High resolution dinoflagellate cyst record of environmental change in Effingham Inlet (British Columbia, Canada) over the last millennium

Manuel Bringué a,⁎, Vera Pospelova a, Stephen E. Calvert b, Randolph J. Enkin c, Terri Lacourse d, Tara Ivanochko b

a School of Earth and Ocean Sciences, University of Victoria, BC, Canada
b Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, BC, Canada
c Geological Survey of Canada-Pacific, Sidney, BC, Canada
d School of Earth and Ocean Sciences, University of Victoria, BC, Canada

Article history:
Received 15 May 2015
Received in revised form 1 October 2015
Accepted 18 October 2015
Available online 26 October 2015

Keywords:
Primary productivity reconstructions
Warming in the second half of the 20th century
Little Ice Age
Medieval Climate Anomaly
Laminated sediments
Paleoseismicity

Abstract
We present a high resolution sedimentary record of dinoflagellate cysts spanning the last ~900 years recovered from Effingham Inlet, a glacial fjord on the west coast of Vancouver Island, Canada. The combination of seasonal coastal upwelling supporting high levels of marine primary productivity in surface waters, together with restricted bottom water circulation in the silled fjord, fosters the preservation of laminated sediments in the inner basin of Effingham Inlet. Geochemical data are used to assess the sedimentary facies of the core, which is composed primarily of laminated units (50.2%) occasionally interrupted by “seismites” (39.5%) and homogenous units (10.2%). The chronology of the ~2 m-long core is based on varve counting and fifteen 14C dates, and is anchored by a seismites previously dated at AD 1946. The dinoflagellate cyst assemblages are diverse (total of 47 taxa), abundant (average concentrations of 102,900 cyst g⁻¹ of dry sediment), and characterized by a proportionally equal contribution of autotrophic and heterotrophic cyst taxa in most samples. Overall, cyst assemblages are characterized by Operculodinium centrocarpum (36.2%) accompanied by Brigantedinium spp. (18.0%) and Dubridinium spp. (6.6%). Multivariate analyses are used to extract the dominant patterns of variability in autotrophic and heterotrophic dinoflagellate cyst assemblages separately, and help in identifying the temperature and primary productivity gradients encoded in the cyst sedimentary record in this particular estuary. Specific intervals identified in the dinoflagellate cyst record are interpreted to represent the local expression of the “Medieval Climate Anomaly” (from the base of the record, ~AD 1090 to 1230), the “Little Ice Age” (~AD 1230 to late 19th century) and warming in the second half of the 20th century. The timing of these intervals are consistent with the regional paleoclimate and help constrain past climatic and oceanographic variability on the west coast of Vancouver Island. The origin of homogenous units in the sedimentary record of Effingham Inlet and paleoseismicity in the region are also discussed.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Recent observations of globally rising temperatures have highlighted the necessity of putting 20th century warming into the context of long-term climatic variability. Within the last millennium, sometimes regarded as a time of relative climate stability (e.g., Clague et al., 2009), generally warmer and cooler intervals known as the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA), respectively, have been recognized from various climate proxy records such as glacier fluctuations, tree rings, ice cores and marine sediments (e.g., O'Brien et al., 1995; Stuiver et al., 1995; Smith and Larouque, 1996; Cronin et al., 2003; D’Arrigo et al., 2005, 2006; Eiriksson et al., 2006; Graham et al., 2007; Mann et al., 2009; Menounos et al., 2009; Ribeiro et al., 2012; Harland et al., 2013). However, the climatic expression of such intervals is not spatially uniform and strong regional discrepancies have been documented in the timing or even in the direction of change (e.g., D’Arrigo et al., 2005; Graham et al., 2007; Mann et al., 2009). Along the Pacific coast of southern British Columbia (henceforth, BC), western Canada, only a few studies have provided fragmented insights on the local expressions of the MCA and LIA (Gavin et al., 2003; Patterson et al., 2004; Marshall et al., 2009; Vázquez Riveiros and Patterson, 2009) and the detailed history of climatic and oceanographic variations over the past millennium has yet to be determined.

Here we present a high resolution record of dinoflagellate cysts from a sediment core collected in Effingham Inlet, a silled glacial fjord located on the west coast of Vancouver Island (BC, Canada). The accumulation of predominantly laminated sediments in the inlet’s inner basin over most of the Holocene (Dallimore et al., 2005; 2008), together with the fjord’s key location on the Pacific coast in the Cascadia Subduction Zone, have led many...
investigators to study the hydrology and sedimentary geology of the inlet (e.g., Patterson et al., 2000, 2004; Chang et al., 2003; Dallimore et al., 2005, 2008; Ivanochko et al., 2008a; Hay et al., 2009; Enkin et al., 2013), microfossil distribution in surface sediments for foraminifers (Patterson et al., 2000), dinoflagellate cysts (Kumar and Patterson, 2002; Radi et al., 2007) and diatoms (Hay et al., 2003), as well as diatom, dinoflagellate and fish paleo productivity (Patterson et al., 2005, 2011, 2013; Wright et al., 2005; Hay et al., 2007; Ivanochko et al., 2008a; Chang et al., 2013), paleoclimate (Chang et al., 2003; Patterson et al., 2004, 2011, 2013; Chang and Patterson, 2005; Hay et al., 2007; Ivanochko et al., 2008b) and local paleoseismicity (Dallimore et al., 2005, 2008; Enkin et al., 2013).

Dinoflagellates are one of the major groups of phytoplankton in coastal and estuarine waters both in terms of diversity and biomass (e.g., Taylor, 1987). About half of the dinoflagellate species are autotrophic and contribute directly to primary productivity, while the other half are heterotrophic and feed mainly on diatoms and smaller flagellates, although mixotrophy is also common (e.g., Dale, 1996; Jacobson and Anderson, 1996). As part of their life cycle, many dinoflagellates produce resting cysts which are highly resistant to physical, chemical and biological degradation (e.g., Dale, 1976, 1996; Versteegh and Blokker, 2004). Although some taxa may be sensitive to oxidative degradation within bottom sediments (e.g., Dale, 1976; Zonneveld et al., 1997, 2008), the dinoflagellate cysts recovered from Effingham Inlet sediments are diverse and abundant (e.g., Kumar and Patterson, 2002; Radi et al., 2007; Patterson et al., 2011), and they are minimally affected by oxidation in the inner basin sediments, where bottom waters are almost permanently anoxic (e.g., Patterson et al., 2000; Dallimore et al., 2005). Thus, cyst abundances in these sediments provide a record, although fragmentary, of the phytoplanktonic populations that formerly thrived in the basin. In the Northeastern (NE) Pacific, and in particular in Effingham Inlet, sea-surface temperature (SST), salinity (SSS) and primary productivity have been identified as the major factors controlling the composition of cyst assemblages (e.g., Radi and de Vernal, 2004; Radi et al., 2007; Pospelova et al., 2008; Limoges et al., 2010; Bonnet et al., 2012). In addition, recent sediment trap studies from the region have shown that cysts produced by heterotrophic dinoflagellates, in particular from the family Protoperidiniaceae, can be used as additional indicators of diatom abundance in sedimentary records (Pospelova et al., 2010; Price and Pospelova, 2011; Bringué et al., 2013).

In this study, we use changes in dinoflagellate cyst assemblages to reconstruct past variations in phytoplanktonic communities, which respond to climatic and oceanographic changes in the inlet, over the last millennium. In particular, we seek to identify changes in the dinoflagellate cyst assemblages that reflect variations in SST, SSS, as well as decadal scale variability in dinoflagellate cyst production (and hence, primary productivity) in the sedimentary record from hydrographically-restricted Effingham Inlet. Our high resolution analysis of the sediment core spanning the last millennium constitutes one of the most detailed dinoflagellate cyst records in the NE Pacific published to date. In addition, this work provides further constraints on the local paleoseismicity of the region.

2. Environmental setting

2.1. Modern regional climate and oceanography

Vancouver Island lies at the northern edge of the Coastal Upwelling Domain that stretches along the west coast of North America (e.g., Thomson, 1981; Ware and McFarlane, 1989). The ocean and climate dynamics in this upwelling system vary seasonally and respond to changes in the relative strength and position of the North Pacific High (NPH) and Aleutian Low (AL) atmospheric pressure systems (e.g., Thomson, 1981; Ware and McFarlane, 1989; Hickey, 1998). Modern climate on the west coast of Vancouver Island is temperate, characterized by relatively cool and rainy winters, and warmer and drier summers.

In the NE Pacific, the eastward-flowing North Pacific Current bifurcates about 600 km off the coast of Vancouver Island and splits into the northward flowing Alaska Current and the southward flowing California Current (e.g., Tabata, 1975; Ware and Thomson, 1991). The latitude of the bifurcation region varies seasonally. Consequently, the wind-driven Shelf-Break Current that dominates the surface circulation over the outer portion of the shelf and continental slope off Vancouver Island is seasonally dependent (Thomson, 1981; Thomson et al., 1989). In winter (October – March), the AL and its associated cyclonic wind pattern dominate the NE Pacific, and the Shelf-Break Current flows poleward. In summer (April – September), as the NPH strengthens and shifts northward, the prevailing winds and currents on the outer shelf reverse (e.g., Thomson, 1981; Thomson et al., 1989; Ware and Thomson, 1991). Beneath the Shelf-Break Current, an extension of the California Undercurrent carries relatively warm, low-oxygen and high-salinity water from the south along the continental slope at depths of up to 500 m (e.g., Mackas et al., 1987; Hickey, 1998). Over the inner portion of the continental shelf, the Vancouver Island Coastal Current (VICC) flows northward throughout the year (Thomson et al., 1989). The VICC is driven primarily by the flux of low density water from the Strait of Juan de Fuca and fluvial runoff along the west coast of the island (Thomson, 1981; Thomson et al., 1989). During summer, prevailing northwesterly winds tend to retard or reverse the surface flow, whereas the VICC is enhanced by southeasterly winds in winter (Thomson et al., 1989).

Seasonal upwelling along the west coast of the island is most prevalent from May to August, when northwesterly winds force a seaward Ekman transport of the surface layer (e.g., Thomson, 1981; Thomson et al., 1989). Nutrient-rich slope waters are upwellled from depths of 200–500 m, particularly through the numerous submarine canyons that cut from the continental slope into the shelf (e.g., Allen et al., 2001; Allen and Hickey, 2010). In winter, prevailing southeasterly winds lead to persistently poleward flow along the continental slope and result in downwelling conditions along the coast of Vancouver Island.

Large-scale ocean-atmosphere variability in the NE Pacific is dominated by El Niño-Southern Oscillation (ENSO) on interannual timescales (e.g., Enfield, 1989) and the Pacific Decadal Oscillation (PDO) on decadal timescales (Mantua et al., 1997). In the vicinity of Effingham Inlet, El Niño conditions and positive PDO phases are expressed as positive winter temperature anomalies, while precipitation anomalies are only slightly negative, when detected (Stahl et al., 2006). La Niña conditions and negative PDO phases are characterized locally by negative temperature anomalies and virtually no change in precipitation (Stahl et al., 2006).

2.2. Effingham Inlet

Effingham Inlet is a 17 km-long glacial fjord located on the southwestern coast of Vancouver Island, and opens to the Pacific Ocean through Barkley Sound (Fig. 1). The Effingham River, draining a small forested basin of ~79 km² (Dallimore et al., 2005), empties at its head from the north. The inlet comprises two basins separated by shallow bedrock sills that restrict bottom water circulation within the basins. The inner basin, about 800 m-wide, is separated from the outer basin by a sill at ~40 m depth. A second ~65 m-deep sill separates the outer basin from the channel connecting the inlet to Barkley Sound. The maximum depths of the inner and outer basin are 120 m and 210 m, respectively. The shoreline is flanked by steep, forested slopes, with the exception of a few, relatively small marsh areas concentrated around the head and outer basin. Although the surrounding area is unpopulated, logging activities have taken place in the drainage basin and on the slopes since the 1970s (Dallimore, 2001).
heavier rainfall from October through February resulting in increased run-off reaching the inlet through the Effingham River and small streams along the steep basin walls during late fall and winter. With winter temperatures generally above freezing in the watershed, snow accumulation is limited and the spring freshet is muted. At the head of the inlet, the freshwater input creates a thin lens of brackish water that mixes gradually with the underlying saltier waters as it progresses seaward, creating a weak estuarine circulation (Patterson et al., 2000; Dallimore et al., 2005; Hay et al., 2009). The combination of weak estuarine flow, weak tidal mixing and the presence of the two shallow sills along the inlet axis foster the development of almost permanent suboxic to anoxic conditions at the bottom of the inner basin (e.g., Patterson et al., 2000; Dallimore et al., 2005). Rare oxygenation events, lasting for up to a few months, occur when the density contrast between the bottom waters of the inner basin and offshore waters allows for the intrusion of oxygen-rich waters into the basin (Dallimore et al., 2005). Such oxygenation events are less common in the inner basin and seem to require the combination of enhanced stratification of the surface waters, intensified estuarine circulation, weak tidal and turbulent mixing, decreased deep water density in the basin (through gradual vertical diffusion) and strong upwelling of denser (colder and saltier) waters along the coast (Patterson et al., 2000; Dallimore et al., 2005; Hay et al., 2009).

