” of basin waters by vertical diffusion after a prolonged period of bottom water quiescence, i.e. after suppressed coastal upwelling associated with strong El Niño conditions.
preceeded by strong (>0.2 N/m²) persistent northwest winds along the coast. Relatively high density oceanic water was transported inward toward the inlet.

2) A stratified near-surface water column in the inlet: high precipitation and runoff increases the stratification of the upper layer of the water column reducing vertical mixing over the sills.

3) Weak tidal currents: shear-induced vertical mixing is minimal during weak (neap) tides, preserving the density of the intruding bottom water and supporting oxygenation of the basins.

4) Pre-conditioning of the water column: an oceanographic condition whereby vertical diffusion, combined with weak turbulent mixing (negligible tidal and wind-induced currents) within silled basins gradually lowers the density of the deep and intermediate waters, preparing (i.e. “pre-conditioning”) the basin for flushing by more dense intrusive water from the open ocean (such as by condition 1 above).

4.3. Sediment flux

Total mass flux to the upper Baker sediment trap cylinders during the trap deployment between May 1999 and September 2000 consisted of organic material, diatom hash and terrigenous fragments with maximum flux values in the inner basin occurring in the spring months, from April to June of 2000 (Fig. 5). A significant sediment flux occurred on the July 14, 1999 opening date, coinciding with the oxygenation event of the inner basin on July 8, 1999 (bottom water O₂ = 3.0 ml/L). A high sediment flux peak (~2.5 g/m² d) was recorded only in the lower (OSU) sediment trap, while total fluxes to the upper Baker trap, suspended 10 m above the lower trap on the mooring line, remained constant. A few weeks previous to this event on June 30, flux to both traps were equal, but on the July 14 opening date, the flux to the lower (OSU) sediment trap was almost three times greater than average for the deployment period (Fig. 5).

4.4. Late Holocene sediments

The inner basin sediments represent about 6000 yr of deposition under predominantly anoxic conditions, and consist of three distinct lithological facies: well-laminated sediments (Fig. 6a), massive mud units (Figs. 6b,c, 7a,b), and graded mud units (Fig. 6b). The more rapidly deposited outer basin sediments (Fig. 8) represent about 2600 yr of deposition under oxic and dysoxic conditions since they consist of indistinctly laminated, massive and graded mud units.

4.4.1. Geochronology

Radio carbon dating of twenty-three samples of shell and wood material found in the piston cores indicates that approximately 6000 yr of deposition were recovered in the inner basin, and about 2600 yr of deposition were recovered from the outer basin (Table 1). The average sedimentation rates estimated from radiocarbon ages, are 2.6 mm/yr for the inner basin (average from 3 cores) and 6.4 mm/yr for the outer basin (Fig. 9a,b, Table 1). However, for the inner basin, varve counting in well-laminated sections of the cores gives a variable average sedimentation rate of between 2.1 and 2.8 mm/yr indicating some variability in sedimentation rates downcore. There is roughly 0.3 to 5.0 m of sediment missing from the tops of the piston cores (Table 1, Figs. 9a,b, 11) due to the sediment disturbance inherent in piston coring soft sediments (Bornhold et al., 1998; Blais-Stevens et al., 1997, 2001). This estimate is based on a combination of varve counting, average sedimentation rates and radiocarbon ages.

Dating of the freeze core TUL99B04 by ¹³⁷Cs and ²¹⁰Pb methods confirms that the laminae couplets of Effingham Inlet, consisting of one diatom rich laminae and one terrigenous-rich laminae, are annually deposited varves (cf. Chang et al., 2003). The most recent laminae recovered in the freeze cores has been dated and stratigraphically located at the calendar year 1993 (Fig. 10).

4.4.2. Laminated sediments

The well-laminated sediments of the inner basin (Fig. 6a) consist of alternating annual laminae of olive to dark olive grey diatomaceous mud and dark olive grey to black mud including both clay and silt size particles (Chang et al., 2003), with an average TOC of 5%, indicating anoxic conditions when they were deposited. Some indistinctly laminated sediments (Fig. 8) are present in the outer basin where the TOC is slightly lower at 4% indicating
less organic input than in the inner basin, and dysoxic conditions. In well-laminated sediments, the diatomaceous laminae can be further divided into near mono-specific laminae, mixed species laminae and silty diatomaceous laminae, indicating that the varves are recording on a microscopic level changes in diatom-limiting factors such as nutrient availability and light levels (cf. Chang et al., 2003).

