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Research paper

A high-resolution marine palynological record from the central mainland coast of British Columbia, Canada: Evidence for a mid-late Holocene dry climate interval

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ABSTRACT

Sediments collected in a 12-m long core (VEC02A04) obtained from Frederick Sound in the Seymour–Belize Inlet Complex of British Columbia were deposited between ca. 4540 cal. yr BP and ca. 1090 cal. yr BP in primarily dysoxic conditions. The sediments are characterized by alternating intervals of fine grained massive and laminated units. Laminated sediments consist of light-coloured diatom-rich layers deposited during summer and dark-coloured mineral-rich layers deposited during winter. Laminated sediments are most common in portions of the core deposited between ca. 2840 cal. yr BP and ca. 1820 cal. yr BP, and correspond to a decline in the relative abundance and pollen accumulation rate of Cupressaceae pollen between ca. 3190 cal. yr BP and ca. 2250 cal. yr BP. The preservation of laminated units and decline of Cupressaceae pollen at this time suggest that a drier and possibly cooler climate punctuated otherwise wet and temperate late Holocene conditions in the Seymour–Belize Inlet Complex. We correlate the occurrence of the mid-late Holocene dry climate interval documented in Frederick Sound to dynamics in the relative position and intensity of the Aleutian Low pressure system and suggest that climate change associated with dynamics of this semi-permanent air mass affected primary productivity and vegetation of the Seymour-Belize Inlet Complex.

1. Introduction

Glacially scoured marine inlets along the coast of British Columbia (BC) provide unique settings for paleoclimate investigations because the presence of terminal sills, deposited as moraines by advancing glaciers, restrict the movement of dense, oxygen-rich water into inner basins (Thomson, 1981). The estuarine-type circulation common in coastal inlets further restricts circulation in inner basins and the resulting persistent dysoxia and anoxia in stagnant bottom waters excludes bioturbating organisms and prevents oxidative corrosion of pollen grains, creating an ideal environment for the accumulation of undisturbed sedimentary sequences and preservation of microfossils. In these respects, many coastal inlets of BC may differ from open ocean sites where pollen and spores are less frequently well preserved. Few paleoecological studies, however, have focused on the marine inlets of BC due to the logistical difficulties of coring in remote locations and in deep (>200 m) water. Saanich Inlet and Effingham Inlet on southeastern and southwestern Vancouver Island, respectively, are the only two marine fjords that have been extensively investigated in coastal BC (Fig. 1; Heusser, 1983; Pellatt et al., 2001; Nederbragt and Thurow, 2001; Chang et al., 2003; Dean and Kemp, 2004; Patterson et al., 2004a,b, 2005; Dallimore et al., 2005, 2008; Hay et al., 2007; Ivanochko et al., 2008). Additionally, few continuous decadal-scale resolution records of paleoclimate exist for coastal BC (Nederbragt and Thurow, 2001; Pellatt et al., 2001; Ivanochko et al., 2008). High-resolution marine palynological records can provide insights into both high and low frequency climate oscillations, and thus provide information not available from the relatively short instrumental record or from centennial-scale proxy climate reconstructions from terrestrial sites.

Frederick Sound is a topographically restricted anoxic to dysoxic fjord located at the southeastern extent of the Seymour–Belize Inlet Complex (SBIC) on the central mainland coast of BC (Fig. 2). The SBIC was chosen as an area of interest for research because little is known about the Quaternary environmental history of the central mainland coast of BC; the majority of paleoclimatological work in coastal regions of the province have focused on the southern coast and coastal islands (Mathewes, 1973; Mathewes and Heusser, 1981; Pellatt and Mathewes, 1994, 1997; Brown and Hebda, 2002; Lacourse, 2005). Additionally, the SBIC is located adjacent to the oceanic Coastal Transition Domain that extends from the northern tip of Vancouver Island to Dixon Entrance and is transitional between the upwelling California current system to the south and the downwelling Alaskan current system to the north (Fig. 3; Ware and Thomson, 2000).