2.4. Sedimentary unit types

The bottom sediments of the inlet consist of intercalated fine-grained, slightly diatomaceous massive, graded and laminated muds (e.g., Dallimore et al., 2005, 2008). Laminations in the inner basin sediments are generated by the alternating deposition of predominately terrigenous material from runoff during the rainy season, and lighter-colored diatom-rich layers from the spring and summer phytoplankton blooms, thereby constituting sedimentary varves (e.g., Chang et al., 2003). Some of the occasionally intercalated non-laminated, graded mud units (Chang et al., 2003; Dallimore et al., 2005) sometimes termed “seismites”, are interpreted as debris flows of material previously deposited along the fjord walls, possibly triggered by seismic activity in the region (Blais-Stevens et al., 1997; Dallimore et al., 2005; Enkin et al., 2013). One recent example is the “1946 seismite”, a debris flow dated by $^{137}$Cs and $^{210}$Pb methods (Dallimore et al., 2005) and associated with the magnitude 7.3 crustal earthquake that occurred on June 23, 1946 with an epicenter in east-central Vancouver Island, about 60 km from Effingham Inlet (Rogers and Hasegawa, 1978; Dallimore et al., 2005). Other types of featureless, non-laminated mud units, sometimes referred to as “homogenites” or simply “homogenous units”, appear to form by the re-suspension of recently deposited, poorly consolidated laminated horizons by bottom-hugging currents flowing over the sill during oxygenation events, with the possible addition of allochthonous material advected into the basin by the intruding bottom waters (Dallimore et al., 2005; Hay et al., 2009). The specific geochemical signature and diatom composition of each type of sedimentary unit has been investigated in detail by Hay et al. (2009). In particular, seismites have a distinct terrigenous signature (e.g., having higher $C_{org}/N$ ratios than over- and underlying
3. Material and methods

3.1. Core collection and non-destructive analyses

Core TULK001 was collected in May 2009 in the center of Effingham Inlet’s inner basin (49° 04.25’ N / 125° 09.39’ W) at 116 m water depth (Fig. 1). The ~2.7 m-long core, collected from the CCGS John P. Tully using a 3 m-long, 12.7 × 12.7 cm Kastenlot gravity corer (Kuehl et al., 1985), was stored vertically for six days and allowed to drain. After de-watering, core TULK001 was compacted to 204 cm prior to logging and subsampling. Magnetic susceptibility measurements were acquired at the Geological Survey of Canada-Pacific (Sidney, BC) using a Bartington MS2E high resolution (3 mm × 10 mm) magnetic susceptibility meter.

Two cm-thick slabs of the sediment were collected in multiple sequential 30 cm-long Perspex cases along the vertical axis of the core. The slabs were X-radiographed at the BC Cancer Agency Mamography clinic in Vancouver (BC, Canada). X-radiographs were first processed using Digital Imaging and Communications in Medicine (DICOM) software online. Since considerable shrinkage of the slabs occurred before being X-rayed, the images were altered in Photoshop to close the gaps and stretch the radiographs to the original length of each slab. Nevertheless, laminated and massive units could be clearly discerned in most cases (Fig. 2).

3.2. Geochemical analyses

Samples for geochemical analyses were collected continuously downcore at every centimeter, freeze dried, powdered, homogenized and analyzed at the Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia (Vancouver, Canada) for carbon (total, inorganic and organic), total nitrogen and percent biogenic silica. Major, minor and trace element contents were analyzed at ALS Minerals, (North Vancouver, Canada).

Total C and N concentrations were determined by high-temperature flash combustion using an elemental analyzer with a precision of ± 1.2% and ± 3.2%, respectively. Inorganic C (± 3.7%) was determined using a CO2 coulometer. Organic C concentrations were derived from the difference between total and inorganic C values, with a combined precision of ± 3.9%. Percent opal (biogenic silica), used as a proxy for diatom primary production, was determined by the alkaline dissolution spectrophotometric method of Mortlock and Froelich (1989). Major, minor and trace element contents were determined by inductively coupled plasma optical emission spectrometry (ICP-OES) and mass spectrometry (ICP-MS) methods. Element contents were normalized relative to Al, a reliable index of fine-grained aluminosilicate detritus from common igneous and metamorphic rocks and their weathering products (Calvert and Pedersen, 2007), in order to determine changes in the lithogenous fraction of the deposits and to detect element enrichments/depletions relative to terrigenous sources (Ivanochko et al., 2008b and references therein). Reference standards from the U.S. Geological Survey, Japan Geological Survey, Canada Centre for Mineral and Energy Technology, and the National Institute for Metallurgy of South Africa, were analyzed randomly with the samples for quality control. Precision was better than ± 1.5% for the major element analyses and ± 3% for minor and trace element analyses.

3.3. Palynological analyses

3.3.1. Subsampling and palynological treatment

A U-channel was collected for palynological analysis and was sliced at every centimeter for a total of 206 samples in the Paleoenvironmental / Marine Palynology Laboratory, School of Earth and Ocean Sciences, University of Victoria, Canada. The subsamples were processed following the procedure described in Pospelova et al. (2005, 2010) and used by Bringué et al. (2013, 2014). Briefly, samples were rinsed three times to remove salt residue, oven dried at 40 °C and weighed. In order to estimate concentrations of palynomorphs, two tablets of Lycopodium clavatum (batch no. 177745, produced and distributed by the Department of Quaternary Geology, University of Lund, Sweden) were added to each sample (Stockmarr, 1971; Mertens et al., 2009, 2012a) during the first room temperature 10% HCl treatment performed to dissolve carbonates. Samples were then sieved through a 120 μm Nitex nylon mesh and retained over a 10 μm mesh in order to remove the coarse and fine fractions. Aluminosilicates were removed by a three-day treatment to room-temperature 48% HF, followed by a second 10% HCl treatment to eliminate precipitated fluorosilicates. Samples were then gently sonicated for up to a minute and collected on a 10 μm mesh. One or two drops of residue were mounted in glycerine jelly between a slide and cover slip. Dinoflagellate cysts and other palynomorphs were identified and counted using a Nikon Eclipse 80i transmitting light microscope at 600× and 1000× magnifications. An average of 348 cysts were counted per sample (range of 313 to 1045 cysts). Within the 1946 seismite, samples from the top, bottom and one every 10 cm were counted. Palynomorph concentrations are expressed as specimens per gram of dry weight of sediment (grain g⁻¹ or cyst g⁻¹). All samples and slides are stored at the Paleoenvironmental/Marine Palynology Laboratory, University of Victoria.

3.3.2. Dinoflagellate cyst nomenclature

The dinoflagellate cyst nomenclature follows the palaeontological taxonomy system provided in Lentin and Williams (1993) and conforms to subsequent taxonomic descriptions provided by Lewis et al. (1984), Head (1996, 2002), Zonneveld (1997), Rochon et al. (1999), Head et al. (2001), Ellegaard et al. (2003), Matsuoka et al. (2009), Sundström et al. (2009), Ribeiro et al. (2010), Verleye et al. (2011) and Mertens et al. (2012b, 2013). Cysts of Archaeperidinium cf. saanichii correspond to the description provided by Mertens et al. (2012b) except for processes that are loosely bent rather than being erect. Cysts of Polykrikos cf. kofoidii were identified as in Pospelova et al. (2008), and cysts of Biechelera sp., Echinidinium cf. delicatum and cyst type M1 were identified as in Price and Pospelova (2011) and Bringué et al. (2014). Islandinium? cezare s.l. correspond specifically to the “morphotype 1” described in Head et al. (2001). Some cyst taxa were grouped together due to morphological similarities. Hence, cysts of Protoperdinium nudum were grouped with Selenopemphix quanta, and E. cf. delicatum is grouped with Echinidinium delicatum. Brigantedinium spp. include B. cariaocoenae, B. irregulare, B. majusculum and B. simplex as well as other smooth round brown cysts since archeonephytes were not always visible due to folding or unfavorable orientations. Operculodinium centrocarpum s.l. includes both morphotypes described by Wall and Dale (1966) and “reduced processes”. Table 1 lists all dinoflagellate cysts identified in core TULK001 and provides the thecal equivalents for the cyst taxa and their autotrophic or heterotrophic affinity. Note that the expressions “autotrophic cyst” and “heterotrophic cyst”, used hereafter, refer to cysts produced by autotrophic and heterotrophic dinoflagellates, respectively.

3.3.3. Operculodinium centrocarpum process length measurements

Variations in the average process length of O. centrocarpum have been shown to correlate negatively with seawater density in the North Pacific, in a calibration study that included several samples from Effingham Inlet (Mertens et al., 2012c). In other words, O. centrocarpum cysts bearing longer processes are expected to have
been produced in less dense waters in the region, and vice versa. We measured the average process length of *O. centrocarpum* in twelve samples along core TULK001, following the methodology described in Mertens et al. (2011, 2012c) and used in Verleye et al. (2012), Jansson et al. (2014) and Sildever et al. (2015). The length of the three longest visible processes was measured on more than 50 specimens in each sample, using a Nikon eclipse 80i microscope and coupled Nikon DS Camera Head (DS-Fi1)/DS Camera Control Unit DS-L2 at a magnification of 1000×. As in Mertens et al. (2011, 2012c), no specimen from the "reduced processes" morphotype was considered. The results are presented as a box plot in Fig. 4, except for one sample within the 1946 seismite that was excluded from all further analyses (see Section 4).

In surface waters, density is influenced primarily by water temperature and salinity, with higher SST and lower SSS both leading to lower water density, and inversely lower SST and higher SSS resulting in higher water density. More specifically in Effingham Inlet, shipboard measurements of SST and SSS in the inner basin of Effingham Inlet collected in December 1995 and March 1997 (e.g., Patterson et al., 2000), together with historical measurements of SST and SSS collected near the study site at the Amphitrite Point Lighthouse since 1934 (available at www.pac.dfo-mpo.gc.ca/science/oceans/data-donnees/lighthouses-phares/index-eng.html; Fig. 1B) indicate that estimates of the range of variability in these two parameters are between 5 and 15 °C for temperature, and between 25 and 32 psu for salinity. The density difference along these two gradients is about 1.6 kg m⁻³ for SST and 5.5 kg m⁻³ for SSS, suggesting that salinity has a more important influence than temperature on density. Thus, although temperature also affects density, we expect that variations in *O. centrocarpum* process length will reflect primarily changes in surface salinity in Effingham Inlet.

### 3.4. Statistical and wavelet analyses

Statistical analyses of the dinoflagellate cyst data include zonation, multivariate (PCA) and wavelet analyses. All cyst assemblages (samples) from seismites were excluded from the analyses. Dinoflagellate cyst zones were determined by CONIIC (stratigraphically “CONstrained Incremental Information Clustering”, i.e., cluster analysis by information content) using the program psimpoll 4.25 (Bennett, 1994). The zonation is based on cyst concentrations of all cyst taxa that account for N1.5% in at least one sample, both of autotrophic and heterotrophic affinity, and without data transformation. Note that very consistent results were obtained using other zonation methods (such as optimal and binary splitting), with or without data transformation (e.g., log and square root transformations, normalization) and distance statistics (sum of squares or information content). Principal component analyses (PCA) were used to extract the dominant patterns of variability in the separate autotrophic and heterotrophic cyst assemblages. The analyses were performed on covariance matrices of log-transformed relative abundances using CANOCO 4.5 for Windows (ter Braak and Šmilauer, 2002). Only taxa with maximum relative abundance N1.5% in the total cyst assemblages were included in the analyses.