The terrigenous laminae are mostly made up of microscopic organic debris including robust diatoms and silicoflagellate tests, and silt and clay minerals. The lower contact of the terrigenous laminae is gradational, indicating increasing precipitation in the autumn, whereas the upper contact is sharp, indicating an abrupt end to winter precipitation and run-off, concurrent with increasing biological...
production as a result of increased light levels in spring and summer (Chang et al., 2003; Hay et al., 2003).

4.4.3. Debris flow deposits

Thin (<10 cm) dark olive grey to black massive mud units with no sedimentary structure are commonly intercalated within the well-laminated sediments of the inner basin. The units consist of a silty diatom “hash” containing wood fragments, organic debris, oceanic silicoflagellates, benthic foraminifera from oxygenated regions of the inlet, fecal pellets, and pollen and diatom “blebs” which indicate a disturbance and re-deposition of previously laminated sediments (Fig. 6c) (Chang et al., 1998, 2003). Bottom contacts are gradational, can exhibit disturbed laminae.

Fig. 6. X-rays from inner basin core TUL99B03 showing (a) typically well-laminated sediments illustrating the variability in thickness of diatom varves and the abrupt change to wetter conditions when summer diatom blooms failed at 880 cm (~4250 yr BP), (b) thin homogenite and turbidite massive units separated by about 5 yr of anoxic conditions at 172 cm, (~1100 yr BP), and (c) debris flow unit at 454 cm, (~2500 yr BP).
at the base and can show evidence of erosion. Top contacts are sharp and well-defined indicating a rapid return to anoxic conditions after deposition of the bed. A thin layer of concentrated diatoms is often found at the top of the unit. These features are also common to thin massive mud units in the laminated sediments of Saanich Inlet (Blais-Stevens et al., 1997, 2001) which were interpreted as debris flow deposits (Middleton and Hampton, 1973, 1976) originating from localized failures of the build-up of loose water-saturated mud on the walls of the fjord and near the mouths of ephemeral streams. We use the same terminology for these units in Effingham Inlet and similarly conclude that they are probably the result of localized slope failures.

The thin debris flow units cannot be easily correlated across the inlet. However one of these units has a distinct gravel layer at the base, is traceable across the inner basin and therefore serves as a datum for a stratigraphic cross-section of inner basin sediments recovered in the piston cores (Fig. 11). Two thick (>50 cm) black debris flow deposits containing many large pieces of wood and terrigenous organic debris (Figs. 7b and 10) were found in the Effingham Inlet cores and can, unlike the thin debris flow units, be correlated across the inlet. The thick debris flow unit that occurs near the base of the inner basin piston cores (920–970 cm, TUL99B03; Fig. 7b) was deposited about 4500 14C yr BP, and is underlain by up to 120 cm of disrupted and de-watered previously laminated sediments.
sediments (Fig. 12). The other thick debris flow unit found in Effingham Inlet occurs in all of the freeze cores of the inner and outer basins and was deposited in 1946, an age determined by varve counting, $^{137}$Cs and $^{210}$Pb dating (Fig. 10).

### 4.4.4. Homogenites

Many of the thin massive mud units in Effingham Inlet, unlike the debris flow deposits, do not show evidence of shearing or erosion at the base, contain no varve intraclasts and appear to consist simply of re-worked laminated sediments (Figs. 6b and 7a). These units are particularly concentrated in the well-laminated sediments of the inner basin cores of less than about 4000 $^{14}$C yr BP in age across the inner basin. We refer to these featureless deposits as homogenites, following terminology proposed by Stow and Piper (1984) and Einsele (1991), to describe deposits from highly concentrated suspensions known as fluid mud as would be common in energetic shallow tidal waters (Piper and Stow, 1991) and as has been described at the bottom of estuaries (McCave and Jones, 1988). Further, we suggest below that these homogenites are the result of re-suspension of previously laminated sediments by bottom currents and are not the result of deposition following sidewall failures from oxygenated parts of the inlet.