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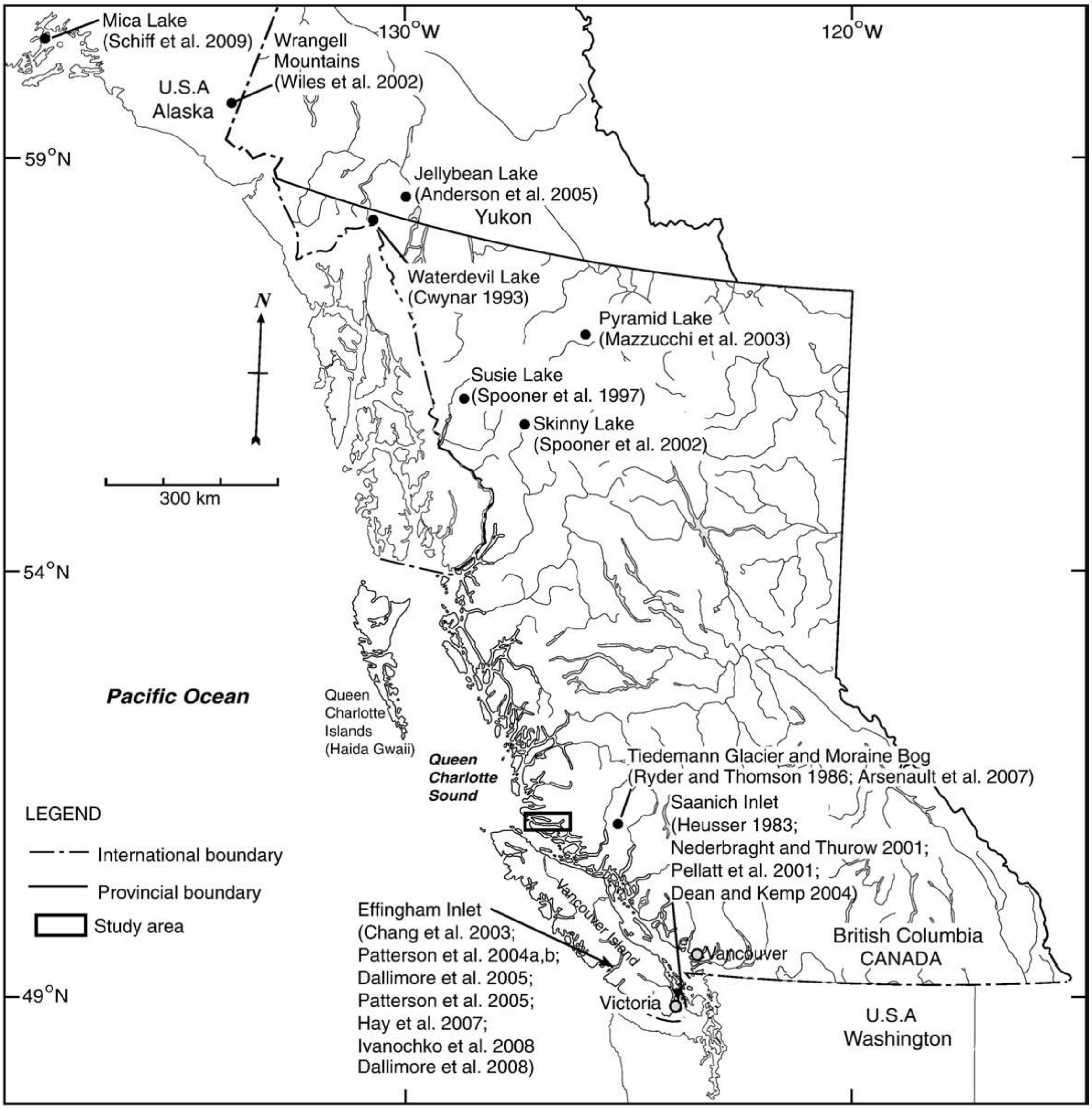

Fig. 1. Map showing the location of the study area and the location of other studies mentioned in the text.
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Because the relative position and strength of the Aleutian Low pressure system has been linked to basin wide ocean circulation patterns (e.g., the Pacific Decadal Oscillation and the El Niño Southern Oscillation; Trenberth and Hurrell, 1994), a near-coastal site at the same latitude as this oceanographically transitory region is expected to be a sensitive recording area of late Holocene atmospheric dynamics. The restricted location of Frederick Sound over 60 km inland from the coast, the position of the SBIC adjacent to an oceanographically transitional domain, and the fact that the SBIC opens to Queen Charlotte Sound and not directly to the open Pacific Ocean were other strategic considerations. The oceanography of this site, unlike Effingham Inlet, is not expected to be dominated by changes in the strength of upwelling or downwelling oceanographic currents.

