

Siliceous microfossil record of late Holocene oceanography and climate along the west coast of Vancouver Island, British Columbia (Canada)

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Abstract

Diatoms, silicoflagellates, and biogenic silica (BSi) were analyzed from two piston cores recovered from Effingham Inlet, British Columbia. Relatively productive marine conditions from 4850 to 4000 cal yr BP were followed by a transition to the modern ocean–climate regime marked by a decreased siliceous microfossil production since 2800 cal yr BP. This change in the northeast Pacific climate was characterized by an apparent cooling associated with higher rainfall and lower light levels. The reduced abundance of most spring–summer bloom diatom taxa (*Skeletonema–Thalassiosira–Chaetoceros*) was coupled with a decreased abundance of diatoms normally associated with incursions of offshore water into coastal inlets. This pattern reflected a weaker summer upwelling along Vancouver Island associated with the insolation-related increase in the strength of the Aleutian Low and a weakened North Pacific High. After ca. 2800 cal yr BP, diatom assemblages also indicated more frequent periods of relatively low spring–summer surface water salinity and a disruption of the typical bloom sequence, indicative of increased climatic variability. A period of warmer and drier climate conditions and possibly increased coastal upwelling offshore occurred ca. 1450–1050 cal yr BP. The most recent 500 yr are marked by reduced diatom production and the appearance of three distinct diatom biomarkers in the stratigraphic record (*Rhizosolenia setigera* ca. AD 1940; *Minidiscus chilensis* ca. AD 1860; *Thalassionema nitzschioides* morphotype A, ca. AD 1550). The oceanographic changes recorded in Effingham Inlet are correlative with other marine and terrestrial paleoenvironmental records in the northeast Pacific Ocean. Crown Copyright © 2006 Published by University of Washington. All rights reserved.

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Introduction

Along the continental margin of southern British Columbia, seasonal changes in local and regional wind forcing coupled with bottom topography on the continental shelf produce predominantly upwelling conditions during the summer (Allen et al., 2001). This summer coastal upwelling, coupled with increased nutrient supply from freshwater run-off and increased seasonal light levels, results in enhanced biological production and a historically important commercial pelagic fishery (McFarlane

et al., 1997). Reduced phytoplankton and zooplankton abundance during years of reduced wind stress (weaker upwelling) are associated with restricted growth and reduced numbers of northern herring and Pacific sardine (Hsieh et al., 1995; Robinson and Ware, 1999). Variability in the strength and duration of regional upwelling and, consequently, nutrient delivery to the coastal ocean impacts all trophic levels within the coastal marine food web.

Instrumental measurements of upwelling along the west coast of North America extend back to the end of the 19th century (Hsieh et al., 1995), providing a relatively short window for determining ocean and climate variability in this region where multi-decadal cycles have a major role in influencing marine ecosystems (Ware, 1995). Paleoenvironmental reconstruction

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allows a longer term understanding of the major forces driving climate and ocean change affecting biological systems. A paleoceanographic perspective provides a more reliable assessment of modern ocean–climate patterns and their impacts on primary and marine fish production. The understanding of upwelling variability and the ecological consequences during the late Holocene remains limited along coastal British Columbia.

In this paper, we present a 4850-yr siliceous microfossil record from Effingham Inlet, a fjord on the west coast of Vancouver Island, British Columbia. The varved (annually laminated) sediment record from this fjord provides the opportunity for high-resolution reconstruction of past environmental conditions within the inlet and offshore oceanic variability. Diatoms (class Bacillariophyceae) are single-celled algae that form the base of the marine food chain in upwelling regions (Cushing, 1989) and represent a major component of phytoplankton along the British Columbia coast (Harrison et al., 1983; Sancetta, 1989; Haigh et al., 1992). Their siliceous cell walls are well preserved in the bottom sediments of Effingham Inlet and the fossil assemblages reflect both spring–summer bloom production and incursions of offshore waters into the fjord (Hay et al., 2003). Downcore changes in diatom assemblage composition and abundance should reflect changes in diatom production related to long-term variations in climate, upwelling strength, and alongshore current transport off the west coast of Vancouver Island.

Study area

Regional oceanography

About 600 km offshore of the west coast of British Columbia, the eastward flowing West Wind drift bifurcates (Fig. 1a), with one branch flowing to the north forming the Alaska Current as part of the Alaskan Gyre while a southward-flowing branch forms the California Current along the west coast of North America (Thomson et al., 1989). Because the central latitude of the bifurcation region varies with season, currents offshore from Vancouver Island lie within a transition zone where the prevailing current direction is also seasonally variable.

Ware and McFarlane (1989) situate the west coast of Vancouver Island within the northern limit of the North American Coastal Upwelling Domain, a region stretching from northern Vancouver Island to Baja California. Wind-induced upwelling over the continental margin off the southwestern coast of Vancouver Island is further modified by bottom topographic gradients and submarine canyons (Allen et al., 2001). Buoyancy forcing is responsible for the formation of the 15- to 20-km-wide Vancouver Island Coastal Current (VICC) that flows northward over the inner shelf throughout the year (Fig. 1b) (Thomson et al., 1989). With the strengthening of the North Pacific High in the spring and summer, northwest winds generate an equatorward flowing, upwelling-favourable “shelf-break” current over the continental slope and outer shelf of the island (Fig. 1b) (Thomson et al., 1989). During strong upwelling conditions, upwelled water from 200 to 500 m

depth is able to penetrate across the inner shelf beneath the VICC into Barkley Sound and the adjoining inlets. In winter, the Aleutian Low strengthens and centers over the Gulf of Alaska. As a result, downwelling-favourable southerly winds prevail along the coast and lead to a persistent poleward flow along the continental slope.

Effingham Inlet

Effingham Inlet is a 17-km-long, 1-km-wide fjord located in Barkley Sound, with an inner and an outer basin separated by a 40-m-deep sill (Fig. 1c). An outer sill having a depth of 65 m separates the outer basin from a channel connecting Effingham Inlet to Barkley Sound. The fjord sides are steep, and marsh areas are restricted to a narrow zone along the steep fjord sides and a few coastal marshes concentrated around the fjord head and outer basin (Fig. 1c).

Pickard (1963) classified Effingham Inlet as a low-runoff fjord. In contrast to fjords along the mainland coast of British Columbia, peak freshwater discharge into Effingham Inlet occurs during late fall and early winter (October–January). Winter temperatures usually remain above freezing at lower elevations, preventing a large amount of snow accumulation and thereby limiting the spring freshet. Reduced freshwater discharge and weak tidal currents favour the development of suboxic–anoxic conditions at the bottom of the fjord (Patterson et al., 2000). Oxygenated offshore waters are able to penetrate into the fjord and, if sufficiently dense, will occasionally recharge the suboxic–anoxic bottom waters (Dallimore et al., 2005). This recharge is more limited in the inner basin than in the less restricted outer basin. A more detailed description of oceanographic conditions within Effingham Inlet is presented in Hay et al. (2003).

Methods

Core recovery and subsampling

In October 1999, sediment cores were recovered from Effingham Inlet. The 1137-cm-long piston core TUL99B03 was obtained from the inner basin (49°04'N, 125°09'W) at a depth of 120 m. Piston core TUL99B11, 1000 cm long, was recovered at a depth of 205 m from the outer basin (49°02'N, 125°09'W). Cores were stored as 1.5-m-long sections at 4°C, logged, slabbed and X-rayed using conventional mammography X-ray film and medical X-ray equipment (see Dallimore, 2001 for an extended description of core recovery and handling). To achieve a continuous age–depth relationship, sedimentary units representing sediment gravity flow events were eliminated from the overall core length and an “adjusted” core length was determined. Samples for siliceous microfossil analysis were collected at the same depth intervals as sediment subsamples used for dinoflagellate (Patterson et al., 2005) and fish scale (Wright et al., 2005) counts. Additional samples for diatom and biogenic silica analysis were obtained along both cores in order to increase the consistency between sample intervals as well as to improve the downcore resolution.

Chronological control

Radiocarbon dating and sedimentation rates

AMS ^{14}C dating of shell and wood material recovered from both cores was performed at IsoTrace Laboratories, University of Toronto. Dates were calibrated to calendar years using INTCAL98 (Stuiver et al., 1998a) for wood material and MARINE98 (Stuiver et al., 1998b) for marine shells. A regional marine reservoir correction of $\Delta R = 390 \pm 25$ (Southon et al., 1990) was applied to shell material using CALIB version 4.4.2 (Stuiver and Reimer, 1993).

To verify the reliability of the radiocarbon-based age model, sedimentation rates in laminated sections of both cores were estimated from repetitive varve counts. Sedimentation rates

within homogeneous massive mud units, deposited during periods of more frequent bottom-water incursion (Dallimore et al., 2005), were estimated from surrounding laminated sections.

Stratigraphic markers

Diatom analyses, coupled with extensive ^{137}Cs , ^{210}Pb and ^{14}C dating of a series of short cores recovered from Effingham Inlet, identified three diatom biostratigraphic markers in the upper portion of the sediment record (Hay, 2005). *Rhizosolenia setigera* Brightwell 1858 appeared within the sediment record ca. AD 1940 in Effingham Inlet, while *Minidiscus chilensis* Rivera 1984 appeared in the inlet ca. AD 1860. The third biomarker, a morphotype of *Thalassionema nitzschioides* Grunow ex.