### 4.4.5. Turbidites

Ten thin ($<10$ cm) graded mud units with clay and silt size particles, dark olive-grey to black in color, with sharp basal contacts, are intercalated within the laminated sediments at irregular intervals, and are identified from the X-rays of inner basin core sediments (TUL99B03) (Fig. 6b). One distinct thick (18 cm) graded unit occurs at the base of some of the inner basin piston cores and is dated at $\sim$5250 $^{14}$C yr BP (1110 cm core TUL99B03; Fig. 11). These units can contain silt and mud, fine to coarse sand grains, terrigenous organic and shell fragments, and occasionally gravel at the base. The characteristics of these graded units suggest emplacement by turbidity flows following sediment disturbance (Bouma, 1962; Middleton and Hampton, 1973, 1976; Middleton and Southard, 1984; Collosson and Thompson, 1989; Einsele, 1991), possibly from shallower oxic, or terrestrial areas of the inlet, and we therefore refer to them as turbidites.

### 4.4.6. Changes in depositional conditions over the late Holocene

A distinct change in the character of sedimentation is evident in sediments older than about 4000 $^{14}$C yr BP in age (820–1137 cm at base of core, TUL99B03). Uninterrupted laminated sediments from $\sim$4000 to 4300 $^{14}$C yr BP, (820–920 cm, TUL99B03) represent three centuries of persistent anoxia and undisturbed annual sedimentation in the inner basin (Fig. 6a) since notably, no debris flow, homogenite or turbidite units are found in these sediments. This persistent anoxia may have lasted for almost a millennia since, beneath these uninterrupted laminated sediments, the record has been disrupted by a thick (50 cm) debris flow unit containing wood fragments (Fig. 7b) which is underlain by another 120 cm (975–1096 cm, TUL99B03) of...
Fig. 9. Plot of radiocarbon dates using the least squares method. Average sedimentation rate for (a) inner basin core TUL99B03 is 2.3 mm/yr and (b) 6.4 mm/yr for the outer basin core TUL99B11. However, inset X-rays show the variability in sedimentation rate as derived by varve counting in laminated sections of the cores.
Fig. 10. X-ray composite of inner basin freeze core TUL99B04, showing well-laminated sediments representing uninterrupted anoxic conditions in the inner basin from 1993 to 1947, followed by the deposition of a debris flow unit associated with the 1946 Vancouver Island magnitude 7.3 earthquake. Core was dated using $^{137}$Cs and $^{210}$Pb methods with the 1963 Cesium peak occurring at 23 cm (cf. Chang et al., 2003).
disrupted, yet previously laminated sediments (Fig. 12) representing another lengthy interval (~450 yr) of persistent anoxic conditions in the inner basin. Laminated sediments of this age contain the thickest diatomaceous laminations of the cores (Chang et al., 2003), and the highest sedimentation rate (~2.8 mm/
yr) due to an increase in the average thickness of diatom laminae in sediments.

In contrast, anoxic conditions appear to have been frequently interrupted in the inner basin from ~4000 \(^{14}\text{C}\) yr BP to the present (from 820 cm, TUL99B03). Inner basin core sediments of this age contain forty-five thin (up to 10 cm) debris flow and homogenite units and ten of the eleven turbidite units found in the inner basin cores (Fig. 11). These indicate frequent oxygenation events and/or an increase in the incidence of sediment disturbance and/or a change in depositional conditions affecting the consolidation and hence stability, of the basin sediments during this time, perhaps due to higher precipitation. Significantly, only one well-laminated unit in this section of the cores is longer than 10 cm, representing a maximum of about 50 yr of uninterrupted anoxic conditions during the period from about 4000 \(^{14}\text{C}\) yr BP to the present.

5. Discussion

5.1. Evidence for a Pacific regime change

The oceanographic conditions recorded prior to and during the oxygenation events of January and July 1999 (Section 4.2), followed a transition from the strong El Niño event of 1997–98 to the moderate La Niña event of 1998–99 (Castro et al., 2002). This disruption of the “normal” (as recorded in our 9-yr water property survey) coastal oceanographic and climatic conditions in January 1999 which facilitated the intrusion of oxygenated waters into the inner basin, is an indication that coastal ocean dynamics influencing Effingham Inlet are likely driven by oceanic events which are affecting the regional climate along the continental margin. Pre-conditioning of the deep portion of the water column within the two basins was also likely strongly facilitated by the intense 1997–98 El Niño.