2. Regional setting

2.1. Atmospheric circulation

The Aleutian Low and the North Pacific High semi-permanent atmospheric pressure systems influence the seasonal climate of coastal BC. The Aleutian Low pressure system intensifies from August to January as its Centre of Action shifts southeastward from the northern Bering Sea to the Gulf of Alaska. Maximum intensity (lowest pressure) occurs in January when the centre of action shifts over the western Aleutian Islands (Fig. 3). This cyclonic air mass, which persists until the late spring, delivers warm and moist maritime air from the south/southwest and frequent North Pacific storms to the coast of BC, resulting in relatively wet and mild winters in the study area (Fig. 3; Trenberth and Hurrell, 1994). The North Pacific High is present year-round off of the coast of California (30°N to 40°N). It reaches maximum intensity (highest pressure) from June to August when it expands in influence to encompass the entire Northeast Pacific Ocean. From May to September, coastal winds from the northeast flow in a clockwise direction and bring cool and dry continental air into coastal BC, causing the warm and dry summers typical of this region (Trenberth and Hurrell, 1994). The relative intensity and position of the Aleutian Low pressure system has changed abruptly with a cyclicity of 50 to 70 years over at least the last 200 years (the Pacific Decadal Oscillation), and at a lower frequency over at least the last ca. 7500 years (Minobe, 1999; Mantua and Hare, 2002; Anderson et al., 2005), possibly driven by changes in solar

