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Geochemical and diatom signatures of bottom water renewal events in Effingham Inlet, British Columbia (Canada)

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ABSTRACT

Sediments from Effingham Inlet, Vancouver Island, British Columbia hold a valuable high-resolution Holocene record of paleoclimatic and paleoceanographic conditions in the northeast Pacific Ocean. Accurate interpretation of this record requires that the depositional environment be well understood. In order to assess deposition within the fjord over the last 1500 years, two cores, a Soutar box core and a Kasten core, were analyzed for fossil diatoms, and biogeochemical properties. The cores contain varved sequences intercalated with homogeneous mud layers and a seismite. We show that homogeneous mud units related to periods of bottom water renewal are geochemically distinct from the seismite and that these bottom renewal events are favored when brackish rather than marine surface water conditions are present. The seismite, deposited in AD 1946, has lower opal and higher organic carbon concentrations and higher organic carbon: nitrogen ratios reflecting greater terrestrial material input. In contrast, homogeneous mud units are marked by a lower organic C/N and more isotopically heavy $\delta^{13}C$ values, suggesting a stronger marine influence. Major metals and trace element data also confirm that the source material of these units differs from that of the AD 1946 seismite. Fossil diatom assemblages within the homogeneous mud units are characterized by a decreased abundance of typical marine spring bloom taxa (*Skeletonema costatum*, *Chaetoceros* spp., *Thalassiosira* spp.) coupled with an increased abundance of the brackish-water taxon *Cyclotella choctawhatcheeana*. Reduced surface salinity enhances stratification of the water column which, in turn, favors an intensified two-layer estuarine exchange across the shallow sills and associated bottom water renewal. The homogeneous mud units are produced through transport of sediment into the fjord coupled with a reworking of the upper layers of the sediment column. Therefore, these units represent a recorder of past changes in regional oceanography and climate.

1. Introduction

As coastal environments experiencing high sedimentation rates, fjords represent potentially useful sites for the reconstruction of both past terrestrial and oceanic conditions (Syvitski and Shaw, 1995). Adjacent to the open ocean, these inlets are natural sediment traps serving as recorders of past environmental conditions along ocean margins (e.g. McMinn et al., 2001; Jensen et al., 2004). Furthermore, the bathymetry of fjords, coupled with an elevated primary production, often favors the formation of anoxic bottom waters and the preservation of annually-laminated (varved) sequences (e.g. Chang et al., 2003).

Effingham Inlet, a small fjord along the west coast of Vancouver Island, British Columbia (B.C.), is an excellent site for high-resolution paleoceanographic research (Chang et al., 2003; Dallimore et al., 2005; Hay et al., 2007; Ivanochko et al., 2008). With an anoxic inner basin and an adjacent suboxic-anoxic outer basin, sediment records from the inlet are mainly composed of diatom-mud varves (Chang et al., 2003; Dallimore et al., 2005). Furthermore, the inlet faces the open ocean and an area of important upwelling (McFarlane et al., 1997). This favors preservation of a distinct offshore oceanographic signal within the sediment record of the inlet (Hay et al., 2007).

As with other fjords, Effingham Inlet is a steep-sided basin with a relatively complex depositional setting. As a result, it is subject to a number of sedimentary processes that require proper identification for accurate interpretation of past environmental conditions. This is especially critical in tectonically active regions, such as the west

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coast of British Columbia (Blais-Stevens and Clague, 2001; Dallimore et al., 2005; Dallimore et al., 2009).

Sediments recovered from the inlet consist of annually laminated diatomaceous silty clays (varves) with occasional intercalations of various types of unstructured or homogeneous silty clays (Chang et al., 2003; Dallimore et al., 2005). The non-laminated units range in thickness from a few millimetres to more than 50 cm. Early studies of laminated sediments in B.C. fjords interpreted most non-laminated units in the sediment column as seismites, namely proxies for disturbance related to seismic events or as the result of debris flows generated by over-steepening of sediment that had accumulated along the fjord walls (Blais-Stevens et al., 1997). However, further studies have shown that some non-laminated, homogeneous mud units within the laminated sediments of anoxic B.C. fjords are not related to seismic events, yet represent indicators of paleoenvironmental conditions (Dallimore et al., 2005; Dallimore et al., 2009).

These homogeneous mud units are interpreted to have formed by re-suspension of previously laminated sediments by bottom currents flowing over the sill into the inner basin of the inlet during re-oxygenation events. Bottom water renewal in coastal inlets along the British Columbia coast is often accompanied by an increased sediment flux to the deeper portion of the basins (Timothy et al., 2003). This renewal in Effingham Inlet requires a "preconditioning" of the waters inside and outside the anoxic basins, including enhanced stratification of the upper water column, intensified estuarine circulation, a decrease in deep water density due to vertical diffusive processes, and/or increased coastal upwelling (Dallimore et al., 2005). Bottom water renewal events in the inlet appear to last a maximum of a few months before anoxic conditions return (Patterson et al., 2000).

In this paper, we utilize geochemical and microfossil tools for distinguishing between seismites and homogeneous mud units related to bottom-water renewal. We analyze two continuously sampled sediment cores, representing 1500 years of sedimentation, recovered from the inner basin of Effingham Inlet. In this paper we compare the geochemical signature of a known earthquake-related sediment deposit (seismite) with that of the homogeneous mud units in order to identify the sources of the biogenous and lithogenous material within the sedimentary units of Effingham Inlet. We then examine the fossil diatom assemblages (class: Bacillariophyceae) to highlight the oceanic and climatic conditions responsible for bottom water renewal and the formation of homogeneous mud units in the inlet.