Continuous wavelet analyses were used in order to detect periodicity, duration and variance in the dinoflagellate cyst record as in Bringué et al. (2014). Log-transformed concentrations of cysts produced by autotrophic and heterotrophic dinoflagellates were analyzed separately. The wavelet function is the 6th derivative of a Gaussian (DOG m=6), a real valued wavelet base that captures both the positive and negative oscillations of the time series as separate peaks in wavelet power (e.g., Torrence and Compo, 1998). Zero padding was applied on the beginning and end of the time-series to reduce the edge effects, and the significance of wavelet functions was evaluated against red-noise (autoregressive lag1) background spectrum at the 5% significance level (Torrence and Compo, 1998). Quantitative reconstructions of sea-surface parameters based on dinoflagellate cyst assemblages were attempted using the Modern

### Table 1

<table>
<thead>
<tr>
<th>Dinoflagellate cyst (Paleontological name)</th>
<th>Dinoflagellate theca (Biological name)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Autotrophic taxa</strong></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Impagidinium paradoxum</td>
<td>Gonadulx sp. indet.</td>
</tr>
<tr>
<td>Impagidinium sp.</td>
<td>Gonadulx sp. indet.</td>
</tr>
<tr>
<td>Operculodinium centrocarpum sensu Wall and Dace (1966)</td>
<td>Protoceratium reticulatum</td>
</tr>
<tr>
<td>Operculodinium centrocarpum - reduced processes</td>
<td>Protoceratium reticulatum</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Spiniferites bentorii</td>
<td>Gonadulx spinifer complex</td>
</tr>
<tr>
<td>Spiniferites bulloides</td>
<td>Gonadulx spinifer complex</td>
</tr>
<tr>
<td>Spiniferites elongatus</td>
<td>Gonadulx elongata</td>
</tr>
<tr>
<td>Spiniferites mirabilis</td>
<td>Gonadulx spinifer complex</td>
</tr>
<tr>
<td>Spiniferites ramosus</td>
<td>Gonadulx spinifer complex</td>
</tr>
<tr>
<td>Spiniferites sp.</td>
<td>Gonadulx sp.</td>
</tr>
<tr>
<td><strong>Heterotrophic taxa</strong></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bradynodinium caricaense</td>
<td>Protoperidinium avellanicum</td>
</tr>
<tr>
<td>Bradynodinium irregularum</td>
<td>Protoperidinium denticulatum</td>
</tr>
<tr>
<td>Bradynodinium majusculum</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Bradynodinium simplex</td>
<td>Protoperidinium conicoide</td>
</tr>
<tr>
<td>Dabrnodinium sp.</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Echinodinium aculeatum</td>
<td>Diplopsalid or Protoperidinoid group</td>
</tr>
<tr>
<td>Echinodinium delictum</td>
<td></td>
</tr>
<tr>
<td>Echinodinium cf. delictum</td>
<td></td>
</tr>
<tr>
<td>Echinodinium translatum</td>
<td></td>
</tr>
<tr>
<td>Echinodinium transparentum</td>
<td></td>
</tr>
<tr>
<td>Echinodinium zonneveldiae</td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Islandinium ? minutum</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Islandinium ? ezeare s.l.</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Lejeunecysta oliva</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Lejeunecysta sabrina</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Polykaryos kofoidii</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Polykaryos kofoidii cf. Polykaryos sp.</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Protoperidinium americanum</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Protoperidinium fukiyo</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Protoperidinium minutum</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Protoperidinium nudum</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Protoperidinium oblongum</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>?Protoperidinium sp.</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Quinquecuspis concreta</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Selenopemphex nephroides</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Selenopemphex quarta</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Selenopemphex undulata</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Trinovantedinum variabile</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Votadinium calvum</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Votadinium spinosum</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Cyst type M1</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Spiny brown cysts</td>
<td>Protoperidinium sp. indept.</td>
</tr>
<tr>
<td>Unknown cysts</td>
<td>Protoperidinium sp. indept.</td>
</tr>
</tbody>
</table>
Analogue Technique (de Vernal et al., 2001, 2005; Guiot and de Vernal, 2007) with the Northern Hemisphere reference database comprising 1492 sites (de Vernal et al., 2013; available at www.geotop.ca). However, because a large number of samples found less than five suitable analogs (distance greater than the acceptable threshold of 1.23; de Vernal et al., 2013), and because many analogs were located in high latitude environments (Chukchi Sea, Baffin Bay and Sea of Okhotsk), the reconstructions were not considered in the interpretations.

4. Sedimentary facies

4.1. Proxies for sedimentary unit types

Before a chronology could be established for core TULK001, it was important to identify its sedimentary facies. The identification of the various stratigraphic units in core TULK001 was based on the investigations by Dallimore et al. (2005, 2008), Hay et al. (2009) and Enkin et al. (2013), who focused on the postglacial sedimentary record from Effingham Inlet and identified sedimentological, geochemical and palaeomagnetic properties associated with the different types of units (laminated and homogenous units, disturbed varves and seismites). In particular, core TULK001 was correlated with freeze core VEC007-FC03 (henceforth “FC3”), collected from Effingham Inlet’s inner basin sediments in April 2005 (Dallimore et al., 2009; Enkin et al., 2013), by comparing 14C dates and proxies of magnetic susceptibility, % opal and Corg/N ratio (Suppl. Fig. 1). Although core TULK001 is more compacted than core FC3, the two facies are coherent with very consistent successions of unit types and only small variations in the thickness of the units (Suppl. Fig. 1).

Criteria used to identify the unit types in core TULK001 include X-radiographs, magnetic susceptibility, geochemical parameters (% opal, Corg/N ratio, % Corg, % Corg), major and minor elements (% Al and normalized Ti, Zr, K, Mg, Cu and Cr), as well as palynological data (ratio of dinoflagellate cysts to pollen grains, “dinos/pollen”).

Table 2

Seismite identification criteria in core TULK001, based on the correlation with core FC3 and previous work by Dallimore et al. (2005, 2008), Hay et al. (2009) and Enkin et al. (2013). Corresponding seismites in Enkin et al. (2013) are indicated on the right.

<table>
<thead>
<tr>
<th>Seismite</th>
<th>TULK001 depth (cm)</th>
<th>Thickness (cm)</th>
<th>EF/D (cm)</th>
<th>Estimated age (years AD)</th>
<th>High % Al</th>
<th>High magnetic susceptibility</th>
<th>High Ti/Al</th>
<th>Low Mo/Al</th>
<th>Low % opal</th>
<th>Low Corg/N</th>
<th>Low Dinos/</th>
<th>Seismite and age estimation in Enkin et al. (2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>15–87</td>
<td>72</td>
<td>15</td>
<td>1946</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>E0 AD 1946</td>
</tr>
<tr>
<td>#2</td>
<td>129–132</td>
<td>4</td>
<td>58</td>
<td>1691 ± 12</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>E1 AD 1699 ± 21</td>
</tr>
<tr>
<td>#3</td>
<td>175–176</td>
<td>2</td>
<td>101</td>
<td>1328 ± 15</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>E2 (a, b &amp; c) AD 1330 ± 43</td>
</tr>
<tr>
<td>#4</td>
<td>192–194</td>
<td>3</td>
<td>117</td>
<td>1199 ± 28</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>E3 AD 1147 ± 27</td>
</tr>
</tbody>
</table>
magnetic susceptibility indicates sedimentary concentration of iron-bearing minerals such as magnetite, which has a higher specific gravity (5.17) than quartz (2.65) and thus travel along with the larger quartz grains during transport in water.

The K/Al and Mg/Al ratios were used as proxies for sediment composition as a means to characterize mineral sources, with higher K/Al ratios indicating a greater contribution from minerals such as illite and K-feldspars, and Mg/Al ratios indicative of mafic minerals (e.g., Ivanochko et al., 2008b). Ti/Al and Zr/Al were considered as indicators for relatively large particles (mostly silt and fine sand-sized), although Ti/Al ratios are not as reliable indicators as Zr/Al. Both titanium and zirconium occur in minerals characterized by higher specific gravity than quartz (e.g., titanite and rutile for Ti, and zircon for Zr) that will typically be found along larger quartz grains in marine sediments. However, unlike Zr, Ti substitutes for Al in a wide variety of abundant clay minerals formed in soils and during the chemical weathering of rock minerals, thus confusing the signal carried by titanite or rutile minerals in sedimentary deposits (e.g., Calvert and Pedersen, 2007).

Mo/Al was used as a proxy for the redox state of the sediment, since molybdenum is precipitated in sediments that have accumulated under anoxic (sulphidic or euxinic) conditions (Helz et al., 2011), although elevated Mo levels can also be found in oxic sediments when Mo is associated with Fe- and Mn-oxhydroxides in surface sediments (Shimmield and Price, 1986). Biogenous components (including % opal, % Corg, Corg/N and dinos/pollen ratios) were also used to determine the relative contribution of organic material to the sediments and the marine or terrestrial origin of the organic matter (see Fig. 2). More information on the interpretation of specific geochemical parameters is detailed in Dallimore et al. (2005; 2008), Ivanochko et al. (2008b), Hay et al. (2009) and Enkin et al. (2013).

4.2. Sedimentary facies of the core

The sedimentary facies of core TULK001 is shown in Fig. 2. The physico-chemical properties and composition of the biogenous fraction indicate that the seismites can be recognized by their higher Al contents and Ti/Al ratios relative to the under- and overlying units, which is consistent with a stronger influence of terrigenous material, as well as an inferred slightly coarser grain size, with Ti-bearing accessory minerals (e.g., titanite and rutile) accompanying coarse silts and sandy grains during particle transport. The Zr/Al profile, however, suggests that grain size differences between sedimentary units are not pronounced (Fig. 2). All Mo/Al values are well above the oxic values of upper continental crust or shales (ratios of ~0.2 × 10⁻⁴; e.g., Calvert and Pedersen, 2007), indicating that all units in core TULK001 are enriched in Mo, including the material forming the seismites (Fig. 2). However, the Mo/Al profile indicates subtle downcore variations that possibly reflect slight changes in the redox conditions of the sediments, with conditions in the varved units more conducive to Mo sequestration than in the seismites. The 72 cm-thick AD 1946 seismite shows particularly high % Corg, % Corg/N and dinos/pollen ratios, with a sharp increase in magnetic susceptibility at the base of the unit (lower three samples of the seismites; Fig. 2), which is consistent with previous observations of this seisme from other nearby cores (e.g., Dallimore et al., 2008; Hay et al., 2009; Enkin et al., 2013). This sharp increase in magnetic susceptibility at the base of the seismite is accompanied by elevated Al contents, higher Ti/Al ratios and an associated decrease in Corg and biogenic silica (Fig. 2).
which is characteristic of debris flows depositing the coarser (denser) material first. The K/Al profile also indicates that the source of the material in the 1946 seismite is different than any other unit (including other seismites), with markedly lower K/Al indicating a reduced contribution from minerals such as illite and K-feldspars.

Overall, varied intervals represent 50.2% of the length of the core (varves: 30.2%; vague or indistinct varves: 17.1%; disturbed varves: 2.9%), whereas homogenous units and seismites account for 10.2% and 39.5%, respectively (Fig. 2). Four seismites were identified in the sequence, including the 72 cm-thick unit associated with the AD 1946 earthquake (seismite E0 in Enkin et al., 2013) based on the criteria listed in Table 2. The other three seismites range from 2 to 4 cm in thickness (Fig. 2). While the 1946 seismite provides an additional age constraint on the sequence, the material within seismites cannot be used for dating and below the AD 1946 seismite were treated separately. The 1946 seismite was previously identified and dated in EFD (Suppl. Fig. 1; Table 3). Two dates from core FC3 that were deemed outliers in Enkin et al. (2013) are included in the age model as a single event in TULK001.

### 5. Core chronology

To determine the chronology of core TULK001, the sections above and below the AD 1946 seismite were treated separately. The 1946 seismite was previously identified and dated in Effingham Inlet inner basin sediments (Dallimore et al., 2005; Hay et al., 2009; Enkin et al., 2013) and the correlation between cores TULK001 and FC3 (Suppl. Fig. 1), as well as our core chronology also indicate that this thick unit most likely corresponds to the 1946 seismic event (Fig. 3). The chronology of the most recent laminated unit (overlying the 1946 seismite) was determined by varve counting on the X-radiograph (Fig. 3A). For the section below the 1946 seismite, the age constraints considered for the age model include five 14C dates from core TULK001 and twelve 14C dates from core FC3. All 14C dates were obtained from single plant fragments carefully selected in non-massive horizons and analyzed at the W.M. Keck Accelerator Mass Spectrometry Laboratory, University of California, Irvine. The age constraints are summarized in Table 3.