Significantly, the uninterrupted laminations of the freeze core record of modern sedimentation in Effingham Inlet (Fig. 10) also indicate that the inlet was persistently anoxic between at least 1946 and 1993, further evidence that oxygenation of the bottom waters in 1999 was a unique event in the past half century. Increasingly, other oceanographic data collected along a monitoring transect in the northern Pacific by the Institute of Ocean Sciences is indicating profound changes in ocean circulation since 1997, further evidence that the sudden shift in coastal oceanographic conditions we recorded in Effingham Inlet may be part of a larger oceanic and climatic phenomena within the North Pacific (Schwing et al., 2002). Other circum-Pacific physical and biological evidence (Minobe, 1999; Ware and Thomson, 2000; Bertram et al., 2001; Chavez et al., 2003) also indicate that the ENSO event of 1997–98 may be related to a possible “regime shift” in the Pacific Ocean heralding a change from warm to cold climatic conditions, counter to the well-known 1976–77 “regime shift” from cold to warm conditions.

5.2. Deposition of homogenites during oxygenation events

We propose, based on the modern sediment trap evidence, that bottom-hugging density currents asso-
ciated with oxygenation events may be capable of carrying sediment loads close to the bottom of the inlet into the outer basin, and infrequently to the inner basin. These currents are then perhaps capable of disturbing several years of recent sedimentation, creating the homogenites found in the sediment record. We rule out bioturbation as an explanation for the homogenites (Anderson et al., 1989; Anderson, 1996; Behl and Kennett, 1996; Kemp, 1996; Blais-Stevens et al., 2001; Kemp, 2003) since distinct evidence for bioturbation burrows (Behl and Kennett, 1996; Sageman et al., 1991; Kemp, 2003) was not found in the X-rays of the inner basin sediments. Furthermore, grab samples of bottom sediments of the inner basin taken in May 1999, 4 mo after the bottom water oxygenation event recorded in January 1999, were devoid of bioturbating benthic organisms. The along-channel water property structure monitoring program indicates that the bottom waters of the inner basin return to their normally anoxic condition after each intrusion within a matter of months, without allowing sufficient time for a bioturbating benthos community to become established in the soft sediments of the inner basin (cf. Savrda et al., 1991; Behl and Kennett, 1996).

Although bottom currents are weak (maximum bottom currents of Effingham Inlet are in the order of 1 cm/s) the incoming density currents are perhaps capable of disturbing poorly consolidated “suspended” sediments since unconsolidated mixed layer sediments with very high pore-fluid contents (up to 90% near the sediment–water interface) typically have low shear strengths (Savrda and Ozalas, 1993). The youngest consolidated laminae sampled in the freeze cores has been dated at 1993, and this indicates that sediments in the quiescent inner basin of Effingham Inlet begin as a slurry of slowly consolidating and hence high pore-fluid content “suspended” sediments, a consequence of several years of recent deposition essentially still floating in the water column near the sediment water interface. Observations from a remotely operated submersible in another of our anoxic B.C. study fjords (Mereworth Sound, B.C.) showed a “suspended” sediment layer of about 0.5 m thickness at the basin floor.

An oceanic sediment source with incoming density currents might also explain why in the outer basin, where bottom waters are oxygenated more commonly than the inner basin, the average sedimentation rate calculated from radiocarbon dates (~6.4 mm/yr) is more than twice that for the inner basin (~2.6 mm/yr), despite the approximately equivalent catchment areas of both basins. A similar phenomenon was observed in Jervis Inlet, on the southern mainland coast of B.C., where increased settling fluxes of sediment coincided with deep-water renewal (oxygenation) events (Timothy, 2001; Timothy and Soon, 2001).