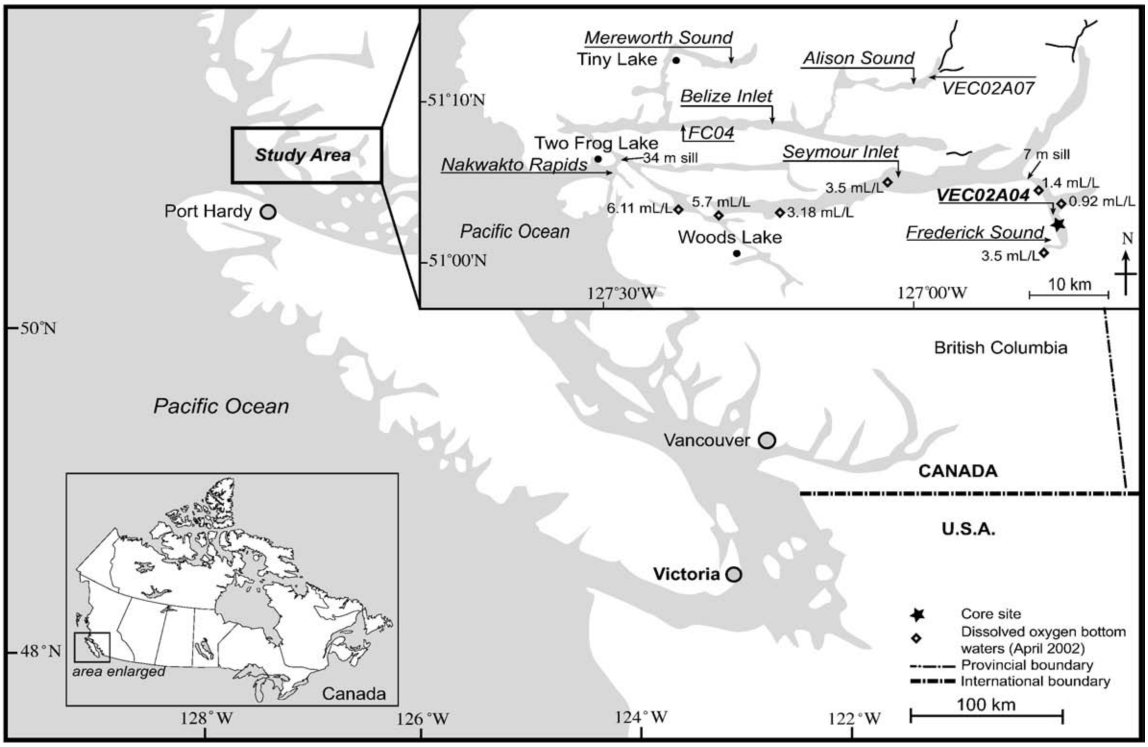

Fig. 2. Map showing the location of the Seymour–Belize Inlet Complex, Frederick Sound, the core site (VEC02A04), and bottom water dissolved oxygen measurements. The location of VEC02A07 (Patterson et al., 2007) and FC04 (Vázquez Riveiros and Patterson, 2009) are also shown.

activity (Christoforou and Hameed, 1997). In general, when the Aleutian Low pressure system is on average more eastward and/or intense, westerly winds form a meridional airflow pattern that generates frequent and intense North Pacific storms that are directed to the northern coast of BC and southern Alaska, resulting in relatively warmer and wetter winters in these regions and leaving the south coast of BC drier than usual. In contrast, a westward positioned and/or weaker Aleutian Low pressure system is associated with a more zonal airflow pattern that does not generate as numerous or intense North Pacific storms. As a result, winters along northern BC and southern Alaskan coasts are cooler and drier than usual and North Pacific storms that do form tend to be directed to south coastal BC (Klein, 1949).

2.2. Geographic setting

The SBIC is a network fjords located on the central mainland coast of BC between latitudes 50°50.2′N and 51°10.6′N and longitudes of 126°30.2′W and 127°40.5′W (Fig. 2). The SBIC opens to the Pacific Ocean through Queen Charlotte Sound by Slingsby and Schooner Channels. Queen Charlotte Sound is located within the Coastal Transition Domain that is situated between the Coastal Upwelling Domain to the south and the Coastal Downwelling Domain to the north (Fig. 3). As the Subarctic Current and West Wind Drift, large west-to-east surface currents situated at approximately 42°N and 29°N, approach North America they bifurcate at the Coastal Upwelling Domain due to divergence in prevailing wind patterns and split into the northern flowing Alaskan Current and the southward flowing California Current (Fig. 3; Ware and McFarlane, 1989).

2.3. Oceanographic setting

An important bathymetric characteristic of the SBIC is the presence of numerous glacially deposited sills that reduce the input of dense, oxygen-rich ocean water into inner inlets that, together with estuarine-type circulation, promote the stagnation of bottom waters that create ideal conditions for the accumulation and preservation of undisturbed sedimentary successions. Seymour Inlet, a 600 m deep basin, is connected to Queen Charlotte Sound at Nakwakto Rapids where estuarine-type circulation and a bedrock sill that is 34 m deep and 300 m wide make this the fastest tidal channel in the world (8 m/s; Thomson, 1981; Fig. 2). This bottleneck is so restrictive that sea level in the SBIC does not equalize with that of Queen Charlotte Sound during ebb and tidal flow (Fisheries and Oceans, 2003). Penetration of oxygen-rich upwelled waters into coastal inlets of BC can occur, particularly in the early spring during a rare combination of weak tidal currents, significant rainfall that strengthens estuarine-type circulation patterns, and strong (>10 m/s) northeasterly winds, although this phenomenon is more common in fjords located in the Coastal Upwelling Domain (Thomson, 1981). At present, upwelling conditions prevail in the open water areas outside of the SBIC, but despite strong seaward currents at Nakwakto Rapids, oxygenated waters do not penetrate into the SBIC (Thomson, 1981). Consequently, modern foraminifera fauna in Belize Inlet are typical of dysoxic marine environments, and are characterized by low diversities and dominated by agglutinated taxa (Sen Gupta, 1999; Vázquez Riveiros and Patterson, 2009). However, in the recent past (ca. 1575 A.D. to 1940 A.D.), diverse calcareous fauna occurred in Belize Inlet in response to higher bottom water oxygen levels associated with more frequent and stronger deep water renewal events into the SBIC (Vázquez Riveiros and Patterson, 2009).