An “Event-Free Depth” scale (EFD) was generated by removing all four seismites from the uncorrected, “TULK001 depth” scale (Bronk Ramsey et al., 2012; Table 2). Then, based on the detailed correlation between cores TULK001 and FC3, all 14C dates from core FC3 were attributed an equivalent depth in the EFD (Suppl. Fig. 1; Table 3). Two dates from core FC3 that were deemed outliers in Enkin et al. (2013) are included in the age model as a single event in TULK001.

### Table 3

*Age constraints summary and seismite age determinations for core TULK001. Cores TULK001 and FC3 were correlated on the basis of 14C dates, magnetic susceptibility, % opal and Corg/N ratio (Suppl. Fig. 1). FC3 core data are from Dallimore et al. (2009) and Enkin et al. (2013). FC3 core depths are given an equivalent in the depth scale of core TULK001. EFD is the event-free depth scale. Dots (‘.’) designate date boundaries possibly out of range, as indicated by the program OxCal. Ages marked with an asterisk (*) were not considered in the age model determination.*

<table>
<thead>
<tr>
<th>Core Informal UCIAMS # Material dated TULK001 FC3</th>
<th>EFD depth (cm)</th>
<th>14C age (BP)</th>
<th>Calibrated age (AD, 95%)</th>
<th>Posterior age (AD, 95%)</th>
<th>Age AD Lithology Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>TULK001 Varves (X-rad)</td>
<td>0–15</td>
<td>1946</td>
<td>E0 seismite</td>
<td>Modern varves</td>
<td>Included (avg of 3 varves cm^-1)</td>
</tr>
<tr>
<td>TULK001 TUL-1</td>
<td>101787 Plant fragment</td>
<td>88</td>
<td>17</td>
<td>110</td>
<td>20</td>
</tr>
<tr>
<td>FC3 FC3-1</td>
<td>20767 Twig</td>
<td>90</td>
<td>73</td>
<td>19</td>
<td>90</td>
</tr>
<tr>
<td>FC3 FC3-2</td>
<td>49837 Grass</td>
<td>98</td>
<td>84</td>
<td>27</td>
<td>160</td>
</tr>
<tr>
<td>FC3 FC3-3</td>
<td>49838 Twig</td>
<td>112</td>
<td>95</td>
<td>41</td>
<td>165</td>
</tr>
<tr>
<td>TULK001 TUL-2</td>
<td>101788 Plant fragment</td>
<td>115</td>
<td>44</td>
<td>185</td>
<td>20</td>
</tr>
<tr>
<td>FC3 FC3-4</td>
<td>49839 Grass</td>
<td>121</td>
<td>111</td>
<td>50</td>
<td>205</td>
</tr>
<tr>
<td>TULK001 E1</td>
<td>1700 seismite</td>
<td>129–132</td>
<td>58</td>
<td>1667</td>
<td>1716</td>
</tr>
<tr>
<td>FC3 FC3-5</td>
<td>20772 Leaf</td>
<td>136</td>
<td>143</td>
<td>62</td>
<td>210</td>
</tr>
<tr>
<td>FC3 FC3-6</td>
<td>49840 Twig</td>
<td>144</td>
<td>156</td>
<td>70</td>
<td>315</td>
</tr>
<tr>
<td>TULK001 TUL-3</td>
<td>101789 Plant fragment</td>
<td>146</td>
<td>72</td>
<td>350</td>
<td>15</td>
</tr>
<tr>
<td>FC3 FC3-7</td>
<td>49841 Twig</td>
<td>157</td>
<td>178</td>
<td>83</td>
<td>375</td>
</tr>
<tr>
<td>FC3 FC3-8</td>
<td>49842 Twig</td>
<td>160</td>
<td>190</td>
<td>86</td>
<td>445</td>
</tr>
<tr>
<td>TULK001 TUL-4</td>
<td>101790 Plant fragment</td>
<td>164</td>
<td>90</td>
<td>575</td>
<td>15</td>
</tr>
<tr>
<td>TULK001 E2</td>
<td>E2 seismite</td>
<td>175–176</td>
<td>101</td>
<td>1300</td>
<td>1360</td>
</tr>
<tr>
<td>TULK001 TUL-5</td>
<td>101791 Plant fragment</td>
<td>176</td>
<td>101</td>
<td>825</td>
<td>20</td>
</tr>
<tr>
<td>FC3 FC3-9</td>
<td>20773 Twig</td>
<td>178</td>
<td>221</td>
<td>103</td>
<td>615</td>
</tr>
<tr>
<td>FC3 FC3-outlier1</td>
<td>179</td>
<td>104</td>
<td>870</td>
<td>25</td>
<td>1047</td>
</tr>
<tr>
<td>TULK001 E3</td>
<td>E3 seismite</td>
<td>192–194</td>
<td>117</td>
<td>1136</td>
<td>1254</td>
</tr>
<tr>
<td>FC3 FC3-outlier2</td>
<td>197</td>
<td>120</td>
<td>1145</td>
<td>40</td>
<td>775</td>
</tr>
<tr>
<td>FC3 FC3-11a</td>
<td>20777 Twig</td>
<td>202</td>
<td>270</td>
<td>125</td>
<td>890</td>
</tr>
<tr>
<td>FC3 FC3-11b</td>
<td>49845 Grass</td>
<td>202</td>
<td>271</td>
<td>125</td>
<td>920</td>
</tr>
<tr>
<td>TULK001 Varves (X-rad)</td>
<td>0–15</td>
<td>1946</td>
<td>E0 seismite</td>
<td>Modern varves</td>
<td>Included (avg of 3 varves cm^-1)</td>
</tr>
</tbody>
</table>

### Table 4

*Event-Free Depth scale (EFD) determination. Seismites were given a thickness of 1 cm in EFD.*

<table>
<thead>
<tr>
<th>TULK001 depth (d)</th>
<th>From (cm)</th>
<th>To (cm)</th>
<th>EFD (cm)</th>
<th>Seismitae</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15</td>
<td>18</td>
<td>EFD = 8</td>
<td>#1</td>
</tr>
<tr>
<td>15</td>
<td>87</td>
<td>EFD = 15 to 16</td>
<td>#2</td>
<td></td>
</tr>
<tr>
<td>87</td>
<td>129</td>
<td>EFD = d-71</td>
<td>#3</td>
<td></td>
</tr>
<tr>
<td>129</td>
<td>133</td>
<td>EFD = 58 to 59</td>
<td>#2</td>
<td></td>
</tr>
<tr>
<td>133</td>
<td>175</td>
<td>EFD = d-74</td>
<td>#4</td>
<td></td>
</tr>
<tr>
<td>175</td>
<td>177</td>
<td>EFD = 101 to 102</td>
<td>#3</td>
<td></td>
</tr>
<tr>
<td>177</td>
<td>192</td>
<td>EFD = d-75</td>
<td>#4</td>
<td></td>
</tr>
<tr>
<td>192</td>
<td>195</td>
<td>EFD = 117 to 118</td>
<td>#4</td>
<td></td>
</tr>
<tr>
<td>195</td>
<td>208</td>
<td>EFD = d-77</td>
<td>#4</td>
<td></td>
</tr>
</tbody>
</table>
shown in Fig. 3B but were not considered for the model. Another two \(^{14}C\) dates fell within seismites (TULK-5 and FC3-10; Fig. 3B; Table 3) and were also not considered in the model. Hence, a total of 15 age constraints – four \(^{14}C\) dates from TULK001 and eleven \(^{14}C\) dates from FC3 – were used to determine the core chronology for the section below the 1946 seismic.

Radiocarbon dates were reported as \(^{14}C\) years BP, and calibrated using the program OxCal, version 4.2 (Bronk Ramsey, 2009; c14.arch.ox.ac.uk/oxcal) and the INTCAL13 calibration curve for terrestrial (plant) material (Reimer et al., 2013). The program OxCal uses Bayesian analyses to combine radiocarbon dating and sedimentological age constraints into a deposition model (Bronk Ramsey, 2008). The \textit{a priori} input is the set of calibrated \(^{14}C\) age likelihood functions at their respective depths. These were incorporated into a “Poisson process deposition model” (Bronk Ramsey, 2008) using a parameter \(k\) (the number of accumulation events per unit depth) of 1 cm\(^{-1}\) (Bronk Ramsey and Lee, 2013; Enkin et al., 2013). OxCal performs a Markov Chain Monte Carlo sampling to build up a distribution of possible solutions, and reduce considerably the concentration of freshwater palynomorphs, reconstructed surface temperature in the PDO region (22.5°N–57.5°N, 152.5°E–132.5°W) relative to the 1961–1990 reference period mean (from Mann et al., 2009), and tree-ring based reconstructed PDO index (from MacDonald and Case, 2005). In the box plot, the middle line in boxes is the median, the sides of the boxes are the 25th and 75th percentiles, and the end of “whiskers” (error bars) are 10th and 90th percentiles. The boxes are color-coded according to the sedimentary facies (as in Fig. 2). Dinoflagellate cyst zones are indicated to the right (see text for details).

6. Results

6.1. Dinoflagellate cyst record

Dinoflagellate cysts recovered from core TULK001 are very diverse and abundant, with a total of 47 cyst taxa (excluding morphotypes; Table 1) and an average concentration of 102,900 cyst g\(^{-1}\) (Fig. 4). Overall, dinoflagellates of autotrophic and heterotrophic affinity represent 54.7 and 45.3% of the assemblages, respectively (Fig. 4). Consequently, both groups are well represented in every sample, although the taxonomic diversity is markedly higher among heterotrophic cyst taxa (Table 1). A few samples in the uppermost section of the core show exceptionally high cyst concentrations (up to 983,200 cyst g\(^{-1}\)), driven entirely by peaks in concentrations of the autotrophic O. centrocarpum (Figs. 4 and 5).

In general, cyst assemblages are characterized by O. centrocarpum (36.2%) accompanied by Brigantedinium spp. (18.0%) and Dubridinium spp. (6.6%); all other cyst taxa account for less than 5.0% on average. Since cysts produced by autotrophic and heterotrophic dinoflagellates are well represented throughout the core (in terms of cyst counts, concentrations and diversity), and because the two groups have very different ecologies (with regard to life strategies and growing or feeding mechanisms), we present the results for “autotrophic and heterotrophic assemblages” separately (Fig. 5).

Among cysts produced by autotrophic dinoflagellates (Fig. 5B), O. centrocarpum dominates the assemblages (average of 78.2%) while as P. dalei, S. ramosus and S. elongatus account for 11.6, 5.5 and 3.5%, respectively. Heterotrophic cyst assemblages (Fig. 5C) are characterized by Brigantedinium spp. (32.8%) and Dubridinium spp. (11.9%), as well as cysts of A. cf. saanichii (8.9%) and P. minutum (7.4%), Q. concreta (7.1%), cysts of P. americanum (5.9%), E. delicatum (5.2%), undifferentiated Protoperidinioids (4.0%) and S. quanta (3.4%).

Fig. 4. Total dinoflagellate cyst concentrations, proportion of cysts produced by autotrophic and heterotrophic dinoflagellates, box plot of O. centrocarpum process length (a proxy for water density), concentrations of freshwater palynomorphs, reconstructed surface temperature in the PDO region (22.5°N–57.5°N, 152.5°E–132.5°W) relative to the 1961–1990 reference period mean (from Mann et al., 2009), and tree-ring based reconstructed PDO index (from MacDonald and Case, 2005). In the box plot, the middle line in boxes is the median, the sides of each box are the 25th and 75th percentiles, and the end of “whiskers” (error bars) are 10th and 90th percentiles. The boxes are color-coded according to the sedimentary facies (as in Fig. 2). Dinoflagellate cyst zones are indicated to the right (see text for details).
Fig. 5. Dinoflagellate cyst concentrations (A.) and proportions in the “autotrophic” (B.) and “heterotrophic” (C.) cyst assemblages from core TULK001. Only a selection of taxa representing > 1.5 % of the cyst assemblage in at least one sample are shown. Samples within disturbed varves and homogenous units might contain some reworked material and are color-coded as in Fig. 2. Zonation is determined from Constrained incremental information clustering (CONIIC) based on cyst concentrations of all cyst taxa > 1.5 % (dendrogram shown on the lower right).
6.2. Dinoflagellate cyst zones

The five dinoflagellate cyst zones, D1 to D5, determined statistically from CONIIC identify intervals containing cyst assemblages that are “least dissimilar” in stratigraphically adjacent samples (Fig. 5). Dinoflagellate cyst zones (henceforth simply “zones”) D1 and D2 are each further divided into two subzones.