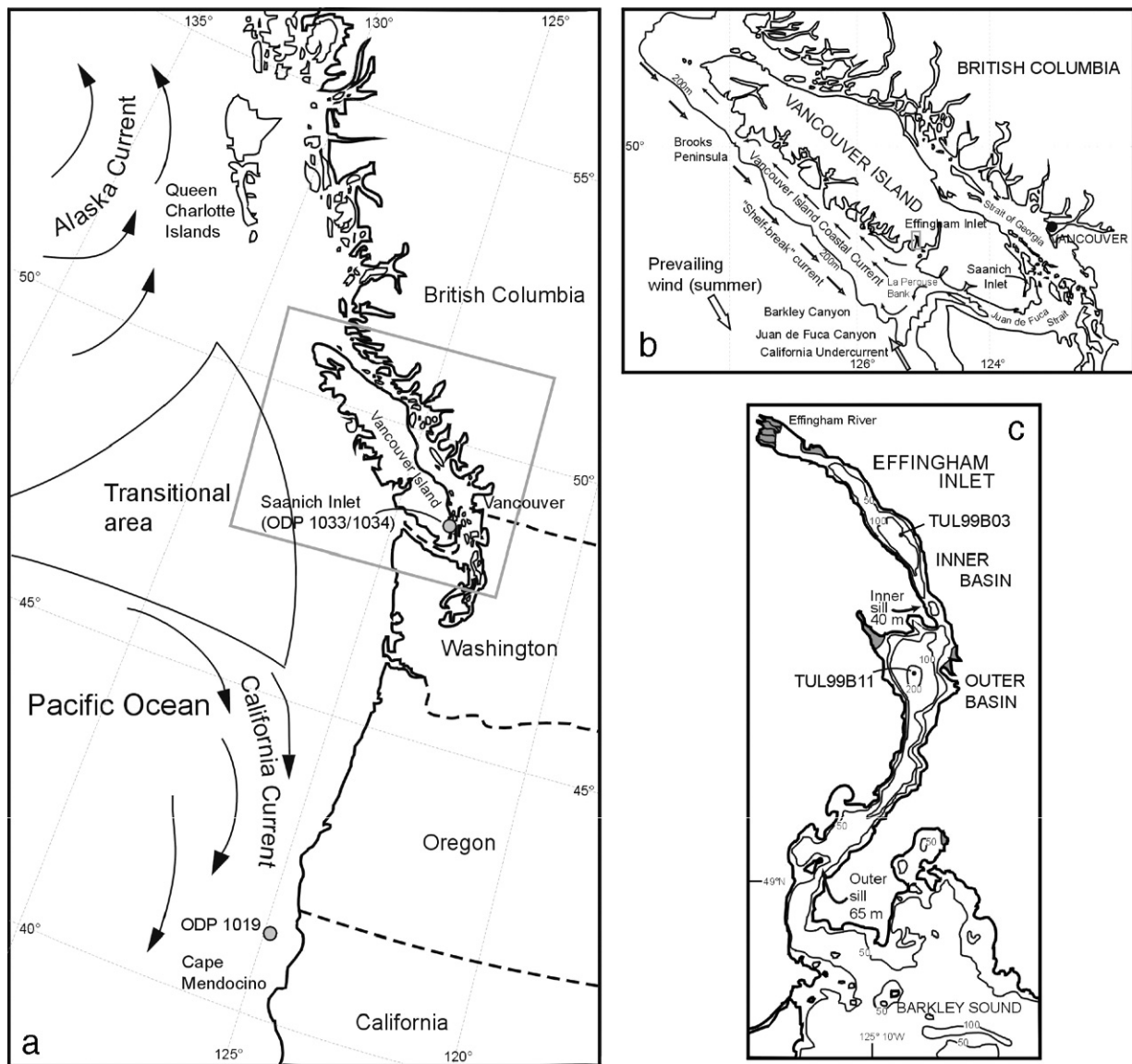


Figure 1. Location of the study area. (a) Regional overview showing major offshore currents and the location of marine cores mentioned in the text. (b) Coastal currents around Vancouver Island. A summer upwelling centre over the La Perouse Bank results from the interaction of the buoyancy-driven Vancouver Island Coastal Current, the southward flowing “Shelf-break” current and the bottom topography of the Juan de Fuca and Barkley canyons. (c) Effingham Inlet with locations of piston core stations (TUL99B03 and TUL99B11).

Mereschkowsky 1902, appeared at ca. 400 cal yr BP (AD 1550). This morphotype is characterized by a shorter (<25 μm), narrower (2–2.5 μm) and consistently linear form, relative to the nominate form that is much longer, slightly wider and often has a subtly inflated centre. These three diatom markers represent additional chronological tie points for the upper portion of the sediment records from Effingham Inlet. An extended discussion of these biomarkers is presented in Hay (2005).

Biogenic silica

Biogenic silica was determined using the technique of Mortlock and Froelich (1989). Biogenic silica (opal) is presented as BSi assuming 10% water content.

Siliceous microfossil preparation

Siliceous microfossil preparation and absolute abundance estimates followed those detailed in Hay et al. (2003). In brief, 20 mg of freeze-dried sediment were added to a scintillation vial with a few drops of 10% HCl and 4 mL of 35% hydrogen peroxide (H_2O_2). The vials were placed on a hot plate and the reaction was allowed to continue until the slurry was transparent. The vials were decanted and then refilled with distilled water at 24-h intervals for 5 days.

After pipetting 500 μL of slurry across a 18 \times 18 mm square coverslip, they were left to dry at room temperature. Coverslips were mounted using the high refractive mounting medium Naphrax[®] (refractive index = 1.78). Diatoms were identified to the lowest taxonomic level possible (e.g., variety) at a magnification of 1000 \times using a Leica DMRB microscope. Vegetative frustules of *Chaetoceros* Ehrenberg 1844, usually found with the setae detached from the valve, were included with *Chaetoceros* resting spore (r. sp.) counts. For samples from the inner basin piston core TUL99B03, a minimum of 500 valves not including *Chaetoceros* r. sp. or silicoflagellates were counted. For the outer basin piston core TUL99B11, a minimum of 400 valves were counted, not including *Chaetoceros* r. sp. or silicoflagellates.

All counts were converted to cells by dividing total counts by two. Mass accumulation rates (MAR; cells $\text{cm}^{-2} \text{yr}^{-1}$) were determined from sediment bulk density estimates for the cores and calculated sedimentation rates (Hay, 2005).

Stratigraphic zones for the diatom absolute abundance data of both cores were determined by CONICC (Constrained cluster analysis by information content) using the program psimoll 4.10 (Bennett, 2002). The validity of the CONICC-derived zones was confirmed by comparing results with other cluster analysis methods (e.g., CONISS, optimal splitting). All taxa and grouped taxa representing more than 5 individuals in at least one sample were included in the zonation analyses. For piston core TUL99B03, 94 taxa were used (representing a mean of 97.5% (1.50 std. dev.) of total counts per sample) and for piston core TUL99B11, 77 taxa were used (representing a mean of 92.7% (1.86 std. dev.) of total counts per sample). Absolute abundance data were transformed using normalized Euclidean distance.

Results

Chronology

All radiocarbon dates for piston cores TUL99B03 and TUL99B11 are presented in Table 1. The ^{14}C -calibrated age estimates for piston core TUL99B03 were in stratigraphic order. Most dated material comes from moderate to well-defined laminated sections. The lowest ^{14}C sample of wood in TUL99B03, found at 937 cm depth, was recovered from a sediment gravity-flow deposit and thus represents reworked material. This date was therefore excluded from the age–depth model. For core TUL99B11, the bottom shell date appeared anomalously young and therefore was excluded from the age–depth model for that core.

After including the biomarker depths of *Rhizosolenia setigera*, *Minidiscus chilensis* and *Thalassionema nitzschioides* with the calibrated ^{14}C shell and wood dates, linear regression analysis was used for both cores (Fig. 2). Core TUL99B03 had an age range of ca. 60–4850 cal yr BP, while core TUL99B11 had an age range of

Table 1
Radiocarbon dates for piston cores TUL99B03 and TUL99B11, Effingham Inlet

Core	Laboratory number	Description	Depth (cm)	Adjusted depth (cm)	^{14}C age with error	Calibrated age range (yr BP)	Relative probability under curve	Median probable age (cal yr BP)
TUL99B11	TO-8683	Shell fragment	531	476	2460 \pm 90	1420–1860	1	1640
	TO-8684	Shell fragment	898	797	2830 \pm 60	1930–2270	1	2080
Outer basin	TO-8685	Wood	939	837	2570 \pm 100	2360–2810	0.975	2610
	TO-8686	Shell fragment	969	867	1820 \pm 60	840–1130	1	980
TUL99B03	TO-8671	Wood	97	97	160 \pm 40	60–230	0.649	170
	TO-8672	Shell valve	169	161	1770 \pm 60	770–1060	1	920
	TO-8673	Twig	286	278	2050 \pm 70	1860–2160	0.954	2020
Inner basin	TO-8674	Twig	553	529	2830 \pm 60	2780–3080	0.968	2940
	TO-8675	Shell fragment	822	757	3890 \pm 90	3160–3610	1	3380
	TO-8676	Wood	937	842	4190 \pm 80	4510–4870	0.984	4710

Adjusted depth calculated with removal of sediment gravity flow units. Radiocarbon dates were converted to calendar years with the program CALIB v. 4.4.2. (Stuiver and Reimer, 1993). Calibration of wood material ages was based on the atmospheric data of INTCAL98 (Stuiver et al., 1998b). Age calibration for the intact marine shell was based on MARINE98 (Stuiver et al., 1998a) using a regional marine reservoir correction of 790 \pm 25 ($\Delta R=390\pm 25$). Age range represents the range having the greatest proportion under the 2-sigma curve.