5.3. Late Holocene climate interpretation

The well-laminated sediments of the inner basin suggest that anoxic bottom waters were the norm throughout the late Holocene. However, the clustered occurrence of debris flow deposits, homogenites and turbidite units in sediments younger than about 4000 14C yr BP, suggests variability in Holocene climate since that time might have been associated with climate deterioration including increasing rainfall and more frequent strong ENSO events in the southern Pacific. This study shows that sediment disturbance in the modern environment is associated with climatic conditions, and other evidence also supports this conclusion. Microscopic analyses of the diatom laminae of Effingham Inlet sediments shows that sediments older than 4000 yr BP contain diatom laminae that consistently exhibit a distinctive annual succession of diatom species indicating conditions that were warmer than those from 4000 yr BP to the present (Chang et al., 2003). Absolute diatom production also appears to have declined from 4000 yr BP to the present with a significant decrease in the taxa generally associated with the spring–summer bloom (M. Hay, oral communication, 2004). A British Columbia Holocene paleoclimate synthesis, based on morphological evidence and pollen data from ten sites in B.C., including one in nearby Barkley Sound (Hebda, 1995) also indicates that a climate warmer and drier than today’s existed from about 4000–10,500 14C yr BP although the exact start and end times of paleoclimate states are difficult to precisely determine from region to region. However, the cooling at about 4000 14C yr BP from a previous state of warmer and drier conditions, has clear indicators along this coast with observed changes in vegetation and neoglacial advances (R. Hebda, oral communication).
An alternative explanation for the apparent persistent anoxia of the inner basin prior to 4000 $^{14}$C yr BP, is that the inlet was isolated from the ocean at that time during a lower sea-level stand. The inner basin sill is only 40 m deep and post-glacial sea levels on Vancouver Island have fluctuated rapidly, by as much as 85 m in less than 1000 yr during isostatic response to deglaciation in the early Holocene (Clague, 1989b). Although the sea level history of the British Columbia coast is notoriously complex (Clague, 1989a,b; Barrie and Conway, 1999, 2001), the interpreted sea level record for the nearby Tofino area just to the north of Effingham Inlet indicates that sea level has been dropping from a higher stand in that area since about 4000 $^{14}$C yr BP to present day sea levels (Clague et al., 1982). A lake core record from our on-going work in the Seymour and Belize Inlet complex further to the north, also shows that sea level has been dropping in that area (Dallimore et al., 2002). We therefore tentatively conclude that the persistent anoxia of the inner basin bottom waters recorded in the Effingham cores prior to about 4000 $^{14}$C yr BP is probably representative of warmer and drier climatic and associated oceanographic conditions and not due to an increased physical isolation of the inner basin from the ocean due to changes in sea level in the late Holocene.

If the homogenites of Effingham Inlet are evidence of incoming oxygenated waters advecting over the sills, these lithological units, which are particularly common in the sediments of less than 4000 yr of age, are a proxy for the regional oceanographic and climatic conditions measured in our oceanographic time series around the time of the 1999 oxygenation events. Similarly, transitions from strong El Niño to moderate to strong La Niña events were perhaps also required throughout the late Holocene for oxygenation events of the inner basin bottom waters, and deposition of the homogenite units to occur. Evidence from the Santa Barbara Basin (Bull et al., 2000) shows that modern interannual depositional variability within laminated sediments in the anoxic Santa Barbara Basin associated with ENSO effects on sedimentation, appears to also have been common throughout the Quaternary (Kemp, 2003). Moy et al. (2002) show that the frequency and strength of El Niños in the equatorial Pacific have varied over the past 12,000 yr with El Niño activity occurring on a 2000 yr cycle throughout the Holocene, with increasing ENSO event frequency towards the present. We therefore conclude that the modern oceanographic and depositional processes in Effingham Inlet may be reliable proxy indicators of the changes in climate and ocean circulation associated with particularly strong ENSO events since about 4000 yr ago in this area.

5.4. Evidence of paleoseismic events

A thick (30 cm) debris flow unit containing wood pieces and terrestrial organics occurs in all freeze cores of the inner and outer basins (Fig. 10), and has been dated by $^{137}$Cs and $^{210}$Pb methods as having been emplaced in 1946. In that year on June 23, an earthquake of $M=7.3$ with an epicenter in east-central Vancouver Island occurred. Liquefaction of sediments, resulting in significant terrestrial and subaqueous sediment slumps and slides, were initiated on both coasts of Vancouver Island by the seismic shaking associated with this earthquake (Rogers, 1980). We conclude that the thick debris flow unit in the freeze cores was deposited during this earthquake and gives a rare modern analogue of the nature of sediment disturbance in Effingham Inlet resulting from a large ($M=7$) earthquake.

In analogy with the 1946 debris flow unit, we suggest that a ~4500 $^{14}$C yr BP thick (50 cm) debris flow unit of the inner basin cores (Fig. 7b), which in places is underlain by disturbed laminated sediments indicating a shaking of the sediment column beyond the sediment consolidation threshold (Fig. 12) (cf. Clague et al., 1992), may also be associated with a large seismic event with an epicenter close to Effingham Inlet. This event has not been previously reported in other paleoseismic proxy records of the area (cf. Atwater, 1987; Atwater et al., 1995a,b; Blais-Stevens et al., 1997, 2001; Clague and Bobrowsky, 1999).