6.2.1. Zone D1a (AD 1090 to 1126)

Zone D1a is marked by relatively low abundances of O. centrocarpum (average of 48,000 cyst g$^{-1}$) and relatively lower concentrations of most other taxa. In particular, cysts of P. dalei and S. elongatus contribute less to the autotrophic cyst assemblages (averages of 3600 and 1400 cyst g$^{-1}$, respectively). Among heterotrophic cyst taxa, relative abundances of cysts of P. minutum and A. cf. saanichi decrease to values close to the core average (4.0 and 8.1%, respectively) while Brigantedinium spp. (average of 34.5%), S. quanta (5.5%) and cysts of P. americanum (5.2%) show a very slight increase.

6.2.2. Zone D1b (AD 1126 to 1228)

This interval is characterized by an increase in concentrations of O. centrocarpum (average of 48,000 cyst g$^{-1}$) and relatively lower concentrations of most of other taxa. In particular, cysts of P. dalei and S. elongatus contribute less to the autotrophic cyst assemblages (averages of 3600 and 1400 cyst g$^{-1}$, respectively). Among heterotrophic cyst taxa, relative abundances of cysts of P. minutum and A. cf. saanichi decrease to values close to the core average (4.0 and 8.1%, respectively) while Brigantedinium spp. (average of 34.5%), S. quanta (5.5%) and cysts of P. americanum (5.2%) show a very slight increase.

6.2.3. Zone D2a (AD 1228 to 1438)

In this interval, O. centrocarpum concentrations (average of 26,100 cyst g$^{-1}$) are well below the core average of 44,500 cyst g$^{-1}$, while P. dalei cyst concentrations (5000 cyst g$^{-1}$) are higher than the core average of 4500 cyst g$^{-1}$. Concurrently, average concentrations of Brigantedinium spp., A. concreta and cysts of A. cf. saanichi increase to 18,600, 4400 and 6500 cyst g$^{-1}$, respectively. Some samples show increased abundances of Dubridinium spp., cysts of P. schwartzii and P. minutum, although their concentrations do not remain consistently higher throughout the entire zone.

6.2.4. Zone D2b (AD 1438 to 1724)

Zone D2b is marked by high concentrations of cysts of P. dalei (average of 6400 cyst g$^{-1}$), Brigantedinium spp. (16,600 cyst g$^{-1}$) and cysts of P. americanum (3600 cyst g$^{-1}$). Concentrations of O. centrocarpum are variable but generally high (average of 44,700 cyst g$^{-1}$). Concentrations of P. minutum cysts (2000 cyst g$^{-1}$) remain well below the core average (4000 cyst g$^{-1}$) throughout the zone.

6.2.5. Zone D3 (AD 1724 to 1776)

Total dinoflagellate cyst concentrations are relatively high in zone D3, with S. ramosus (average of 4500 cyst g$^{-1}$), cysts of P. minutum (13,100 cyst g$^{-1}$) and A. cf. saanichi (10,700 cyst g$^{-1}$) showing the most pronounced increases (Figs. 4 and 5). Concentrations of O. centrocarpum (29,800 cyst g$^{-1}$ on average) and S. quanta (800 cyst g$^{-1}$) are well below their respective core averages.

6.2.6. Zone D4 (AD 1776 to 1954)

Concentration profiles of several cyst taxa in zone D4 show a gradual decreasing trend, including cysts of P. dalei, P. minutum and A. cf. saanichi. Concentrations of O. centrocarpum (average of 20,000 cyst g$^{-1}$) and S. ramosus (900 cyst g$^{-1}$) are the lowest of the record. However, most heterotrophic cyst taxa show concentrations close to or above their respective core averages, including Brigantedinium spp. (average of 15,300 cyst g$^{-1}$), E. delicatum (3100 cyst g$^{-1}$), E. granulatum (1300 cyst g$^{-1}$) and cyst type M1 (500 cyst g$^{-1}$).

6.2.7. Zone D5 (AD 1954 to 1990)

Cyst assemblages from zone D5 show the highest degree of dissimilarity when compared to the rest of the sequence (see the CONIIC dendrogram in Fig. 5). Zone D5 is marked by the highest abundances of O. centrocarpum for the record (up to 945,600 cyst g$^{-1}$, average of 159,000 cyst g$^{-1}$) and decreased contributions of cysts of P. dalei (average of 1100 cyst g$^{-1}$) and Brigantedinium spp. (9000 cyst g$^{-1}$). Although relatively modest in amplitude, several taxa show a slight increase in abundance, including cysts of P. minutum and P. fukuyoi, V. spinosum and cyst type M1.

6.3. Principal component analyses

Biplots illustrating the ordination of species and downcore variations of sample scores are shown in Fig. 6. In the autotrophic cyst assemblages, the first two ordination axes Auto PC1 and Auto PC2 capture 46.8% and 24.6% of the total variance in the species data, respectively. Operculidinium centrocarpum drives virtually all of the variation along Auto PC1 (fit of 0.77) and samples characterized by high levels of O. centrocarpum have positive scores along this first axis (Fig. 6). Auto PC2 attributes negative scores to cysts of P. dalei, S. ramosus and S. elongatus, and positive scores to O. centrocarpum and S. ramosus.

In the heterotrophic cyst assemblages, the first axis Hetero PC1 explains 16.6% of the total variance, and illustrates a gradient primarily influenced by S. quanta and cysts of P. americanum on the negative side, and cysts of P. minutum and A. cf. saanichi on the positive side (Fig. 6).

The second ordination axis, Hetero PC2, captures 10.5% of the total variance in the assemblages. Cysts of P. minutum and cyst type M1 have particularly strong, positive scores along this axis.

The environmental gradients associated with each axis described above are presented in Section 7.1.3, after the ecology of some key dinoflagellate cyst taxa in this specific system is discussed.

6.4. Wavelet analyses

The wavelet power spectra reveal several periodicities that are significant against a red-noise background spectrum at the 5% significance level (Fig. 7). Some (multi)centennial-scale variability is detected in both autotrophic and heterotrophic cyst concentrations with periodicities ranging between ~110 years and 380 years. However, these periodicities are mostly detected close to the beginning of the end of the time-series and are affected by the “edge effect” (e.g., Torrence and Compo, 1998; cone of influence indicated by the shaded area in Fig. 7); thus they will not be discussed further.

The wavelet power spectrum of autotrophic cyst concentrations shows intermittent decadal-scale periodicities generally centered on ~20 and 38 years. The periodicity of ~38 years is the first one to appear in the record and is present from ~AD 1170 to 1250, then between ~AD 1430 and 1550, later from ~AD 1620 and 1720, and finally during the second half of the 20th century. The periodicity centered around ~20 years is first detected in the record during the 15th century, then broadly appears between ~AD 1640 and 1700, and becomes a consistent feature from ~AD 1800 until the end of the record.

In heterotrophic dinoflagellate cyst concentrations, the dominant modes of variability are identified in the higher frequencies, with periodicities generally between ~15 years (the shortest periodicity detectable by the analyses given the temporal resolution of the sedimentary record) and 35 years. These periodicities are present throughout most of the record, but they disappear between ~AD 1200 and 1275, then from AD 1340 to 1550, and they are only weakly expressed during the second half of the 19th century. The power spectrum also identifies a periodicity centered on ~93 years, apparent in the record from ~AD 1550 to 1770.
7. Discussion

The high resolution analysis of core TULK001 provides one of the most detailed dinoflagellate cyst records in the NE Pacific published to date. The cyst species recovered at this location (Table 1) are consistent with the species recorded from surface sediment in Effingham Inlet and the surrounding area (e.g., Kumar and Patterson, 2002; Radi and de Vernal, 2004; Radi et al., 2007). The assemblages reported here also include several species recently described and/or emended, such as cysts of *P. schwartzii* and *P. kofoidii* (Matsuoka et al., 2009), cysts of *P. americanum* (Ribeiro et al., 2010); *S. undulata* (Verleye et al., 2011), cysts of *A. saanichi* (Mertens et al., 2012b) and cysts of *P. fukuyoi* (Mertens et al., 2013) which brings some clarification to the often problematic “spiny brown” cysts (see Table 1 and Plates I-IV; see also Radi et al., 2013 for clarification on this topic).

Dinoflagellate cyst assemblages from core TULK001 appear to have had a relatively constant composition over the span of the record, with *O. centrocarpum*, *Brigantedinium* spp. and *Dubridinium* spp. as the main contributors to the assemblages (Fig. 5). This suggests relatively stable paleoenvironmental conditions at the study site over the past millennium. However, within this relative stability, the cyst record encodes more subtle variations on sub-decadal to centennial timescales that appear to be tied to environmental changes in the region, including the termination of the Medieval Climate Anomaly (MCA), the Little Ice Age (LIA) and warming in the second half of the 20th century.

7.1. Ecology of key dinoflagellate cyst taxa

The general ecology of cyst-producing dinoflagellates has recently been reviewed by Zonneveld et al. (2013). The known ecology of some key dinoflagellate cyst taxa, and more specifically in the study region and in other similar estuarine systems, are briefly discussed in this section. Analyses of cyst assemblages in surficial sediments from British Columbia coastal waters (e.g., Kumar and Patterson, 2002; Radi and de Vernal, 2004; Radi et al., 2007; Krepakevich and Pospelova, 2010) provide useful insights on the major environmental parameters controlling the distribution of dinoflagellate cyst species. Sediment trap studies (Pospelova et al., 2010; Price and Pospelova, 2011) help resolve the seasonal occurrence of cyst species in the region. In addition, despite their distant geographical location, several Norwegian and Swedish silled fjords that open on the Skagerrak present many similarities to Effingham Inlet, in terms of estuarine type and nutrient loading, with slightly greater ranges of temperature and salinity. Thus, studies of dinoflagellate cyst records from Oslofjord, Norway (e.g., Dale et al., 1999), Koljö Fjord, Sweden (Harland et al., 2004a, 2004b) and Gullmar Fjord, Sweden (Harland et al., 2006, 2013) provide relevant
insights on the paleoecological significance of some cyst species such as *O. centrocarpum* and cysts of *P. dalei*.

### 7.1.1. Autotrophic cyst taxa

The dominant species in the Effingham Inlet cyst record, *O. centrocarpum*, is an opportunistic species of autotrophic affinity, known to tolerate a wide range of environmental conditions (e.g., Marret et al., 2001; Zonneveld et al., 2013). Dale et al. (1999), investigating the effects of cultural eutrophication in the Osofjord over the last ~200 years, recorded an increase of *O. centrocarpum* abundances with the initial increase in nutrient loading, confirming that it responds positively to an increasing nutrient supply. In coastal British Columbia, *O. centrocarpum* has been reported to dominate cyst assemblages in the Seymour–Belize and Effingham inlets (e.g., Kumar and Patterson, 2002; Radi et al., 2007). In the Strait of Georgia (Fig. 1a), a sediment trap study showed that *O. centrocarpum* was present year-round, with increased abundances in late summer (Pospelova et al., 2010). Thus, *O. centrocarpum*, an important contributor to primary productivity in Effingham Inlet, indicates conditions of moderate to high nutrient supply and likely occurs predominantly in summer and early fall.

*Pentapharsodinium dalei* is the second most important autotrophic species in the Effingham Inlet cyst record (Fig. 5). In north European fjords, *P. dalei* is known to occur in the spring plankton and its cysts are used as indicators of spring conditions (e.g., Dale, 1977; Dale et al., 1999; Harland et al., 2004a, 2004b, 2006, 2013). Multivariate analysis of the abundance of this species in surface sediments from the Strait of Georgia suggests a close correlation with spring productivity and lower salinities (Radi et al., 2007), and sediment trap data in the region indicate that this taxon occurs predominantly in winter and spring when SST is at its lowest (Pospelova et al., 2010; Price and Pospelova, 2011). In temperate estuarine waters from New England (USA), Pospelova et al. (2004) showed that *P. dalei* cyst abundances are negatively correlated with SST, indicating an affinity for cooler waters in these systems. Since this species mostly occurs in coastal waters of southern Vancouver Island during the rainy winter and spring seasons, it is also possible that *P. dalei* responds to reduced SSS.