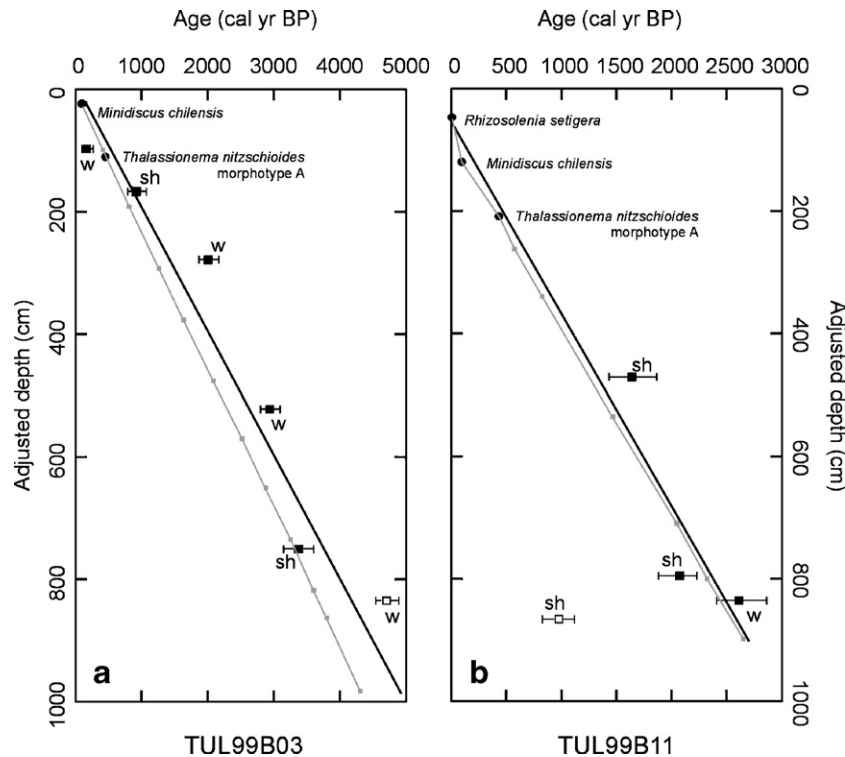


Figure 2. Age versus “adjusted” depth relationships for the core material with ^{14}C samples (filled squares; w: wood, sh: shell) are plotted with the cumulative varve chronology (grey lines) and diatom biomarker horizons (filled circles). Radiocarbon calibration used CALIB version 4.4.2 (Stuiver and Reimer, 1993), a marine reservoir correction of $\Delta R=390\pm 25$ for shell material using MARINE98 (Stuiver et al., 1998b), with wood sample calibration using INTCAL98 (Stuiver et al., 1998a). Error bars represent $2\text{-}\sigma$ error. (a) Inner basin piston core TUL99B03. Solid dark line represents a linear fit of ^{14}C samples and *Minidiscus chilensis* (AD 1860–90 cal yr BP) and *Thalassionema nitzschioides* morphotype A (AD 1550–400 cal yr BP) biomarker horizons. Thin grey line represents the cumulative varve chronology with biomarker horizon tie-points. Note that open square indicates ^{14}C sample not used in linear fit due to position within a sediment gravity flow deposit. (b) Outer basin piston core TUL99B11. Solid dark line represents a linear fit of ^{14}C samples and the *Thalassionema nitzschioides*, *Minidiscus chilensis* and *Rhizosolenia setigera* (AD 1940) biomarker horizons. Thin grey line represents the cumulative varve chronology with biomarker horizon tie-points. Note that open square indicates ^{14}C sample not used in the linear-fit model.

ca. AD 1980 to 2680 cal yr BP. For core TUL99B03, the linear age–depth model followed the varve-estimate model, although it produced a slightly older bottom age estimate (Fig. 2a). Varve thickness increased gradually downcore, although the linear model provided a consistent age–depth relationship. In core TUL99B11 from the outer basin, the varve-based age–depth model and the linear ^{14}C -based model were quite similar (Fig. 2b). This similarity occurred in spite of the scatter of the ^{14}C dates and the commonly poor preservation of the varved record for much of the core. Estimated sedimentation rates based on multiple varve counts (after exclusion of sediment gravity-flow units) were $0.212\pm 0.003\text{ cm yr}^{-1}$ and $0.351\pm 0.0372\text{ cm yr}^{-1}$ for cores TUL99B03 and TUL99B11, respectively.

Effingham Inlet siliceous microflora

The sediment record from the inner basin had a mean sampling resolution of 24 yr (std. dev. = 18.2 yr) for BSi samples and 49 yr (std. dev. = 44.5 yr) for microfossil counts along the core length of TUL99B03. Mean sampling resolution for the outer basin core TUL99B11 was 31 yr (std. dev. = 19.9 yr) and 19.5 yr (std. dev. = 18.3 yr) for the microfossil and Bsi samples, respectively. Radiolaria, sponge spicules, and ebridians (*Ebria tripartita* (Schumann) Lemmermann 1899) were rarely

observed within the sampled sediment material and will not be discussed further. Diatom and silicoflagellate absolute abundance stratigraphies are presented using the original core depth, with radiocarbon dates listed at the associated depths (Figs. 3, 4).

TUL99B03 (Fig. 3)

Zone 1 (1137–835 cm; ca. 4850–3780 cal yr BP)

This zone was characterized by some of the highest absolute abundance estimates for diatoms over the last 4850 yr in Effingham Inlet (Fig. 3). This section was also characterized by strongly laminated sediments with few intervening homogeneous mud units. *Skeletonema costatum* (Greville) Cleve 1878 was the dominant taxon, often representing greater than 70% of the diatom assemblage (excluding *Chaetoceros* resting spores (r. sp.)). Many species of *Thalassiosira*, including *T. nordenskioeldii* Cleve 1873 and *T. decipiens* (Grunow) Jørgensen 1905, were at peak late Holocene abundance. *Thalassionema nitzschioides*, as well as a group of infrequently occurring taxa associated with the outer portion of Effingham Inlet and Barkley Sound (e.g., *Pseudo-Nitzschia* spp. and *Odontella longicuris* (Greville) Hobban 1983), were also common in zone 1. *Fragilariopsis cylindroformis* (Hasle in Hasle and Booth) Hasle 1990 and *F. pseudonana* (Hasle) Hasle 1993, two taxa usually not recorded