Frederick Sound is a 240 m deep inlet that is located at the southeastern extent of the SBIC where it is further restricted from the Pacific Ocean by a 7 m sill at its mouth (Fig. 2). Vertical salinity profiles measured during research cruises of the Canadian Coast Guard Ship *Vector* in August 2000, April 2002, April 2003, and October 2003 reveal consistent and well-developed estuarine-type stratification throughout Frederick Sound. A low salinity surface plume (17 to 21) generated by freshwater input via rivers and streams concentrated at the head of the inlet is present throughout Frederick Sound above a bottom water layer characterized by a constant salinity near 27.5. Oxygen and temperature profiles indicate that Frederick Sound also

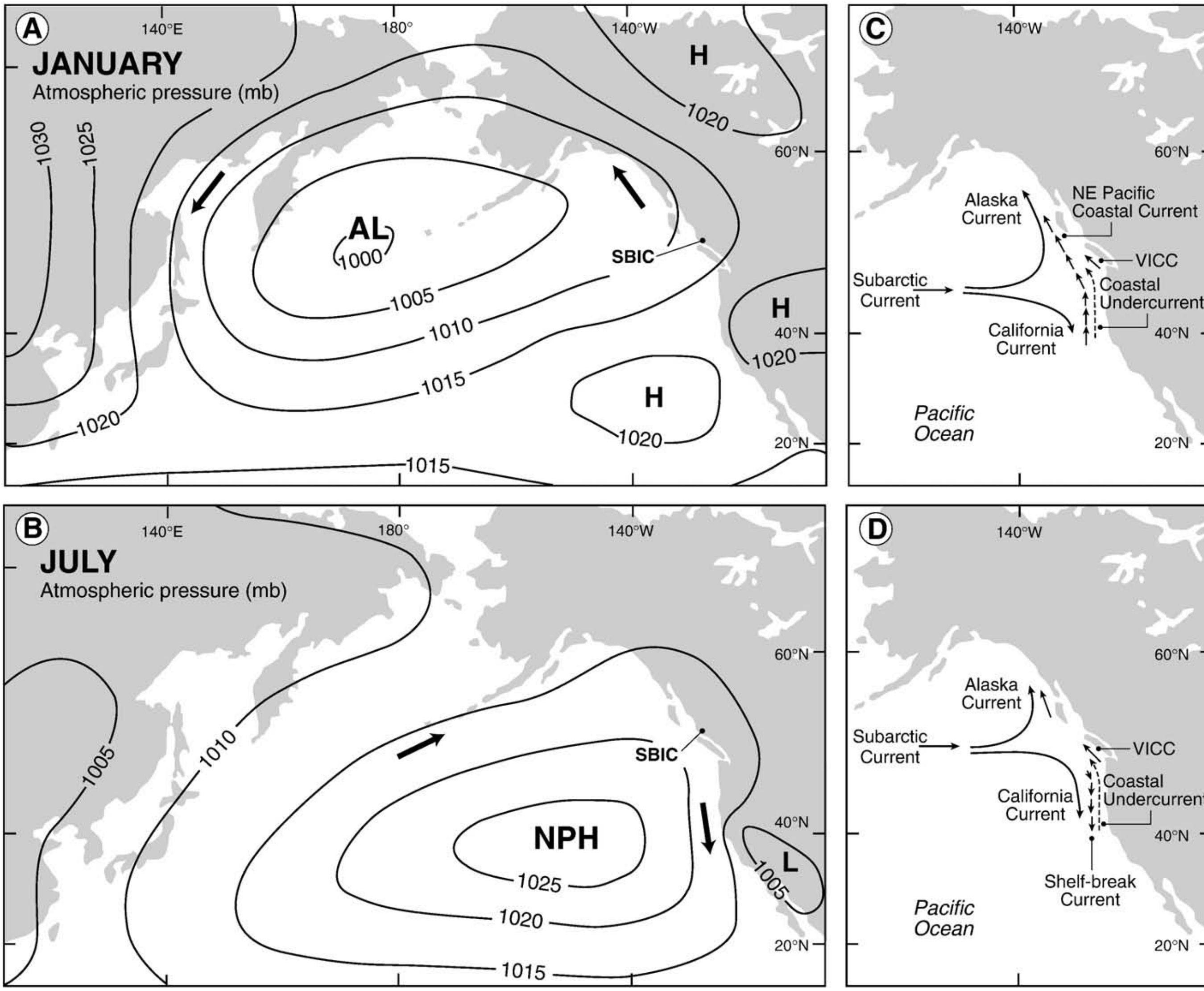

Fig. 3. Maps showing main ocean–atmosphere circulation features for the NE Pacific region in winter (A,C) and summer (B,D) months and the location of the Seymour–Belize Inlet Complex (SBIC) (after Favorite et al., 1976). In summer, northerly North Pacific High (NPH) winds generate the southward Shelf-Break Current at the surface and consequent offshore Ekman transport induces upwelling. During winter, southerly winds generate a northward drift producing the NE Pacific Coastal Current and consequent onshore Ekman transport. This causes an accumulation of low density, less saline water on the surface, thus restricting the upwelling of deep water. The Vancouver Island Coastal Current (VICC) and Coastal Undercurrent are permanent features although they vary in strength seasonally.

has a thermal gradient and that bottom waters are persistently dysoxic to anoxic below pressures of 50 to 100 dbar (dissolved $O_2 < 1$ mL/L to 3.5 mL/L; unpublished cruise reports 2000, 2002, 2003; Fig. 2).

2.4. Vegetation and physical setting

The landscape surrounding the SBIC is rugged and steep, reaching up to 900 m in elevation. Granitic and volcanic rocks of Mesozoic age dominate the bedrock of this region. Soils are poorly developed and acidic, derived from underlying igneous material and influenced by input from the coniferous canopy (Pojar and MacKinnon, 1994). Frederick Sound lies within the Coastal Western Hemlock Zone Very Wet Maritime Submontane variant (CWHvm1) that