Two species of the genus *Spiniferites*, *S. elongatus* and *S. ramosus*, are also consistent contributors to the autotrophic cyst assemblages in Effingham Inlet (Fig. 5). In general, the distribution of *S. elongatus* is limited to polar to sub-tropical regions of the Northern Hemisphere, whereas *S. ramosus* is observed at all latitudes in both hemispheres (including intertropical regions), suggesting that it can at least tolerate much higher temperatures than *S. elongatus* (e.g., Zonneveld et al., 2013). In southern New England lagoons, abundances of *S. elongatus* are negatively correlated with SST, indicating an affinity for colder waters in these temperate estuarine systems (Pospelova et al., 2004).

### 7.1.2. Heterotrophic cyst taxa

*Brigantedinium* spp. are the most abundant taxa in the heterotrophic cyst assemblages (Fig. 5). Representing several species, this genus is clearly associated with high levels of primary productivity (e.g., Dale, 1996; Pospelova et al., 2008; Radi and de Vernal, 2008; Price and Pospelova, 2011; Bringué et al., 2013; Zonneveld et al., 2013). *Brigantedinium* spp. also show the highest correlation with the % biogenic silica record in core TULK001 (Pearson’s *r* = 0.42, *p* < 0.001). The occurrence of *Brigantedinium* spp. is expected to be mostly controlled by the availability of diatoms, their preferred prey, that typically peak in the spring and early summer in the vicinity of Barkley Sound (e.g. Taylor and Haigh, 1996; Chang et al., 2013).

In addition to *Brigantedinium* spp., there are other members of the family *Protoperidiniaceae* that are associated with elevated levels of primary productivity in the region, in particular cysts of *P. americanum* and *S. quanta* (e.g., Radi et al., 2007; Pospelova et al., 2008; Radi and de Vernal, 2008; Price and Pospelova, 2011; Bringué et al., 2013; Zonneveld et al., 2013). In Saanich Inlet, *P. americanum* cyst abundances in sediment trap samples correlated negatively with SST (Price and Pospelova, 2011), and in the Strait of Georgia, maximum abundances were recorded during spring and early summer (Pospelova et al., 2010). *Selenopemphix quanta* was recorded in greater abundances during spring sampling in Koljö Fjord (Harland et al., 2004b), but was more abundant from spring to fall in Saanich Inlet (Price and Pospelova, 2011), and at the beginning and end of summer in the Strait of Georgia (Pospelova et al., 2010). Thus, both species most likely respond to elevated levels of diatom productivity.

Many species of the genus *Echinodinium* are also important contributors to the assemblages, including *E. delicatum, E. granulatum* and *E. aculeatum* (Fig. 5). In sediment trap studies from the NE Pacific, these species are typically recorded in summer, when primary productivity is still relatively high and surface temperatures are either rising or at the annual maximum (Pospelova et al., 2010; Price and Pospelova, 2011; Bringué et al., 2013). Although little is known about cyst type M1, it is recorded mostly during the fall in the Santa Barbara Basin (off Southern California), suggesting that this taxon also favors relatively warmer waters (Bringué et al., 2013).

Cysts of *P. fukuyoi* usually represent only a minor fraction of the assemblages in the region (e.g., Radi and de Vernal, 2004; Radi et al., 2007; Pospelova et al., 2008; Mertens et al., 2013). They were dominant during summer and early fall in sediment trap time-series from the NE Pacific (as “cyst type A” in Pospelova et al., 2010; Price and Pospelova, 2011 and Bringué et al., 2013).

The cyst of *P. minutum* (not to be confused with *Islandinium minutum*) is one of the most abundant species among cysts produced by heterotrophic dinoflagellates in the core record (Fig. 5). In Saanich Inlet, this taxon shows a clear seasonality with maximal abundances in spring, and in the NE Pacific (as “cyst type A” in Pospelova et al., 2010; Price and Pospelova, 2011 and Bringué et al., 2013).

Lastly, *A. saanichii* is the third most abundant taxon in the heterotrophic cyst assemblages (Fig. 5). Assuming a similar ecology as *A. saanichii*, *A. saanichii* cysts are expected to indicate conditions of relatively lower SST and SSS in the area (Mertens et al., 2012b).

### 7.1.3. Paleoenvironmental interpretation of PCA biplots

Based on current knowledge of key dinoflagellate cyst ecologies in the region, we can interpret the environmental gradients illustrated by the PCA biplots presented in Fig. 6. A reconstruction of North Pacific SST over the “PDO region” (22.5°N–57.5°N, 152.5°E–132.5°W; data from Mann et al., 2009) and the percent biogenic silica from core TULK001 are plotted passively (i.e., without intervening in the ordination) on the PCA biplots (Fig. 6). We advise caution when interpreting such gradients, since multivariate analyses such as PCA are designed to extract the dominant modes of variability, and their “principal components” may sometimes illustrate an oversimplification of the species preferences and significance. Nevertheless, we identify possible environmental gradients that are relevant in the context of the specific settings of Effingham Inlet.

In the autotrophic cyst assemblages, Auto PC1 is almost entirely driven by *O. centrocarpum* and sample scores along this axis are directly related to its ecology. As discussed in Section 7.1.1, *O. centrocarpum* indicates conditions of moderate to high nutrient supply, and likely occurs predominantly in summer and early fall in Effingham Inlet. Auto PC2 seems to separate species associated with cooler waters (the cyst of *P. dalei* and *S. elongatus* on the negative side, with at least cysts of *P. dalei* occurring most likely in winter and/or spring, from species associated with warmer conditions in this system (*O. centrocarpum*, occurring mostly in summer, and *S. ramosus*; Fig. 6). The interpretation of a surface temperature gradient depicted by Auto PC2 is supported by the strong, positive correlation of the variable “Reconstructed North Pacific SST” on the PCA biplots (Fig. 6).

Among heterotrophic cyst assemblages, the ordination of species illustrates an environmental gradient ranging from cooler and highly
7.2. Interpretation of dinoflagellate cyst zones

Paleoenvironmental interpretations of the cyst assemblages within each zone are based on cyst concentrations (total, auto- and heterotrophic, and individual cyst taxa), relative abundances of cyst taxa in the auto- and heterotrophic cyst assemblages, as well as the environmental gradients depicted in PCA biplots (Figs. 4, 5 and 6).

7.2.1. Zone D1a (AD 1090 to 1126)

Total cyst concentrations in this interval are close to the core average (Fig. 4). With negative scores on Auto PC1 (lower O. centrocarpum abundances) and positive scores along Hetero PC1 (lower diatom productivity), this time interval was likely marked by moderate levels of primary productivity (Fig. 6). In autotrophic cyst assemblages, an apparent displacement of S. ramosus in the oldest samples in the zone by S. elongatus in the overlying samples (reflected in Auto PC2 by a switch from positive to negative values) seems to mark a transition from warmer to cooler conditions in zone D1a (Figs. 5 and 6). This indicates that the oldest section of the core likely contains a record of higher SST and reduced nutrient input. Measurements of O. centrocarpum process length indicate less dense surface waters, thus fresher and/or warmer conditions.

7.2.2. Zone D1b (AD 1126 to 1228)

Lower abundances of cysts of P. dalei and S. elongatus in the autotrophic cyst assemblages, two cyst taxa associated with lower SST in the area, suggest that typical winter and spring conditions might not have been well expressed during this time. An increase in O. centrocarpum concentrations (Fig. 5) may suggest the prevalence of summer-like conditions during this interval. This interpretation is consistent with a marked decrease in concentrations of heterotrophic cyst taxa (Figs. 4 and 5). We interpret that zone D1 captured the end of the relatively warm interval known globally as the Medieval Climate Anomaly (MCA; Fig. 8).

7.2.3. Zone D2a (AD 1228 to 1438)

Half of the samples from zone D2a fall into homogenous units (Figs. 2 and 5) and these cyst assemblages must be interpreted with caution. Assuming that the dinoflagellate cyst assemblages were minimally affected by the advection of allochthonous sediment, increased abundances of cysts of P. dalei suggest well expressed winter and spring conditions with cooler and possibly nutrient rich waters. Increased concentrations of Brigantedinium spp. also indicate that diatom productivity was high, pointing to a stronger (and/or earlier) influence of upwelled waters during this interval. Concurrently, higher abundances of cysts of A. cf. saanichi and negative Hetero PC2 values point relatively cool conditions during this interval. Thus, zone D2a is marked by a general cooling and relatively high levels of primary productivity.

7.2.4. Zone D2b (AD 1438 to 1724)

This interval is marked by high concentrations of cyst taxa associated with elevated levels of primary productivity (Brigantedinium spp. and the cyst of P. americanum), as reflected by the negative scores along Hetero PC1 (Figs. 5 and 6). Although variable, O. centrocarpum concentrations are generally high, also contributing to primary productivity in the inlet and further supporting conditions of high nutrient supply. In terms of temperature, important contributions of cysts of P. dalei to the autotrophic cyst assemblages, together with lower abundances of cysts of P. minutum (reflected in negative Hetero PC2 values), suggest rather cooler conditions. Thus, similarly to zone D2a, zone D2b was characterized by cool and productive conditions, likely associated with strong and/or prolonged upwelling along the coast.

7.2.5. Zone D3 (AD 1724 to 1776)

Autotrophic cyst taxa concentrations in zone D3 are slightly above the core average (Fig. 4), with relatively higher contributions of S. ramosus to the assemblages (Fig. 5). Concentrations of heterotrophic cyst taxa are the highest in the core record (Fig. 4), with markedly higher contributions of cysts of P. minutum and A. cf. saanichi (Fig. 5). This suggests that this ~50 year interval was marked by high levels of marine primary productivity and slightly warmer conditions. It is possible that favorable conditions for phytoplankton growth in the inlet were sustained over a greater portion of each year, suggesting a longer upwelling season and/or sustained nutrient input.
7.2.6. Zone D4 (AD 1776 to 1954)

A gradual decrease in concentrations of heterotrophic cyst taxa is observed in zone D4, with increasingly positive values along Hetero PC2 suggesting a slight, gradual warming. However, the sustained presence of cysts of *P. dalei* and most heterotrophic cyst taxa throughout the zone suggest relatively cool (with negative Auto PC2 values) and productive (negative Hetero PC1 values) conditions in winter and spring and/or prolonged spring conditions. Thus, cyst assemblages from zone D4 may indicate that the influence of spring upwelling was well expressed, but slightly warmer conditions and/or shorter productive seasons gradually took place over this time interval.

7.2.7. Zone D5 (AD 1955 to 1990)

A dramatic increase in *O. centrocarpum* concentrations is observed in the most recent interval from core TULK001, accompanied by a decrease in *P. dalei* cyst abundances (Fig. 5). Heterotrophic cyst taxa concentrations are the lowest in the core record, except for cysts of *P. minutum* and *P. fukuyoi* and cyst type M1 (Fig. 5). With positive values along both Auto PC2 and Hetero PC2, the assemblages indicate warmer conditions during both spring and summer/fall. It appears that a greater proportion of the primary productivity is assumed by autotrophic dinoflagellates in the second half of the 20th century. This is consistent with the record low abundances in most diatom species (including *Chaetoceros* resting spores) documented from the sedimentary record of Effingham Inlet by Hay et al. (2007).

7.3. Climate variability during the last millennium

7.3.1. MCA, LIA and 20th century warming

The evidence for past oceanographic and climatic changes encoded in the dinoflagellate cyst record from Effingham Inlet is put into the context of the global, hemispheric and regional paleoclimate in Fig. 8. A reconstruction of temperature anomalies in the “PDO region” (Mann et al., 2009), representing a large area of the North Pacific, are also provided in Fig. 4 for comparison. Our interpretations of past local conditions from the cyst assemblages appear to be consistent with previously documented hemispheric scale climatic intervals such as the MCA, LIA and warming in the second half of the 20th century.

Dinoflagellate cyst zone D1 (from ~AD 1090 to 1228), marked by conditions of relatively higher SST, lower SSS and lower primary productivity levels in Effingham Inlet, might have captured the end of the MCA, an interval generally characterized by positive air- and sea-surface temperature anomalies (e.g., D’Arrigo et al., 2006; Mann et al., 2009; Fig. 8). Even though the timing of the termination of the MCA varies slightly regionally (Fig. 8), the cyst record indicates that this relatively warmer interval in Effingham Inlet ended locally at ~AD 1230, as previously suggested from global (e.g., Mann et al., 2009), hemispheric (D’Arrigo et al., 2006) and regional (Lucas and Lacourse, 2013) reconstructions.