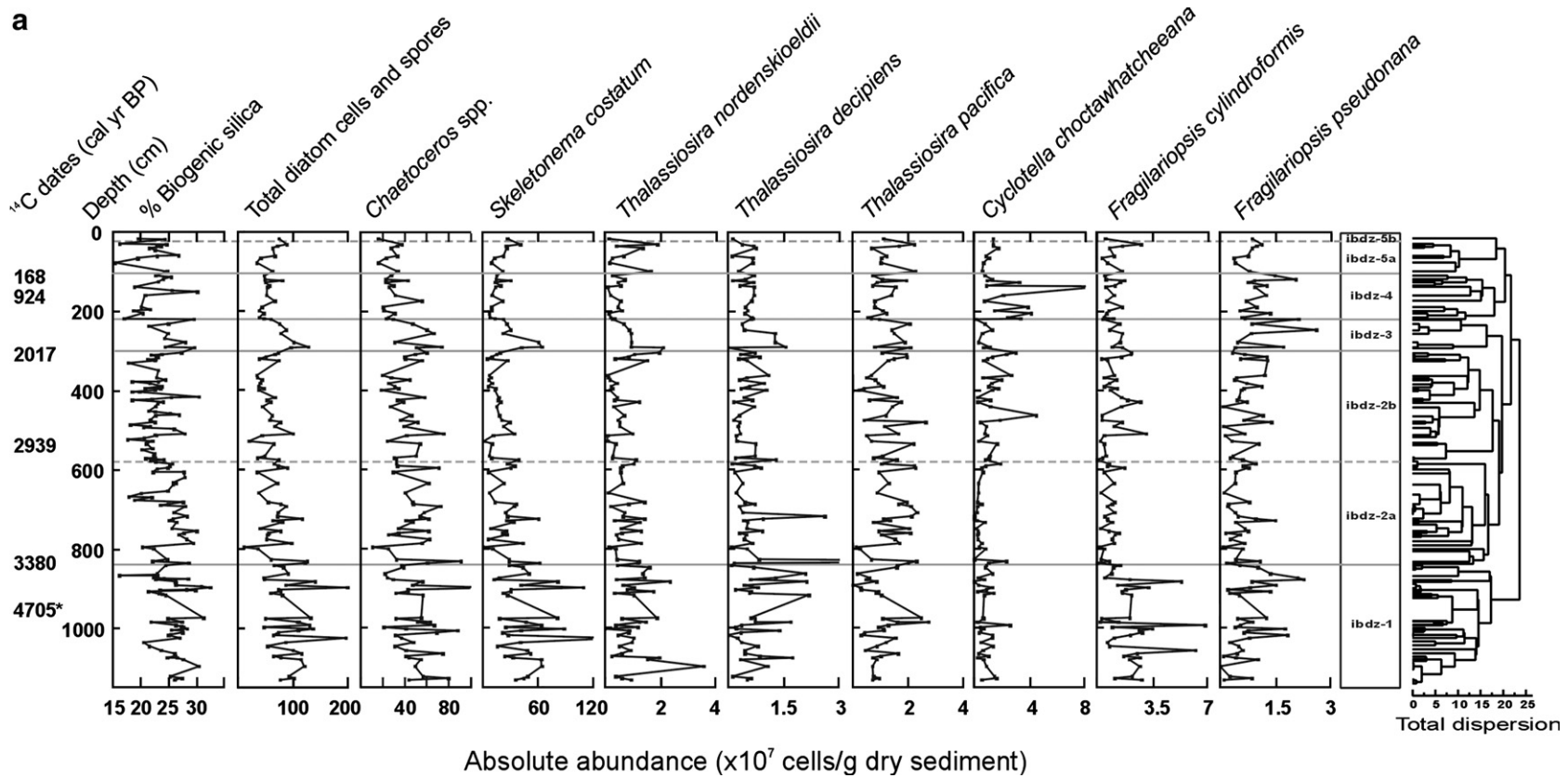
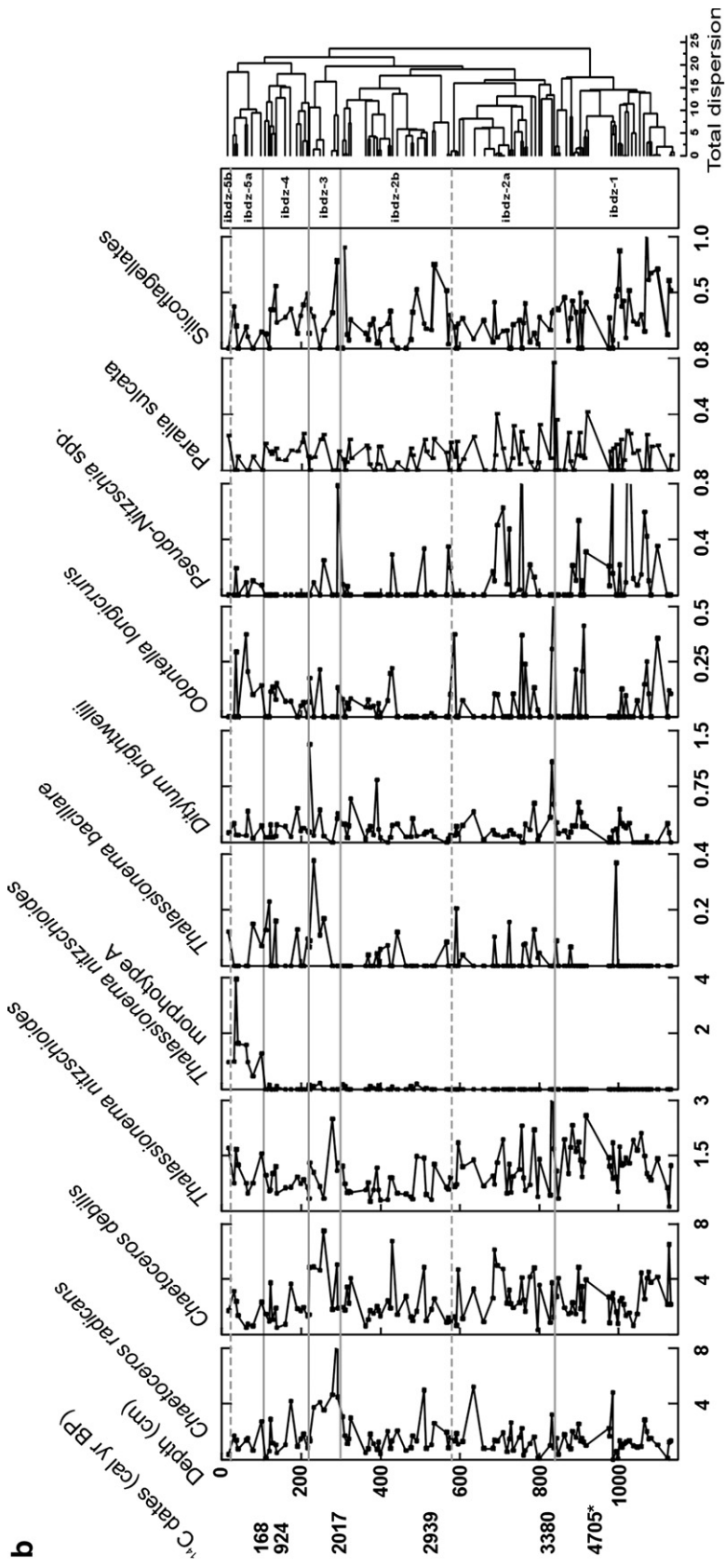


Figure 3. Absolute abundance (cells/g dry sediment) of selected diatom taxa from the inner basin piston core TUL99B03 plotted against total depth of core. Zones and dendrogram established using CONIIC (constrained clustering by information content) using Orloci's chord distance. Diatom taxa presented in the figure (including *Chaetoceros* spp.) account for a mean 78.6% of the total assemblage (5.81 std. dev.). Radiocarbon dates are presented as calibrated years BP; those with an asterisk were not used in the age–depth model. IBDZ=Inner basin diatom zone.



Absolute abundance ($\times 10^7$ cells/g dry sediment)

Figure 3 (continued).

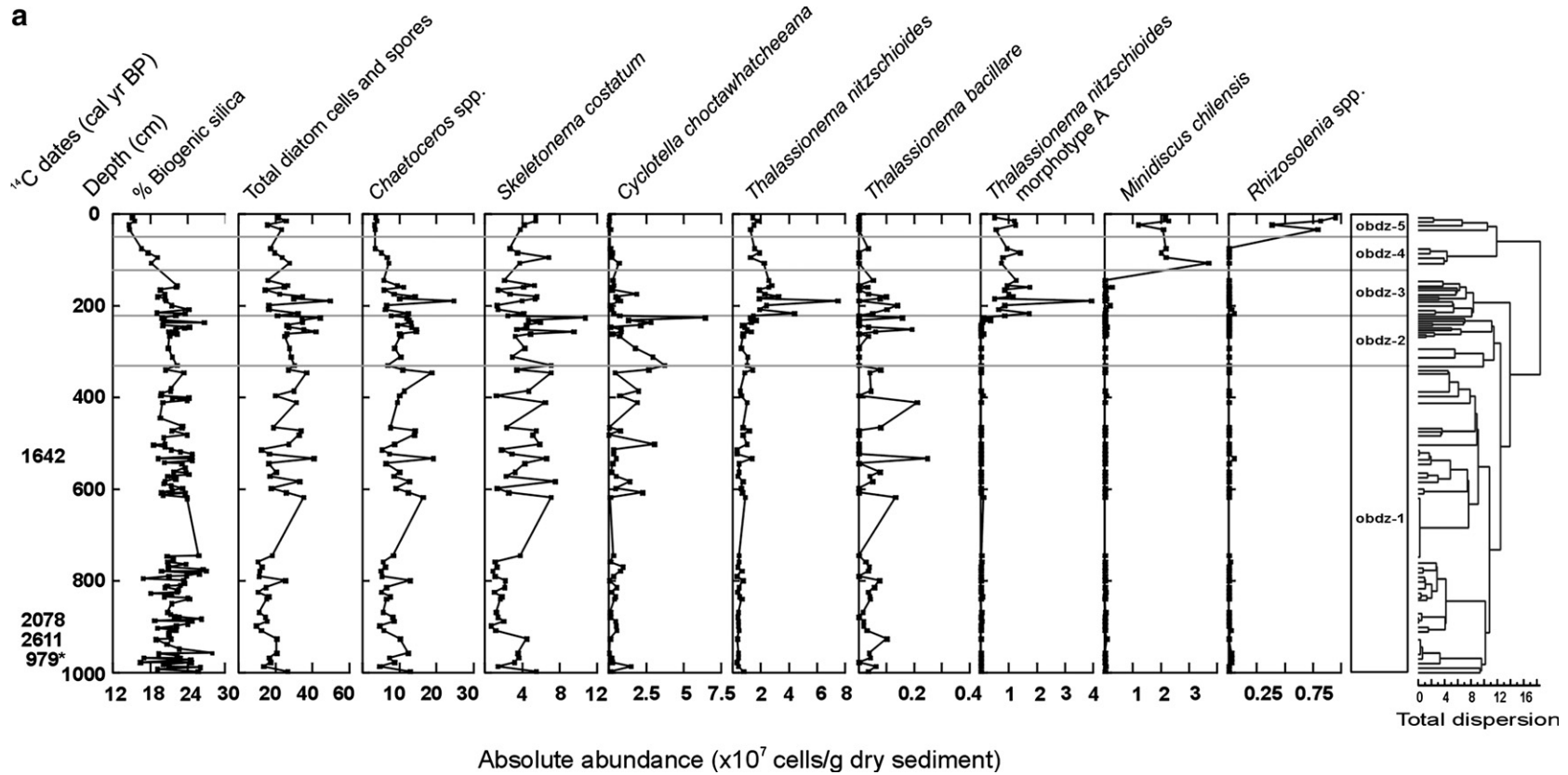


Figure 4. Absolute abundance (cells/g dry sediment) of selected diatom taxa from the outer basin piston core TUL99B11 plotted against total depth of core. Zones and dendrogram established using CONIIC (constrained clustering by information content) using Orloci's chord distance. Diatom taxa presented in the figure (including *Chaetoceros* spp.) account for a mean 71.2% of the total assemblage (5.09 std. dev.). Radiocarbon dates are presented as calibrated years BP; those with an asterisk were not used in the age–depth model. OBDZ=Outer basin diatom zone.