The thin debris flow and turbidite units of the inner basin cores, if they have a paleoseismic origin, are likely associated with events with a seismic impact less than a $M=7.3$ earthquake at about 80 km distance. Particularly since they are difficult to correlate positively across the inner basin, and cannot be correlated to the outer basin. These units are perhaps the result of small debris flows and turbidity currents initiated from localized and/or isolated sediment...
slumps, triggered by minor seismic disturbances or over-steepening of sediments on the side of the basin (cf. Blais-Stevens et al., 1997, 2001).

The average recurrence interval for moderate to large earthquakes on southernmost Vancouver Island as inferred from laminated sediment records in nearby Saanich Inlet is about 150 yr (Blais-Stevens et al., 1997; Blais-Stevens and Clague, 2001). However, this frequency of basin-wide sediment disturbance is not evident in the Effingham Inlet sediment record. Although a full discussion of this discrepancy is beyond the scope of this paper, we propose two possible explanations; differing physical properties in the sediments and difference in concentration of seismic activity between the two study areas.

Several factors indicate that although similar, the laminated sediments of Saanich Inlet may react quite differently to strong seismic shaking as compared to the laminated sediments of Effingham Inlet since the reaction of any particular sediment column to seismic shock depends on the physical properties and coherence of the sediments (Cita and Lucchi, 1984). The sedimentation rate in Saanich Inlet (7 to 11 mm/yr, Blais-Stevens et al., 2001) is substantially greater than that for Effingham Inlet inner basin sediments (2.1–2.8 mm/yr), creating a more frequently unstable sediment package in Saanich Inlet. Additionally, the sediments of northern Saanich Inlet contain a triplet component in the varve sequence, of a clay layer associated with spring run-off of the nearby Cowichan River, therefore they have a higher clay component than those of Effingham and consequently different physical properties (Blais-Stevens and Clague, 2001). Therefore the sediments in Saanich Inlet may be more susceptible to seismic shaking than those in Effingham Inlet due to their higher accumulation rate and difference in physical properties. This could perhaps explain the discrepancy in the apparent frequency of paleoseismic events recorded in the sedimentary records of the two inlets.

Perhaps more plausible is that the significant difference in concentration of crustal seismicity in the two study areas may explain the apparent lower frequency of large earthquakes in the Effingham Inlet area. Both areas are exposed to strong shaking from infrequent giant Cascadian subduction earthquakes but Saanich Inlet will be exposed to a higher rate of strong shaking from crustal earthquakes due to its more proximal location to the concentration of seismicity in Southern Georgia Strait and Puget Sound (Hyndman et al., 2003).

6. Conclusions

Oceanographic, sedimentological and micropaleontological evidence from Effingham Inlet reveal that oxygenation of the bottom waters in the partially isolated inner and outer basins has occurred comparatively more frequently since about 4000 $^{14}$C yr BP, indicating that the late Holocene climate along the B.C. coast has become progressively cooler and wetter towards the present. The occurrences of homogenite mud units, considered to be proxy indicators of sedimentation during strong ENSO events, are assumed to mark the onset of major changes in the coastal ocean off British Columbia throughout the late Holocene. Therefore, strong El Niño–La Niña transitional events were perhaps more common since about 4000 $^{14}$C yr BP. Prior to about 4000 yr ago, uninterrupted laminated sediments indicate that centuries of sustained bottom water anoxia occurred in the absence of strong ENSO events, during a climate state warmer and drier than today’s. The recent sedimentary record indicates that the rapid basin-scale transition from the strong 1997/1998 El Niño event to the ensuing moderate 1998–99 La Niña event which was associated with enhanced coastal upwelling is the first ENSO transitional event to affect sedimentation in the inner basin of Effingham since at least 1946, and may signal a modern regime shift of the North Pacific coastal climatic and oceanographic system. Although possible evidence for two major earthquakes were also found in the sediments, (ca. 1946, $M=7.3$ and approximately 4500 $^{14}$C yr BP) the apparent frequency of major pre-historic earthquakes in this area interpreted from other studies, about one every 150 yr, was not found in the Effingham Inlet record. This may reflect that the lower frequency of seismic activity in the Effingham area and/or the subtle differences in physical properties of annually laminated marine sediments may explain the lower frequency of paleoseismic activity recorded in the Effingham Inlet sediments as compared to that interpreted from more southern areas of the B.C. coast.
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