Zone D2 in the dinoflagellate cyst record (AD 1228 to 1724) is characterized by lower SST and relatively higher levels of primary productivity (Fig. 8). This interval most likely corresponds to the local expression of the LIA, although the exact timing of this generally cooler interval seems to vary regionally (see Fig. 8). On a hemispheric scale, tree-ring records indicate a general cooling reconstructed between AD 1100 and 1400 (Fig. 4), but the LIA is identified as a markedly cooler interval starting only at ~AD 1450 (D’Arrigo et al., 2006). In coastal Alaska, episodes of ice expansion documented from land-terminating glaciers associated with the LIA started as early as the middle 13th century (Calkin et al., 2001), a timing that was also observed in the Canadian Cordillera (Claus et al., 2009; Menounos et al., 2009).

The timing of the termination of the LIA is somewhat ambiguous in the dinoflagellate cyst record. The cyst assemblages in zone D3 suggest that highly productive but slightly warmer conditions have prevailed for ~50 years in the mid-18th century. Interestingly, zone D3 appears to have occurred between two marked glacial advances recorded in Strathcona Park, central Vancouver Island (Lewis and Smith, 2004; Fig. 8), suggesting that local hydrographic conditions might differ from the previous and subsequent intervals, with a possible decrease in (winter) precipitation and/or an increase in air temperature. Later in the dinoflagellate cyst record, the base of zone D4 (AD 1776 to 1800)}

---

**Fig. 8.** Summary of NE Pacific coastal region paleoclimate over the last millennium, from a selection of previously published studies providing reconstructions on global, hemispheric and regional scales (organized along a north to south gradient). The dinoflagellate cyst zones from core TULK001 are indicated on the right and in the background coloration. Abbreviations: BC: British Columbia; LIA: Little Ice Age; MCA: Medieval Climate Anomaly; MWP: Medieval Warm Period; MXD: Maximum latewood density; NE: Northeastern; SST: Sea-surface temperature; US: United States; wAL: winter Aleutian Low.
1954) is characterized by relatively cool and productive conditions, with a gradual warming toward the end of the zone (Fig. 8). It is thus possible that the LIA extended locally until the end of the 19th century, when dinoflagellate cyst data record the last “strong” signals of cooler SST and elevated levels of primary productivity (Figs. 5 and 6B). We conclude that the LIA in Effingham Inlet was likely initiated as early as the beginning of the 13th century and probably lasted until the end of the 19th century.

More recently, instrumental temperature records around the world have identified a clear warming trend during the 20th century, regarded as anomalous in the context of the variability over at least the past millennium (e.g., Cane et al., 1997; Mann et al., 1999, 2009; Jones and Mann, 2004; D’Arrigo et al., 2006; Field et al., 2006a). An “early” warming pulse in the first decades of the 20th century is documented from several records in the Northern Hemisphere (e.g., Field et al., 2006a; Barron et al., 2010, 2013; Bringué et al., 2014; Johnstone and Mantua, 2014). However, it is in the second half of the 20th century that the warming trend is strongest (e.g., Jones and Mann, 2004; Field et al., 2006b), particularly in the extra-tropical NE Pacific (e.g., Cane et al., 1997) with a clear contribution from anthropogenic forcings (e.g., Levitus et al., 2001; Barnett et al., 2005). In Effingham Inlet, the dinoflagellate cyst record shows a dramatic increase in O. centrocarpum during the second half of the 20th century, with peak concentrations almost 10 times higher than the next highest peak during the rest of the millennium (Fig. 5). In addition, the composition of dinoflagellate cyst assemblages in zone D5 (AD 1955–1990) indicates warmer conditions and reduced primary productivity. While we do not quantify the magnitude of the change in temperature, the dinoflagellate cyst record indicates a marked warming since – AD 1955 at the study site.

An onset of warming around AD 1955 in the region might appear rather late, considering the growing body of evidence for warming in the California Current System in the early 20th century with noticeable changes in the pelagic ecosystem (e.g., Field et al., 2006a; Barron et al., 2010, 2013; Bringué et al., 2014; see also Fig. 4). However, evidence from glacier recession in central Vancouver Island suggest that cooler conditions have endured locally until the 1930s (Smith and Laroque, 1996; Lewis and Smith, 2004). In core TULK001, the hiatus induced by the 1946 seismite in the record prevents us from documenting the variability between 1919 and 1946. However, the cyst assemblages from the three samples directly overlying the seismite (representing the years 1946 to 1955) cluster with the previously deposited assemblages from zone D4 in the CONIC dendrogram (Fig. 5). This confirms that conditions during the first half of the 20th century were more similar to those prevailing in the 19th century than to the rest of the 20th century, with warmer conditions impacting the local phytoplanktonic communities no earlier than the mid-1950s.

Thus, our results improve the constraints on the timing of the MCA, LIA and warming in the second half of the 20th century in the vicinity of Effingham Inlet. However, much regional variability is observed in the expression of such generally cooler or warmer intervals, even within the NE Pacific region (Fig. 8). For instance, the MCA is expressed as a cooler interval in the Santa Barbara Basin sedimentary record and further south, while the LIA was likely marked by positive SST anomalies in these coastal regions (e.g., Barron et al., 2010; Graham et al., 2007; Fig. 8). Considerable variability is also observed within each interval (e.g., D’Arrigo et al., 2006; Mann et al., 2009), as exemplified by the complex, dynamic behavior of glaciers in the Canadian Cordillera during the LIA (e.g., Clague et al., 2009; Menounos et al., 2009). This highlights the regional and complex character of such intervals and we reiterate that appropriate spatial and temporal scales must be specified when using terms such as MCA or LIA (e.g., D’Arrigo et al., 2006).

7.3.2. The salinity (precipitation) signal
Sea-surface salinity has been identified as one of the factors controlling dinoflagellate cyst distribution in surficial sediments from the world’s oceans (e.g., Zonneveld et al., 2013), including in the NE Pacific (e.g., Radi and de Vernal, 2004; Radi et al., 2007; Pospelova et al., 2008). In addition, variations in the process length of O. centrocarpum can be used as a proxy for seawater density in the region (Mertens et al., 2012c), which in Effingham Inlet is primarily influenced by salinity (see Section 3.3.3).

Average process length of O. centrocarpum, together with concentrations of freshwater palynomorphs, seem to indicate slightly fresher conditions in zone D1a (AD 1090 to 1126), during the second half of the 16th century, and in zone D4 (AD 1776 to 1954; Fig. 4). Reduced salinities in zone D1a are consistent with the observation of elevated abundances of the brackish water diatom Cyclotella choctawhatcheeana recorded during this interval in Effingham Inlet inner basin sediments (Hay et al., 2007). Possibly fresher conditions in zone D4 might be associated with a documented increase in precipitation inferred from foraminiferal and thecamoebian faunal changes in the Seymour–Belize Inlet, located just north of Vancouver Island, although this wetter interval is thought to have begun – AD 1575 (Vázquez Riveros and Patterson, 2009; Fig. 8). Hay et al. (2009) also recorded increased abundances of C. choctawhatcheeana in Effingham Inlet inner basin sediments during the interval corresponding to cyst zone D4.

Although salinity variations are encoded in the dinoflagellate cyst record from core TULK001, they appear to be of minor importance compared to the temperature and primary productivity signals. This might be explained as follows. Firstly, the annual range of SSS variations in Effingham Inlet inner basin is relatively small for an estuary (between 25 and 32 psu; see Section 3.3.3), which reflects the small size of the catchment area of the Effingham River (~79 km²) and the absence of glacial meltwater within the drainage basin (e.g., Dallimore et al., 2005). Secondly, the bulk of the precipitation typically occurs locally in late fall and winter, at times when primary productivity as a whole and most likely dinoflagellate cyst production is at its annual minimum. Thus, the cyst record is not likely to encode strong signals of winter precipitation in the area. This might also explain the poor correspondence between the dinoflagellate cyst record and reconstructions of wintertime strength of the AL (e.g., Osterberg et al., 2014; Fig. 8). Rather, variations in dinoflagellate cyst assemblages seem to reflect changes in the strength and/or duration of seasonal coastal upwelling, which depends on the summertime NPH pressure system. However, note that intervals of stronger wintertime AL reconstructed by Osterberg et al. (2014) might have resulted in higher precipitations in winter and higher sedimentation rates in the Effingham Inlet record, as suggested by slightly steeper slopes in the age-depth relationship in the 14th century and since – AD 1664 (Figs. 3 and 8).

7.3.3. Dominant modes of variability in dinoflagellate cyst concentrations
Wavelet analyses of dinoflagellate cyst concentrations shed additional light on the local variability in cyst production over the past millennium (Fig. 7). While the sampling resolution does not allow the documentation of multiannual variability in the range of ENSO, the wavelet power spectra identify significant periodicities between ~15 and 38 years in both autotrophic and heterotrophic dinoflagellate cyst concentrations that may reflect variability associated with the PDO. Whether or not this variability is a consequence of environmental changes induced by PDO phases remains unclear, as we find almost no correlation between the dinoflagellate cyst data and the tree-ring based reconstruction of the PDO index of MacDonald and Case (2005; Fig. 4). Nevertheless, this “high frequency” variability is consistent with observations of Ivanochko et al. (2008a) who noted that (multi)decadal oceanic variability was prevalent over the last 10,000 years in a % biogenic silica record from Effingham Inlet inner basin sediments.

Within the last millennium, we were able to identify several intervals of reduced expression of periodicities in the range of PDO variability (Fig. 7). In general, these periodicities are only intermittent from the beginning of the record up to ~ AD 1600. A weaker expression of high
frequency variability between AD 1200 and 1400 might simply be due to the nature of the sedimentary record, with the possibility of homogenous units smoothing the signals. Alternatively, this may be partly explained by the presence of prolonged phases of mostly negative (from the base of the record to AD 1300) and positive (AD 1450 to 1600) reconstructed values of the PDO index during this interval, without any pronounced shift (MacDonald and Case, 2005; Fig. 4). An absence of signal may also result from the interaction between ENSO and PDO, which tends to reduce the expression of temperature and precipitation signals in the region when the two phenomena are out of phase (e.g., Gershunov and Barnett, 1998; Wang et al., 2014). Later in the record, a relatively short interruption in decadal scale variability is suggested in the heterotrophic dinoflagellate cyst concentrations during the second half of the 19th century (Fig. 7), which may correspond to a reconstructed weaker expression of PDO variability in the region, documented for instance by Biondi et al. (2001), Gedalof and Smith (2001) and Bringué et al. (2014).

Another interesting feature detected in the power spectrum of heterotrophic dinoflagellate cyst concentrations is a periodicity centered on ~93 years recorded between AD 1550 and 1770 (Fig. 7) that
may be associated with the 18.6 year lunar nodal cycle. Interestingly, 93 years is the smallest whole-number multiple of the lunar nodal cycle (18.6 × 5 = 93 years), which means that “it can lock onto seasons, while an 18.6 year cycle cannot” (Berger et al., 2004). The lunar nodal cycle has been documented in tree rings from western North America (Cook et al., 1997; Yasuda, 2009), in the Santa Barbara Basin (Berger et al., 2004; Bringué et al., 2014), in the NE Pacific (McKinnell and Crawford, 2007) and even offshore at Ocean Station P (Whitney, 2011). Changes in tidal forcings could modulate the delivery of nutrients to the surface layer in Effingham Inlet, ultimately affecting diatom and dinoflagellate production. However, if the lunar nodal cycle is the cause of this periodicity, it should be detected throughout the record, which is not the case. Therefore, we cannot state with confidence that the 93 year periodicity is related to the 18.6 year lunar nodal cycle in the record from core TULK001.