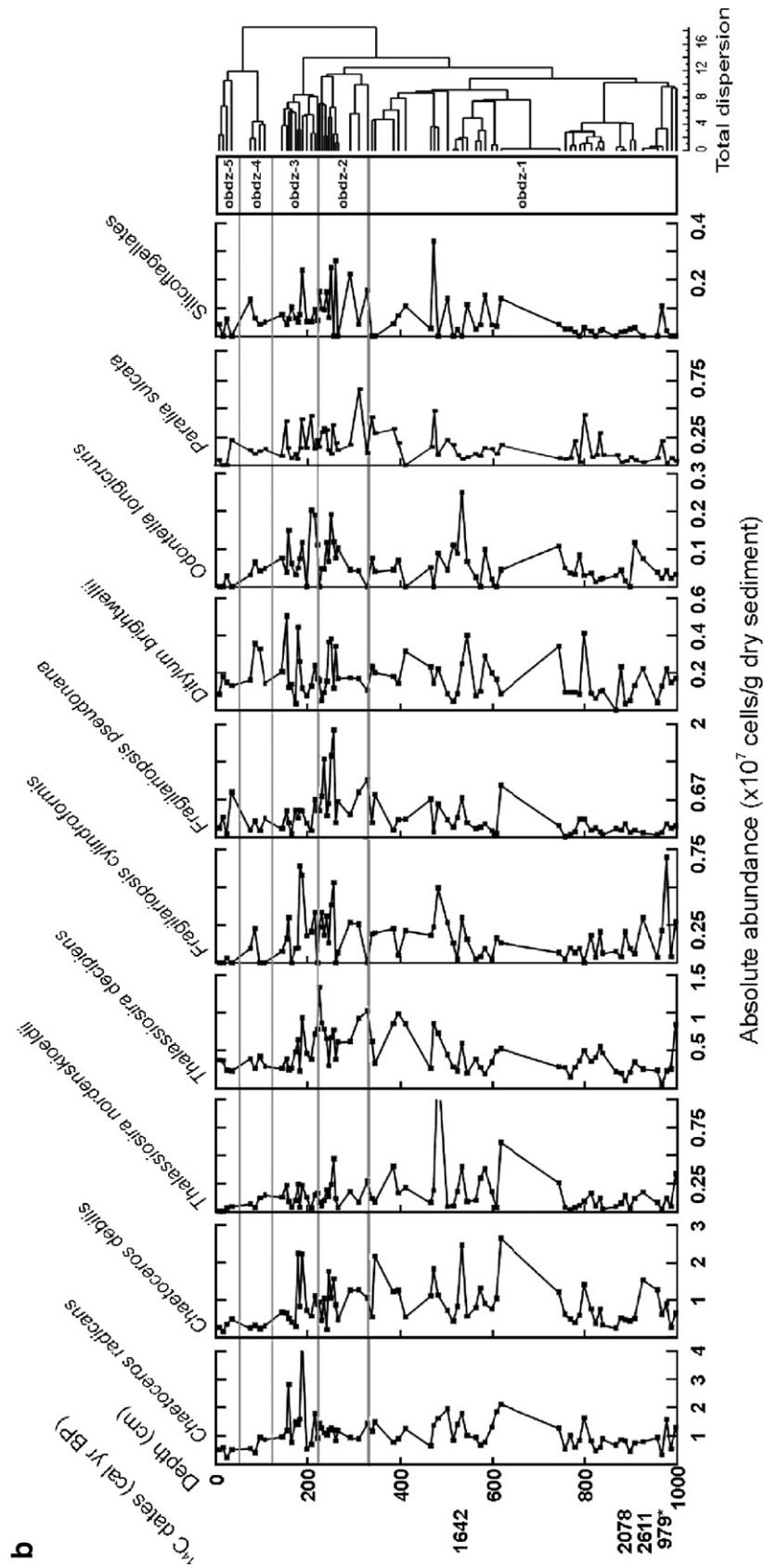


Figure 4 (continued).

from British Columbia fjords, were also found at their maximum abundance. Silicoflagellates (mostly *Dictyocha speculum* Ehrenberg 1839 with minor amounts of *Dictyocha fibula* Ehrenberg 1839) were also most abundant in this bottom zone.

Zone 2 (835–290 cm; ca. 3780–1440 cal yr BP)

Zone 2 was marked by a reduced abundance of *Skeletonema costatum* and other taxa. This zone was subdivided into two sub-zones. Diatom zone 2a (835–590 cm; 3780–2750 cal yr BP) was marked by a strong decline in diatom cell abundance, in particular *S. costatum*. Other taxa showing strong declines included *F. pseudonana* and *F. cylindroformis*, *T. decipiens*, *T. nordenskiöldii* and silicoflagellates. *Chaetoceros* resting spore abundance remained high with only a small decrease relative to zone 1. Similarly, *T. nitzschioides* experienced little or no decrease. *Thalassiosira pacifica* Gran and Angst 1931 and *Paralia sulcata* (Ehrenberg) Cleve 1873 were relatively more abundant in this zone, although overall they showed no consistent pattern along the core. BSi mirrored the *Chaetoceros* resting spore abundance and remained relatively high in this portion of the core.

Zone 2b (590–290 cm; 2750–1440 cal yr BP) was characterized by low diatom and *Chaetoceros* r. sp. abundance. For some taxa (*F. pseudonana*, *Odontella longicruris*) there was a subtle increase throughout this zone. *Cyclotella choctawhatcheeana* Prasad 1990 began to increase in importance during this period. BSi was relatively low throughout this sub-zone.

Zone 3 (290–210 cm; ca. 1440–1050 cal yr BP)

This zone was characterized by relatively high abundances of diatom cells and *Chaetoceros* r. sp., specifically *Skeletonema costatum*; numerous *Thalassiosira* spp., *T. nitzschioides*, and *F. pseudonana*; and a moderate increase in *Thalassionema bacillare* (Heiden) Kolbe 1955 and silicoflagellates. *Cyclotella choctawhatcheeana* remained low during this period. Total diatom cell concentrations, however, remained below those observed within zone 1.

Zone 4 (210–130 cm; ca. 1050–700 cal yr BP)

Zone 4 was marked by the late Holocene peak abundance of *Cyclotella choctawhatcheeana* and abundant *F. pseudonana* and silicoflagellates. These changes coincided with decreases in BSi, *S. costatum*, *T. nordenskiöldii*, and *Chaetoceros* r. sp.

Zone 5 (130–0 cm; ca. 700–70 cal yr BP)

The upper zone was defined by the appearance of a morphotype of *Thalassionema nitzschioides*, absent below this zone. Two subzones were also identified. In Zone 5a (130–25 cm), the abundance estimates for diatom taxa *Chaetoceros* r. sp. and silicoflagellates remained low, with BSi values at their lowest throughout the core. *Cyclotella choctawhatcheeana* decreased in this zone whereas *Thalassiosira nordenskiöldii* increased.

Zone 5b (25–0 cm) was distinguished by the abrupt appearance of the small centric taxon *Minidiscus chilensis* (not shown in Fig. 3) in the uppermost sample as well as a very low abundance for most other taxa.

Outer basin piston core TUL99B11 (Fig. 4)

Zone 1 (998–335 cm; ca. 2680–850 cal yr BP)

This diatom zone was characterized by (relatively) low diatom abundances especially in its lower portion. A number of diatom taxa, including *Chaetoceros* r. sp., *C. choctawhatcheeana*, *T. decipiens*, *S. costatum*, *T. nitzschioides*, *P. sulcata*, and silicoflagellates, showed an increase in the upper portion of this zone. BSi showed only small shifts within this zone.

Zone 2 (335–225 cm; ca. 850–550 cal yr BP)

Zone 2 was marked by the dominance of *C. choctawhatcheeana*, although this taxon's abundance was characterized by two peaks. Diatom abundance remained at a relatively constant level, similar to the uppermost section within zone 1. *Chaetoceros* r. sp. showed a slightly reduced abundance in this zone. *F. cylindroformis* and *F. pseudonana* were more abundant in the upper portion of this zone, as were silicoflagellates and *P. sulcata*.

Zone 3 (225–120 cm; ca. 550–90 cal yr BP)

This zone was defined by the appearance of *T. nitzschioides* morphotype A, quickly establishing itself as an important diatom in the fossil sediment assemblage. There was an increase in the nominate form of *T. nitzschioides*, reflecting, in part, the subtle differentiation between the nominate form and the morphotype. *Cyclotella choctawhatcheeana* abundance fell to extremely low values, with *Chaetoceros* r. sp. peaking in the lower part of the zone before gradually decreasing as reflected in the BSi values. *P. sulcata* remained relatively abundant. Both *Fragilariopsis* taxa declined in this zone.

Zone 4 (120–50 cm; ca. 90 cal yr BP–AD 1940)

The appearance and dominance of *Minidiscus chilensis* marks this zone. A reduced abundance of total diatom cells and *Chaetoceros* r. sp. persisted throughout this zone, with *C. choctawhatcheeana* disappearing almost entirely from the sediment record. *Odontella longicruris*, *T. bacillare*, *P. sulcata* and BSi all declined throughout this zone.

Zone 5 (50–0 cm; ca. 1940–AD 1980)

The appearance of *Rhizosolenia setigera* defines this zone. Most diatom taxa and resting spore abundance remained low, with low occurrences of *O. longicruris*, *P. sulcata*, *T. bacillare*, *C. choctawhatcheeana*, *F. cylindroformis*, and silicoflagellates. The morphotype of *T. nitzschioides* maintained a relatively high abundance. BSi values continued to decrease to reach their lowest values for the last 2750 yr in the outer basin core.

Discussion

Paleoenvironmental conditions—Effingham Inlet

The sedimentary record of Effingham Inlet reflects the heterogeneous nature of fjord environments due to their position at the interface between terrestrial, coastal and open marine systems. Although the spring bloom succession of diatoms

within British Columbia coastal inlets generally follows the *Thalassiosira–Skeletonema–Chaetoceros* pattern (Harrison et al., 1983; Sancetta, 1989; Haigh et al., 1992), the various forcings within fjord environments produce a strong interannual variability in the composition and production of the phytoplankton assemblage (Sancetta, 1989; Ziemann et al., 1991). This variability was represented by the somewhat noisy estimates of downcore diatom abundance. However, the comparable diatom zones from the inner and outer basins (Fig. 5), a significant ($P < 0.01$) pairwise correlation between BSi and total diatom abundance, as well as the striking similarity of diatom changes identified from cores in the inner and outer basins of Effingham Inlet (Fig. 6) show that reliable diatom production patterns and paleoenvironmental inferences can be retrieved from the sediment record of coastal temperate fjords.