occurs on windward slopes from 0 m to 650 m above mean sea level several kilometers inland from the immediate coast, and extends north from near the Fraser River and to approximately 52°N latitude (Meidinger and Pojar, 1991; Green and Klinka, 1994; Pojar and Mackinnon, 1994). The climate of the CWHvm1 is cool (mean annual temperature 8.3 °C; range 7.0 °C to 10.1 °C) and wet (mean annual precipitation of 2682 mm; range 1555 mm to 4387 mm; unknown observation period; Green and Klinka, 1994). Forests of the CWHvm1 are dominated by *Tsuga heterophylla* (Raf.) Sarg. (western hemlock) and *Abies amabilis* (Dougl.) Forb. (amabilis fir) with *Thuja plicata* Donn ex D. Don (western redcedar; Meidinger and Pojar, 1991; Green and Klinka, 1994). At higher elevations, *Tsuga mertensiana* (Bong.) Carr. (mountain hemlock) grows in wet sites with deep organic soils and *Chamaecyparis nootkatensis* (D. Don) Spach, recently reclassified as *Callitropsis nootkatensis* (D. Don) Örsted (Little et al., 2004; yellow-cedar), is common in moist to wet rocky or boggy sites (Pojar and MacKinnon, 1994). *Taxus brevifolia* Nutt. (western yew) is an important mid-canopy or understory tree in mature *T. heterophylla*–*T. plicata* forests of this region (Pojar and MacKinnon, 1994). *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir) occurs in minor amounts in the CHWvm1 (Green and Klinka, 1994). Deciduous trees present in the CWHvm1 include *Acer glabrum* Torr. var. *douglasii* (Hook.) Dipp. (Douglas maple) that grows as a shrub or small tree on open, dry ridges as well as in moist, well-drained sites, and *Alnus* Mill. (alder), which is common in open, wet sites, such as avalanche tracks, burns, and along freshwater shore-lines (Pojar and MacKinnon, 1994). Both *A. rubra* Bong. (red alder) and shrubby *A. sinuata* (Regel) Rydb. (Stika alder), also known as *A. crispa* (Ait.) Pursh ssp. *sinuata* (Regel) Hulten (green alder), occur in this region (Pojar and MacKinnon, 1994). Various ferns, such as *Blechnum spicant* (L.) Sm. (deer fern), and *Polystichum munitum* (Kaulf.) C. Presl (western sword fern), bryophytes, and shrubs, such as *Vaccinium* L. species, form a dense understory in the forests of the CWHvm1 (Meidinger and Pojar, 1991; Green and Klinka, 1994).