2. Study site

Effingham Inlet is a 17-km long fjord located in the northeastern corner of Barkley Sound on the west coast of Vancouver Island (Fig. 1). The narrow inlet, with an average width of 1 km, is characterized by the presence of two suboxic to anoxic basins. An inner sill with a depth of 40 m separates the inner and outer basins, with depths of 125 m and 205 m, respectively (Patterson et al., 2000). The outer basin is separated from Barkley Sound by a sill having a minimum depth of 60 m. Barkley Sound opens directly to the Pacific Ocean and has an irregular bathymetry with an average depth of 70 m. The sides of the fjord are steep and are covered by a coastal temperate rainforest. Littoral marsh areas are restricted to narrow zones at the base of the fjord walls and to a few areas concentrated around the fjord head and outer basin (Fig. 1B).

Pickard (1963) classified Effingham Inlet as a low runoff fjord. The predominant freshwater source, the Effingham River, enters at the head of the fjord with an estimated mean flow of 6 to 8 m^3s^{-1} and maximum mean monthly discharge of 14 m^3s^{-1} (Stronach et al., 1993). Peak freshwater discharge into Effingham Inlet occurs during late fall and early winter (October–January) when annual precipitation is at a maximum. Winter temperatures usually remain above freezing at lower elevations, preventing a large amount of snow accumulation, thereby limiting the spring freshet typical of most mainland fjord systems.

The limited freshwater input produces a weak estuarine circulation during the summer months. Weak estuarine circulation coupled with weak tidal currents favor the development of suboxic–anoxic conditions at the bottom of the fjord (Patterson et al., 2000). Freshwater input from the Effingham River forms a thin lens of brackish surface water in the inner fjord. The salinity of this layer increases rapidly seaward through vertical mixing with the salty water beneath. This outflow, and accompanying loss of salt as a result of vertical entrainment from underlying waters, is compensated by inflow within a relatively warm (>10 °C) intermediate-depth layer with salinities ranging from 29.0 to 32.0. This layer, likely representing upwelled offshore waters that have mixed with the bottom waters of the Vancouver Island Coastal Current (Fig. 1), penetrates into Effingham Inlet in mid- to late summer and reaches the innermost portions of the inlet by late fall. Depending on temperature and salinity distributions within the basins at the time of intermediate to deep water intrusion into the inlet, denser deep water (<9 °C and salinity >32.3) entering the two basins can extend from the shallow inner and outer sills downslope to the sea floor. Oxygenated upwelled waters are able to penetrate into the fjord and, if sufficiently dense relative to the deep waters in the basins, will occasionally renew the bottom waters. Although renewal events typically affect both the inner and outer basins, some events are too weak to penetrate from the outer into the inner basin.

3. Materials and methods

A Soutar box core (EFBC9703-2) and Kasten core (EFKC9703-1) (Kogler, 1963) were recovered from the inner basin of Effingham Inlet at depths of 122 m and 120 m, respectively (Fig. 1B). Core material was recovered and transported to Scripps Institution of Oceanography (SIO), La Jolla, CA and were kept in cool (4 °C) storage for 2 years. After draining, the box and Kasten cores had lengths of 73 cm and 197 cm, respectively. The cores were cut into a number of slabs and X-rayed using SIO standard slab preparation techniques. Slabs were X-rayed with a 40 kV, 40 Ma belt-feed X-ray machine using Kodak™ XTL-2 X-ray film.

Preliminary inspection of the X-ray radiographs showed three principal units in the Soutar box core: (1) a laminated sequence underlain by (2) a massive (homogeneous) unit, and (3) a basal unit of distorted laminae. Based on the X-ray plates, the upper section of the box core was sampled every two laminar couplets. The sediment gravity flow unit located immediately below the laminae was sampled at 1-cm intervals. Disturbed laminae below the massive unit were sampled at approximately 2-cm intervals, following the laminar planes.

Sampling of the Kasten core was based on laminae patterns and homogeneous mud units identified in the X-ray images. Laminae and disturbed laminae sequences were sampled at <1-cm intervals. Homogeneous mud sections within the core were sampled at 1-cm intervals.

3.1. Radiometric analyses

All ^{137}Cs and ^{210}Pb analyses of cores EFBC9703-2 and EFKC9703-1 were conducted at GEOTOP, Université de Québec à Montréal. Values for ^{137}Cs and ^{210}Pb were corrected for salt content. Lead-210 estimates were made from the activity of the radioactive daughter product ^{210}Po using alpha spectrometry and ^{210}Pb values were back calculated to the time of coring. The chronology was estimated using a constant rate of supply (CRS) ^{210}Pb model (Binford, 1990).

For all radiocarbon dating, AMS techniques used predominantly wood samples and a single marine shell. Samples were analyzed at BETA Laboratories, Florida (BETA-2 samples) and the Keck Carbon Cycle AMS Facility, Earth System Science Department, University of California at Irvine (UCIAMS-12 samples). All dates were calibrated to calendar years using INTCAL98 (Stuiver et al., 1998a) for wood samples and MARINE98 (Stuiver et al., 1998b) for shell material. A regional marine reservoir