Comparison of the inner and outer basins for selected taxa (Fig. 6) showed similar MAR patterns in both basins for the more heavily silicified taxa (e.g., *Chaetoceros* r. sp.), while preservation of more dissolution-susceptible taxa (e.g., *S. costatum*) was clearly favoured in the inner basin sediments. The timing of diatom appearances often matched in both cores (e.g., *Minidiscus chilensis*, *Thalassionema nitzschioides* morphotype A) as did some distinct peaks in abundance for selected taxa (e.g., *Cyclotella choctawhatcheeana*, *Odontella longicruris*, *Fragilariopsis pseudonana*). Taxa such as *Ditylum*

brightwellii (West) Grunow in Van Heurck 1883, *Thalassionema nitzschioides*, *Odontella longicruris*, *Paralia sulcata* and *Thalassiosira decipiens*, found by Hay et al. (2003) to be more abundant in surface sediments towards the outer portion of the fjord, also showed a more persistent occurrence in the outer basin core. An understanding of inter-basin differences in preservation and distribution of microfossils in the sediment record is clearly critical for proper paleoenvironmental reconstruction.

The late Holocene diatom record from Effingham Inlet was dominated by taxa associated with the spring–early summer blooms represented by *Skeletonema costatum* as well as several species of *Thalassiosira*, *Chaetoceros*, and *Fragilariopsis*. *Skeletonema costatum* is a widely distributed neritic taxon common in spring blooms along the coast of British Columbia (Sancetta, 1989; Haigh et al., 1992). *Skeletonema costatum* is limited by low temperatures (Smayda, 1973) and reduced light incidence (Hitchcock and Smayda, 1977) and tends to follow low-light-adapted *Thalassiosira* spp. (e.g., *T. nordenskiöldii*) within the bloom sequence in British Columbia fjords (e.g. Haigh et al., 1992). Elevated *S. costatum* production requires a good re-supply of nutrients into the fjord, bloom periods with relatively warm waters and high light incidence (i.e. fewer clouds and less coastal fog). This taxon is rarely preserved in open ocean sediments and its presence within the sediment record reflects a high production and a rapid transfer to the

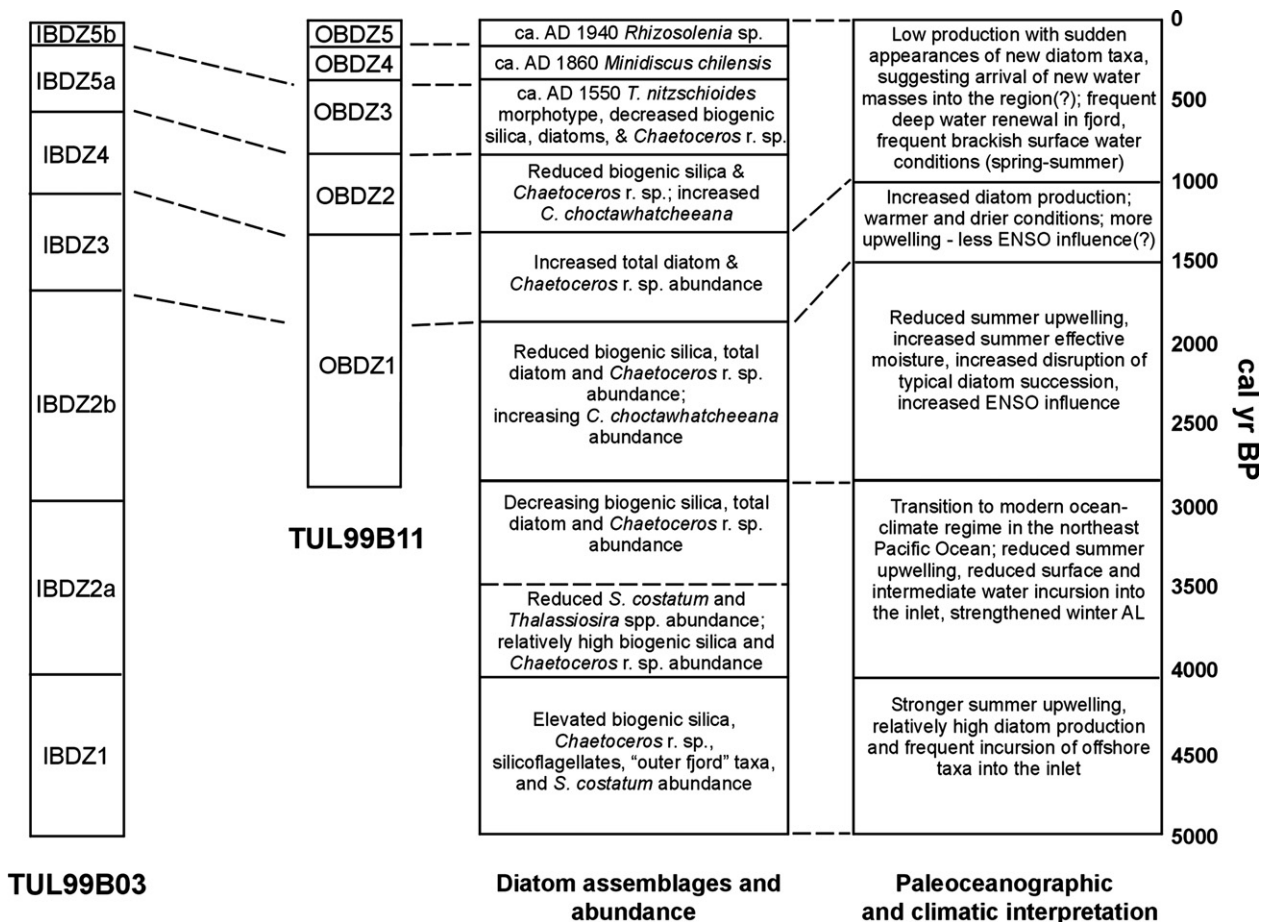


Figure 5. Diagram showing correlation between paleoenvironmental interpretations of piston cores TUL99B03 and TUL99B11 with a summary of diatom changes in Effingham Inlet. AL=Aleutian Low, ENSO=El Niño Southern Oscillation, IBDZ=Inner basin diatom zone, OBDZ=Outer basin diatom zone.

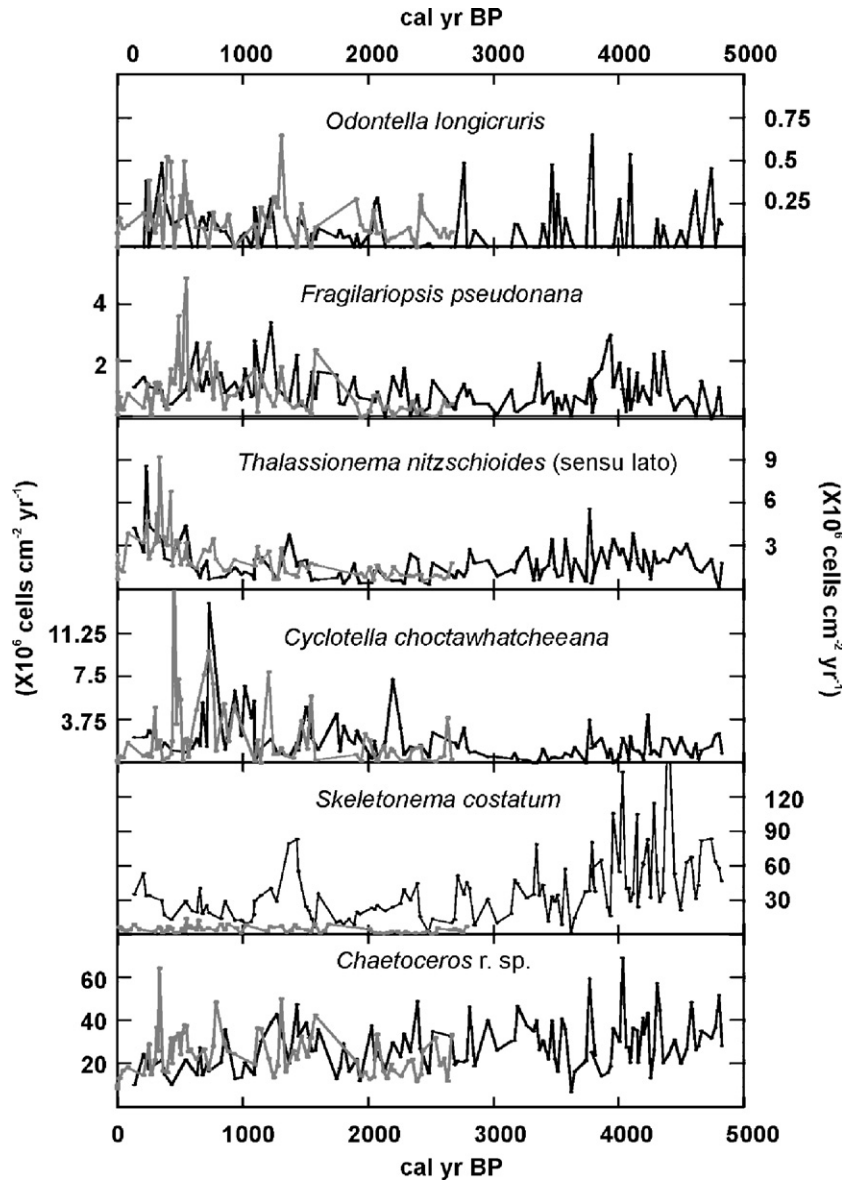


Figure 6. Comparison of mass accumulation rates (MAR $\times 10^6$ cells/cm²/yr) of selected diatom taxa from piston cores TUL99B03 and TUL99B11. Grey lines and points represent TUL99B11 samples. Dark lines and points represent TUL99B03 samples.

sediment, and a reduced dissolution in the bottom waters and sediment.