Time-series analysis of a dinoflagellate cyst sedimentary record from the Santa Barbara Basin spanning the last 260 years documented very similar patterns in the variability of heterotrophic cyst taxa, with
periodicities centered on 9, 13 and 30 years and 93 years (Bringué et al., 2014). In addition, these periodicities are also within the range of variability documented in high resolution biogenic silica records from Effingham Inlet that partially overlap our core record (from approximately AD 1000 to 1450 in Ivanochko et al., 2008a; and between AD 1947 and 1991 in Patterson et al., 2013). This provides additional evidence for the coherent variations between diatom populations and heterotrophic dinoflagellates. More importantly, this suggests that the changes in environmental conditions driving the variability in diatom and heterotrophic dinoflagellates were coherent at the two sites. In the autotrophic dinoflagellate cyst records from Effingham Inlet and Santa Barbara Basin (Bringué et al., 2014), the wavelet power spectra show some common periodicities centered on ~16–20 years, but the coherence is less pronounced than the periodicities in the heterotrophic dinoflagellate cysts power spectra. This might be explained by the difference in species composition between the two sites and/or the difference in environmental conditions, for instance in terms of SST, SSS and terrestrial influence.
7.4. Seismites and homogenous units in Effingham Inlet inner basin sediments

Core TULK001 contains several seismites and homogenous units (Fig. 2). Our interpretation of the sedimentary facies and detailed age model for the core provides additional insights on the regional paleoseismicity and the processes leading to the formation of homogenous units in Effingham Inlet inner basin sediments.

This work confirms the timing of occurrences of seismites E1, E2 and E3 established by Enkin et al. (2013), who extended on the work of Dallimore et al. (2005; 2008) and Hay et al. (2009). Although most of the $^{14}$C dates used to establish the age model for core TULK001 were derived from core FC3 that was also used in the study by Enkin et al. (2013; see Fig. 3 and Table 3), four additional $^{14}$C dates from core TULK001 were included in this age model, providing further constraints on the local paleoseismicity, thus improving the robustness in the estimated timing of the deposition of seismites E1, E2 and E3. Comparison of the seismite age estimation from this study and by Enkin et al. (2013) indicates nearly identical results, with the exception of seismite E3 for which our estimated age (AD 1199 ± 28) is ~52 years younger than in Enkin et al. (2013; Table 2). A slightly younger estimated age for this particular seisomite is due to our choice to exclude $^{14}$C dates.

Plate IV. Bright-field photomicrographs of selected dinoflagellate cysts from Effingham Inlet core TULK001. Scale bars are 10 μm. 1. Cyst of Protoperidinium americanum, UVic 09-633, slide 2, T56/2-0; dorsal view, dorsal surface. 2. Cyst of Protoperidinium fukuyoi, UVic 09-511, slide 1, M37/1; orientation uncertain. 3. Dubridinium spp., UVic 09-562, slide 2, U330/0; apical/ventral view. 4. Cyst of Polykrikos schwartzii sensu Matsuoka et al., 2009, UVic 09-539, slide 1, S48/0; orientation uncertain. 5. Cyst of Polykrikos kofoidii sensu Matsuoka et al., 2009, UVic 09-540, slide 1, T50/0; orientation uncertain. 6. Cyst of Polykrikos cf. kofoidii, UVic 09-517, slide 2, Y33/4; orientation uncertain. 7. Cyst of cf. Polykrikos spp., UVic 09-610, slide 2, X58/1; ventral view, ventral surface. 8. Cyst of Gymnodinium spp., UVic 09-436, slide 1, Q44/1; orientation uncertain.

2. Cyst of Protoperidinium americanum, UVic 09-633, slide 2, T56/2-0; dorsal view, dorsal surface. 2. Cyst of Protoperidinium fukuyoi, UVic 09-511, slide 1, M37/1; orientation uncertain. 3. Dubridinium spp., UVic 09-562, slide 2, U330/0; apical/ventral view. 4. Cyst of Polykrikos schwartzii sensu Matsuoka et al., 2009, UVic 09-539, slide 1, S48/0; orientation uncertain. 5. Cyst of Polykrikos kofoidii sensu Matsuoka et al., 2009, UVic 09-540, slide 1, T50/0; orientation uncertain. 6. Cyst of Polykrikos cf. kofoidii, UVic 09-517, slide 2, Y33/4; orientation uncertain. 7. Cyst of cf. Polykrikos spp., UVic 09-610, slide 2, X58/1; ventral view, ventral surface. 8. Cyst of Gymnodinium spp., UVic 09-436, slide 1, Q44/1; orientation uncertain.
from samples within seismites, which are formed by remobilized material and provided slightly older 14C dates (see the likelihood functions of 14C dates TUL-5 and FC3-10 in Fig. 3). Our age model also provides additional evidence that seismite E1 likely corresponds to the AD 1700 megathrust earthquake (Enkin et al., 2013; Table 2).

Our geochemical and palynological data from core TULK001 provide further evidence of a more marine influence and sediment mixing during the formation of homogenous units. The four homogenous units identified show a relatively constant elemental composition within each unit (Fig. 2), indicating a high level of sediment mixing. Generally lower normalized molybdenum concentrations (Mo/Al ratio in Fig. 2) relative to the under- and overlying laminated horizons suggest that these units were deposited under less reducing (more oxygenated) conditions. One homogenous unit dated at ~AD 1720 appears to have a slightly different composition, with a possible coarser grain size (higher Ti/Al) and a higher Corg/N ratio, the latter suggesting a greater terrestrial influence than in the other three homogenous units. This unit is distinct from the AD 1700 (E1) seismite, being separated by ~2 cm of vague varves that clearly show lower Corg/N ratios (Fig. 2). One possibility is that the debris flow triggered by the 1700 megathrust earthquake temporarily altered the bathymetry around the sill, leaving some remobilized material at locations where it was more likely to be entrained by the bottom-hugging currents during oxygenation events. Another possibility, unrelated to the 1700 earthquake but rather climatically driven, would be the suppression of seasonality with more abundant year-round precipitation and muted diatom productivity. Increased precipitation in summer and suppressed diatom blooms could have promoted longer optimal growth conditions for P. dalei, whose cysts are particularly abundant in these samples (Fig. 5). Hay et al. (2009) also noted a suppression of the typical Thalassiosira–Skeletonema–Chaetoceros spring bloom succession in diatom assemblages from a homogenous unit (H1) in core EFKC9703-1 that likely corresponds to the same unit based on age estimation and geochemical properties.

The mechanism proposed for the formation of homogenous layers involves enhanced stratification by a freshening of surface waters that allow for sub-surface inflows into the inner basin (Dallimore et al., 2005), as indicated by generally increased abundances of the brackish water diatom C. choctawhatcheena in samples within homogenous units (Hay et al., 2009). We find no consistent evidence for reduced surface salinities in the cyst assemblages or freshwater palynomorph concentrations, although some samples within homogenous units have relatively higher concentrations of P. dalei cysts, which may indicate sustained spring conditions (Fig. 4).

Measurements of O. centrocarpum process length also suggest generally denser (saltier) conditions within homogenous units, consistent with the advection of allochthonous sediment previously deposited under more marine (saline) conditions, but arguing against fresher surface waters (Fig. 4). Only in the sample dated at AD 1216 does the wider range of values in O. centrocarpum process length suggest the presence of cysts formed under both fresher and saltier conditions. Therefore, we cannot confirm that all homogenous units in the inner basin sediments have formed during times of enhanced freshwater input to the basin, and several different mechanisms could be responsible for the formation of each specific unit.

8. Conclusions

The high resolution dinoflagellate cyst record from core TULK001 provides evidence of past climate variability along the west coast of Vancouver Island over the last millennium, and indicates that the past millennium was characterized locally by relatively stable conditions. However, within this relative climatic stability, several intervals showing subtle but distinct variations in temperature and primary productivity were recognized, which we associate with the local expressions of the Medieval Climate Anomaly, the Little Ice Age and warming in the second half of the 20th century.

A generally warmer and less productive interval was identified from the beginning of the record up to ~AD 1230, which we associate with the end of the Medieval Climate Anomaly. The Little Ice Age, characterized by lower temperatures year-round and more productive conditions in the inlet, immediately follows the MCA. Generally cooler conditions may have prevailed until the end of the 19th century, although the LIA appears to have been somewhat interrupted at least once in the mid-18th century. Dinoflagellate cyst assemblages suggest warmer conditions and lower diatom productivity in the second half of the 20th century, indicated by a dramatic increase in O. centrocarpum abundances and lower concentrations of heterotrophic cyst taxa.

Predominant decadal scale variability in total dinoflagellate cyst concentrations that may be associated with the PDO is detected among both autotrophic and heterotrophic cyst assemblages. Such decadal variability is only recorded intermittently from the beginning of the record up to ~AD 1600, and the heterotrophic cyst record also suggests a reduced expression of PDO-scale variability during the second half of the 19th century.

This study also provides further evidence on past seismic shaking in the region, estimated to have occurred at AD 1946, 1691 ± 12 (likely corresponding to the AD 1700 megathrust earthquake), 1328 ± 15 and 1199 ± 28. In addition, we confirm that the sediments within homogenous units were deposited under somewhat more oxygenated bottom water conditions, consistent with the reworking of recently deposited laminae by bottom currents during oxygenated inflows. However, not all homogenous units in the core have a stronger “marine” signature and homogenous lithologies might also be the result of the suppression of seasonality in the system.

While we are confident in our interpretations of the dinoflagellate cyst assemblages, largely based on current knowledge of the ecology of each species in this region and in other similar estuarine systems, a detailed study of a sediment trap time-series from the inlet is required to better constrain the seasonality of dinoflagellate cyst production in this particular system.

Supplementary material accompanying this article consists in Suppl. Fig. 1 (“Correlation between cores TULK001 and FC3 based on magnetic susceptibility, %opal and Corg/N ratio profiles”). Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.palaeo.2015.10.026.

Acknowledgments

We are grateful to the officers and crew of the CCGS John P. Tully for their help during the sampling. Financial support for this research was provided by a Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery grant (224236) to V. Pospelova and the Canadian Foundation for Climate and Atmospheric Research (CFCAS) to S.E. Calvert. M. Bringué was supported by the Fonds Québécois de la Recherche sur la Nature et les Technologies (FQRNT) B2 doctoral fellowship, the University of Victoria Bob Wright Graduate Scholarship, and Commander Peter Chance MAS Graduate Fellowship. We also wish to thank M. Soon (University of British Columbia) for supervising the C, N, carbonate C and opal determinations, as well as Z. Sandwith and A. Lew for their help in processing the samples and mounting the microscope slides, and C. Nittouer (University of Washington) for the loan of the Kasten corer. We are grateful to Dr. Fabienne Marret and one anonymous reviewer for their constructive comments that helped improve the manuscript.

References


Jacobson, D.M., Anderson, D.M., 1996. Widespread phycocyanin of ciliates and other pro-

Janson, J.A., Mertens, K.N., Head, M.J., de Vernal, A., Londeix, L., Marret, F., Matthiessen, J., Sangiorgi, F., 2014. Statistically assessing the correlation between salinity and mor-


Karepavich, A., Pospelova, V., 2010. Tracing the influence of sewage discharge on coastal 
ays of Southern Vancouver Island (BC, Canada) using sedimentary records of phyto- 

core for sedimentological and geochemical investigation of 
post-glacial evolution of a northeast Paci 

dinoflagellate cyst production and biogenic silica flux in Saanich Inlet (BC, Canada). 
Mar. Micropaleontol. 80, 18–43.


Radi, T., de Vernal, A., 2008. Dinoflagellate cysts as proxy of primary productivity in mid-high lati- 


Radi, T., Bonnet, S., Cornier, M.A., de Vernal, A., Duranton, L., Faubert, E., et al., 2013. Ope-

IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. 
Micropaleontology 63, 185–1887.


Ribeiro, S., Ellegaard, M., Kuijpers, A., 2012. Climate variability in West Greenland during the past 15,000 years: evidence from a high-resolution marine palynolog- 
ical record from Disko Bay. Boreas 41, 68–83.

Casey, 1911. Index to Genera and Species. The Protoceratium reticulatum from sur-
variance of sewage discharge on coastal 
ays of Southern Vancouver Island (BC, Canada) using sedimentary records of phyto-


Ruttenberg, J.E., de Vernal, A., Barrie, J.V., 2007. Distribution of dino-
variance. Mar. Micropaleontol. 80, 18–43.


Simpson, A.J., 1932. The Protoceratium reticulatum from sur-
variance of sewage discharge on coastal 
ays of Southern Vancouver Island (BC, Canada) using sedimentary records of phyto-

Smith, D.J., Larouque, C.P., 1996. 14C radiocarbon dating of a little ice age glacial ad-

Stahr, K., Moore, R.D., McKenzie, L.G., 2006. The role of syngenetic-scale circulation in the link- 
}