Chaetoceros r. sp. are often used as a proxy for higher marine production, as their presence is often associated with coastal upwelling (Sautter and Sancetta, 1992). They are major constituents of the phytoplankton of British Columbia fjords from late spring through fall (Sancetta, 1989; Haigh et al., 1992; McQuoid and Hobson, 1997). *Chaetoceros* spp. tend to dominate following *S. costatum* blooms and also throughout the summer, when offshore waters penetrate into coastal inlets bringing nutrients into the photic zone (Takahashi et al., 1977).

Fragilariopsis pseudonana and *F. cylindroformis* have not been previously identified from British Columbia fjords. *F. pseudonana* has been listed previously under different names (e.g., *Nitzschia nana*, *Nitzschia pseudonana*) and tends to be associated with pelagic conditions (Sautter and Sancetta, 1992),

although Cremer et al. (2003) noted *F. pseudonana* within coastal marine assemblages in East Antarctica. *F. pseudonana* was an important component of the spring bloom assemblage in sediment trap samples recovered from the inner basin and entrance to Effingham Inlet (A. Chang, Carleton University, Ottawa, Ontario, personal communication, 2004). However, its ecological preferences and its relationship with *S. costatum* and other spring–early summer bloom taxa remain poorly constrained.

Elevated abundance of spring–summer diatom taxa from 4850 to 4000 cal yr BP testifies to favourable conditions for diatom production. This in-fjord production was coupled with an increase of diatom taxa associated with summer and fall intrusions of water from outside the fjord (i.e., *T. nitzschioides*, *Pseudo-Nitzschia* spp., *O. longicruris*, *D. brightwellii*, *Coscinodiscus* spp. and silicoflagellates). The fossil diatom assemblages infer more frequent incursions of nutrient-rich offshore

waters into the fjord with upwelling strength and duration off the west coast of Vancouver Island being greater during this time relative to the last 4000 cal yr BP. Strongly laminated sediments prior to 4000 cal yr BP attest to continuous anoxic conditions and limited bottom water ventilation.

At ca. 4000 cal yr BP, numerous diatom taxa experienced significant declines in abundance, notably *S. costatum*, both *Fragilariopsis* taxa, and *T. decipiens*. Other diatoms, including *Chaetoceros* r. sp. and *T. nitzschioides*, as well as biogenic silica values experienced a brief decrease from ca. 4000 to 3600 cal yr BP, before recovering close to prior maxima. These taxa subsequently declined beginning ca. 3200 through 2800 cal yr BP.

Diatom production within Effingham Inlet remained low from ca. 2800 to 1750 cal yr BP. However, after ca. 2800 cal yr BP, *Cyclotella choctawhatcheeana* abundance increased (Fig. 6). Sancetta (1989) noted that *Cyclotella caspia* (likely the same species as *C. choctawhatcheeana* (see Håkansson et al., 1993)) was observed in the modern plankton of Jervis Inlet, a fjord along the mainland of southern British Columbia. It was most abundant when increased spring river discharge reduced salinities (11.5–13.6‰) and increased the turbidity of surface waters. These conditions favoured *C. caspia*, while the expected spring bloom of *S. costatum* and *Thalassiosira* spp. was limited. A similar inverse relationship between *C. choctawhatcheeana* and the typical spring–summer bloom flora was observed in sediment cores recovered from Effingham Inlet (Hay, 2005).

Prasad et al. (1990) noted that *C. choctawhatcheeana* was limited by salinities >20‰ in Choctawhatchee Bay, Florida. In the Baltic Sea, this taxon prefers coastal, brackish (8–10‰ optimum salinity; 2 to 20‰ range) waters (Håkansson et al., 1993; Ryves et al., 2004). Therefore, surface conditions favouring abundant *C. choctawhatcheeana* and a limited typical spring–summer bloom sequence would require either increased spring precipitation or a deeper winter snow pack, leading to an enhanced spring–summer freshet marked by increased turbidity and a reduced salinity in the surface waters of Effingham Inlet (Hay, 2005).

More frequent conditions of reduced salinity (increased runoff) within Effingham Inlet since 2800 cal yr BP is supported by sedimentological interpretations of these cores (Dallimore et al., 2005), an increase of river-bourne thecamoebians (Schell, 2003) in piston core TUL99B03, and regional pollen records inferring more moist and cold conditions (Hebda, 1995).

Within both the inner and outer basin piston cores, the sediment record since ca. 2800 cal yr BP has also been marked by less clearly defined laminations and a more common occurrence of homogeneous massive mud units representing deep-water renewal events (Dallimore et al., 2005). During these deep-water renewal events, aided by increased water column stratification due to reduced surface salinity, sediment material is transported from the outer portion of the fjord towards the outer and inner basins. Diatom taxa found in greater abundance within surface sediments in the outer basin and channel leading to Barkley Sound (Hay et al., 2003) also become reworked and re-deposited within the inner portion of Effingham Inlet.

An increase in BSi, spring diatom taxa, *Chaetoceros* r. sp., and diatom taxa associated with offshore and late summer–fall conditions was evident between ca. 1440 and 1050 cal yr BP. In contrast, *C. choctawhatcheeana* abundance was low. The increased presence of both spring–summer bloom taxa (*Chaetoceros* r. sp., *S. costatum*, *Thalassiosira* spp.) and summer and fall taxa would suggest that climate conditions favoured strong spring–summer blooms (e.g., less cloudiness) coupled with a possible increase in upwelling and/or greater penetration of nutrients and offshore waters into Effingham Inlet.

Following this period of increased diatom production, *S. costatum* and *Chaetoceros* r. sp. abundance decreased dramatically, while *C. choctawhatcheeana* reached a maximum absolute abundance between ca. 1050 and 700 cal yr BP. After ca. 700 cal yr BP, *C. choctawhatcheeana* abundance was reduced, reaching an almost complete absence in the late 20th century sediments in piston core TUL99B11 and in box and freeze cores recovered from Effingham Inlet (Hay, 2005). *Chaetoceros* r. sp. have continued to decrease in abundance through to the present day with minimal values occurring in the late 20th century (Hay, 2005).

The most recent 750 yr have been marked by a relatively low abundance of *S. costatum* and *Chaetoceros* r. sp., despite the moderately high abundance peaks of some taxa associated with the outer portion of Effingham Inlet (e.g., *Odontella longicruris*, *T. nitzschioides*, *Paralia sulcata* and silicoflagellates). As sedimentary units within this period are poorly laminated or homogeneous, peaks in abundance of these taxa over the last 750 yr likely represent an increased frequency of deep-water renewal events in Effingham Inlet and the transport of re-worked sediment and microfossils, rather than surficial or intermediate-layer incursions of water into the fjord.

Regional late Holocene paleoclimate–paleoceanography

The patterns observed in the diatom record of Effingham Inlet are consistent with regional marine and terrestrial paleoenvironmental records (Fig. 7). The overall decrease in the diatom production (Figs. 7a, b) within Effingham Inlet over the last 4850 yr correlates with decreased summer insolation associated with a gradual weakening of the North Pacific High and increasing dominance of the Aleutian Low over the northeast Pacific (Kutzbach et al., 1993; Barron et al., 2003). This progression resulted in cooler summer temperatures and an increase in precipitation along the west coast of British Columbia, Washington and Oregon (Pellatt and Mathewes, 1997; Long and Whitlock, 2002). These conditions produced a decreased regional fire frequency (Long et al., 1998; Long and Whitlock, 2002) and fostered glacier advances in the Coast Mountains of British Columbia (Ryder and Thomson, 1986) (Figs. 7f, g, h). More frequent suppression of blooms due to increased cloud cover would have been likely. Increased precipitation could have resulted in greater stratification of the upper water layer of the inlet, suppressing vertical tidal mixing over the sills. As a result, intruding nutrient-rich coastal waters would be more likely to slide over the inner and

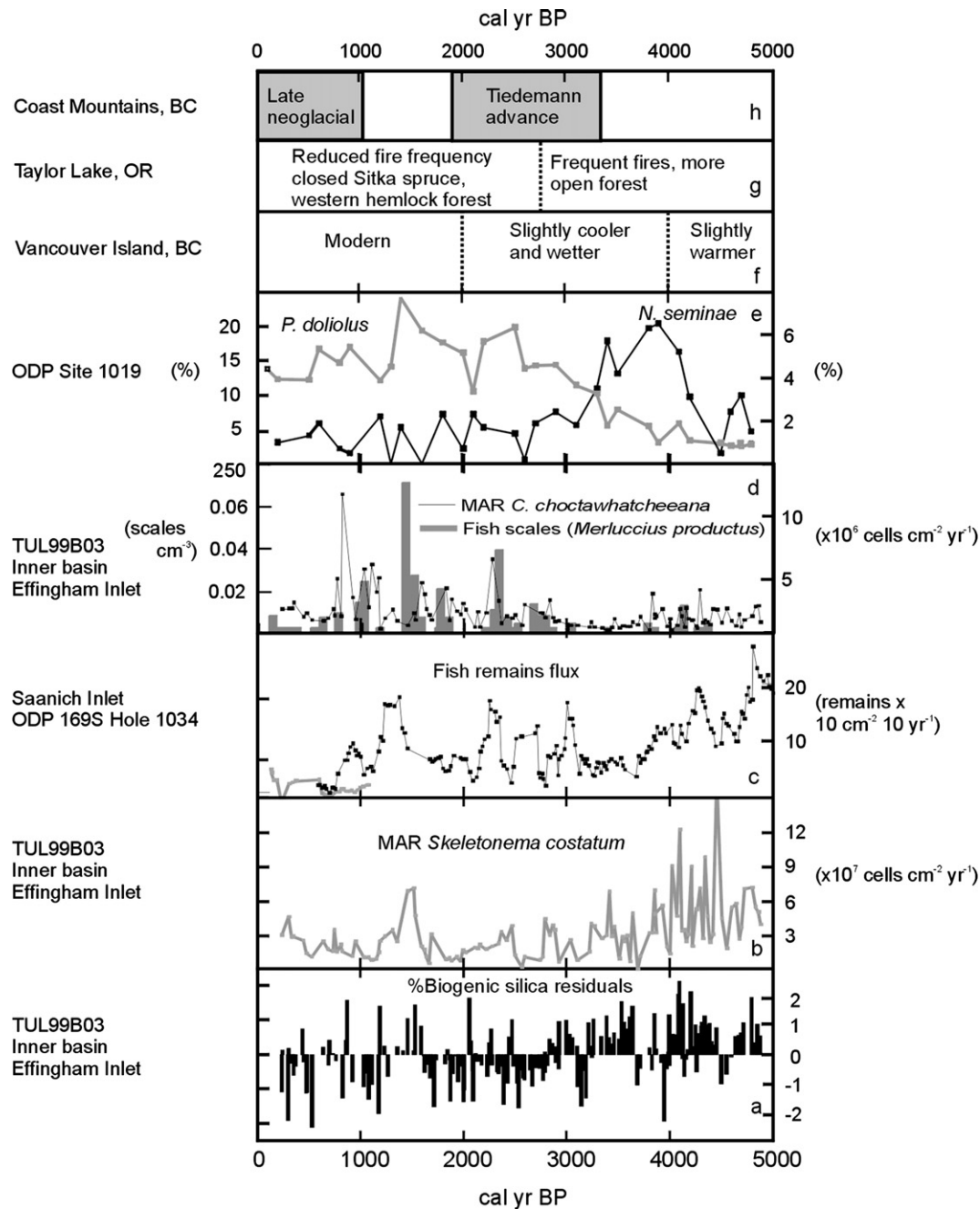


Figure 7. Comparison of the Effingham Inlet diatom record with other regional marine and terrestrial records. (a) Residual BSi in core TUL99B03, inner basin Effingham Inlet; (b) Mass accumulation rates (MAR) of *Skeletonema costatum* from TUL99B03; (c) flux of fish remains from ODP Leg 169S, Site 1034, Saanich Inlet, British Columbia (data from Tunnicliffe et al., 2001); (d) MAR of *Cyclotella choctawhatcheana* and Pacific hake (*Merluccius productus*) fish scales/ cm^3 from TUL99B03 (fish scale data from Wright et al., 2005); (e) relative abundance of *Pseudonotia doliolus* and *Neodenticula seminae* from ODP site 1019, Oregon coast (data from Barron et al., 2003); (f) climate patterns of Vancouver Island based on pollen assemblages (Hebda, 1995); (g) climate patterns from Taylor Lake, Oregon (Long and Whitlock, 2002); (h) glacial advances, Coast Mountains, British Columbia (Ryder and Thomson, 1986).

outer sills into the deeper portions of the basin rather than penetrating to intermediate depths where they would fuel higher surface production (Dallimore et al., 2005). The period from 4000 to 2800 cal yr BP therefore represents a transition period as summer insolation decreased, thereby reducing production of spring–early summer diatoms due to a less favourable climate. These decreases were coupled to a reduction in favourable upwelling conditions and a less

frequent advection of offshore waters at shallow to intermediate depths into the inner basin of Effingham Inlet.

Barron et al. (2003) suggested that the modern ocean–climate regime was established ca. 3200 cal yr BP at ODP Site 1019 off the Oregon coast (Fig. 7e). The increased strength of the Aleutian Low and the establishment of the current position of the North Pacific Front led to a weakening of the California Current (reduced abundance of the subarctic diatom *Neodenti-*

cula seminae (Simonsen and Kanaya); Akiba and Yanagisawa 1990), increased winter SSTs and to a greater influence of the warm central gyre (increased abundance of the warm-water diatom *Pseudoeunotia doliolus* Grunow in Van Heurck 1881) off the Oregon coast (Barron et al., 2003). The timing coincides with the shift to reduced diatom production and limited offshore influence in Effingham Inlet. During this period, fjords along southern British Columbia were marked by reduced diatom production of spring and summer bloom taxa (McQuoid and Hobson, 2001), decrease in varve thickness (Dallimore, 2001; Nederbragt and Thurow, 2001), and decline in fish production (Tunnicliffe et al., 2001) (Fig. 7c).

Increased diatom production between ca. 1440 and 1050 cal yr BP relates to increased regional upwelling and/or warmer–drier conditions favouring strong spring–summer diatom blooms (and less frequent suppression of these blooms by brackish surface-water conditions). A number of regional events also coincide with this productive period in the Effingham Inlet sediment record. In Saanich Inlet, pelagic fish abundance was higher between 1500 and 1100 cal yr BP (Fig. 7c). Long and Whitlock (2002) documented a small increase in fire frequency along coastal Oregon between 1800 and 1200 cal yr BP, suggesting reduced effective moisture. Coast range glaciers that had experienced a “Neoglacial” corresponding to the “Tiedemann advance” (Ryder and Thomson, 1986) showed a hiatus from 1500 to 1100 cal yr BP prior to the latest Holocene advances (Fig. 7h), inferring drier winter conditions because they are dependent to a large degree on winter snowfall accumulation. The paleoceanographic record of Effingham Inlet appears coupled to larger, regional-scale climate patterns of the late Holocene.

Barron et al. (2003) also noted an increased variability of pollen assemblages after 3200 cal yr BP and proposed increased climate variability linked to a heightened El Niño influence in the northeastern Pacific Ocean. Decreased summer and winter insolation over the late Holocene has been modelled to produce a higher frequency and magnitude of El Niño events after 5000 cal yr BP (Clement et al., 2000). Coupled with a stronger Aleutian Low, the impact of these El Niño events was more readily transferred poleward along the west coast of North America. At present, El Niño events have a greater impact on the northeast Pacific when the winter Aleutian Low is relatively strong and positioned more to the east (Gershunov et al., 1999). La Niña events are most influential in the region when the Aleutian Low is relatively weak and displaced westward.

Sediment diatom assemblages from Effingham Inlet also support the suggestion of increased El Niño–La Niña influence along Vancouver Island after 2800 cal yr BP. The increase of the brackish water species *C. choctawhatcheeana* (Fig. 7d) and more frequent suppression of spring–summer diatom blooms due to less saline surface conditions in the fjord likely reflect this stronger influence. Increased winter snowfall as well as increased spring precipitation and spring snowmelt flooding are favoured during La Niña winters, in particular when the Aleutian Low is relatively weak (Bitz and Battisti, 1999; Barlow et al., 2001). Coupled with this increase of *C. choctawhatcheeana*, fossil fish scales of northern anchovy (*Engraulis mordax*

mordax Girard 1854) and Pacific hake (*Merluccius productus* Ayres 1855) recovered from piston core TUL99B03 also became more abundant after 2800 cal yr BP (Wright et al., 2005). At present, Pacific hake are more abundant off Vancouver Island during El Niño events when coastal SSTs are increased, allowing a more northern extension of its normal range. Similarly, a greater abundance of northern anchovy along Vancouver Island appears to be related to weakened upwelling and warmer sea surface temperatures (Wright et al., 2005). The sediment fossil record from Effingham Inlet therefore suggests that both El Niño (Pacific hake scales) and La Niña (*C. choctawhatcheeana* and increased runoff) events had a greater influence along Vancouver Island with the establishment of the modern ocean–climate regime (Fig. 7d). Although the record from Effingham Inlet may suggest an increased El Niño–La Niña after 2800 cal yr BP, we cannot determine whether this increase was related to strengthened El Niño–La Niña events in the tropical Pacific or to increased poleward propagation of these events to mid-latitudes through the coastal ocean (Kelvin) wave guide or through atmospheric teleconnections.

One intriguing possibility is that the appearance of three new diatom species in Effingham Inlet over the last 500 yr may reflect this increased influence of El Niño along the British Columbia coast. During strong El Niño events, weakening of the California Current and accompanying poleward displacement of upper ocean isotherms along the continental margin allows for a northward migration of southern zooplankton species off the British Columbia and Alaska coasts (Mackas et al., 2001; Zamon and Welch, 2005). A similar influence on phytoplankton would allow the seeding of anomalous diatom taxa along coastal British Columbia during strong El Niño years. Further coring of northeast Pacific coastal regions may determine if a northward time-transgressive spread of these taxa did occur and specify the precise nature of these species' appearances.

Conclusions

Siliceous microfossil abundance within a pair of cores recovered from Effingham Inlet, Vancouver Island, reflect oceanographic and climatic conditions over the last ca. 4850 yr. Diatom production declined between ca. 4000 and 2800 cal yr BP, as a solar insolation-related decrease in the strength of the North Pacific High and concomitant increase of the winter Aleutian Low established the modern climate regime by ca. 2800 cal yr BP. This produced cooler and moister conditions and a reduction in upwelling strength off the west coast of Vancouver Island. An increased El Niño–La Niña influence after ca. 2800 cal yr BP resulted in more frequent disruption of diatom spring–summer bloom patterns and more frequent periods of reduced salinity in Effingham Inlet. A brief period of more productive conditions between ca. 1450 and 1050 cal yr BP was correlative with increased regional primary and marine fish production. The last 500 yr have been marked by reduced diatom production and the sudden appearance of two diatom taxa and a distinct diatom morphotype in the sedimentary record. The diatom record from Effingham Inlet illustrates the role of changing North Pacific

climate patterns during the late Holocene on regional marine production.

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