3. Materials and methods

3.1. Core collection, sedimentology, and chronology

Scientific cruises to the SBIC aboard the Canadian Coast Guard Ship *Vector* were conducted in April and October of 2002. A 12.24-m long piston core, VEC02A04, was retrieved from a depth of 240 m in Frederick Sound and chosen for detailed study because a large proportion (41%) of the sediments are laminated. The uppermost 113 cm of sediment was observed to have been lost during core recovery. The sediment core was extruded from the liner and cut in half length-wise following collection. From one half of the sediment core, 62 slabs (20 cm long × 3 cm wide × 1 cm thick) were extracted, X-rayed, and logged at the Pacific Geoscience Centre, Sidney, BC. Core depth measurements begin at the top of the recovered sediments. Core depths are not adjusted for the loss of sediments during core extrusion between 195 cm and 178 cm, 175 cm and 135 cm, and 120 cm and 115 cm, or for very minor thicknesses of graded sedimentary sequences and slumps in the Frederick Sound core. Core depth measurements are only void-corrected where de-gassing interrupted the stratigraphy. Core slabs were shipped to Carleton University for sub-sampling and refrigerated (4 °C) storage and an archive of the core remains at the Pacific Geoscience Centre. Sediments were sub-sampled at the same approximate 10-cm intervals for pollen and diatoms (Wigston, 2005). Sub-samples for foraminiferal analysis were collected at approximate 5-cm intervals (Babalola, 2009).

The depths where laminated intervals and other facies occur were assessed by converting 1-cm resolution core log descriptions to binary data to represent the presence or absence of each facies type. These data were then analyzed using stratigraphically constrained cluster analysis (CONISS; Grimm, 1987).

Ten plant macrofossil samples were selected from the Frederick Sound core and submitted for radiocarbon dating by atomic mass spectrometry to IsoTrace Laboratories at the University of Toronto and to the ^{14}CHRONO Centre at Queen's University Belfast. Ages were calibrated to calendar years before present using Calib6.0 (Stuiver et al., 2009) and the IntCal09 dataset for terrestrial material (Table 1; Stuiver and Reimer, 1993; Reimer et al., 2009).

3.2. Pollen and spores

One hundred and sixteen 0.5 cm^3 aliquots of sediment were collected at approximate 10-cm intervals throughout the length of the Frederick Sound core for pollen analysis. Sediment sub-samples were subjected to pollen preparation techniques that followed Fægri and Iversen (1989) with the exception that hydrofluoric acid treatment and sieving were omitted. Briefly, 0.5 cm^3 aliquots of wet sediment were sub-sampled and subjected to hot treatments of 10% hydrochloric acid and 10% potassium hydroxide followed by acetolysis. Slurries were stained with safranin to aid pollen and spore identification, sequentially dehydrated with alcohol (ethanol and tert-butanol), and stored in silicone oil. A known quantity of *Lycopodium clavatum* L. spores was added to each sample prior to processing to calculate pollen and spore accumulation rates (one tablet per sample, batch no. 938934, $n = 10{,}679 \pm 953$ std. error spores/tablet; Stockmarr, 1971). Pollen and spores were enumerated at 400× magnification with an Olympus BX51 transmitted light microscope. The keys of McAndrews et al. (1973), Fægri and Iversen (1989), and Kapp et al. (2000) and reference slides (Aerobiology Institution and Research Pollen Reference Slide Set, Brookline, MA) aided pollen identification. Pollen was identified to the lowest possible taxonomic level. *Pinus* L. pollen was identified as diploxylon-type, haploxylon-type, or was undifferentiated (Fægri and Iversen, 1989). *Juniperus* L. (juniper), *C. nootkatensis, T. brevifolia*, and *T. plicata* pollen were grouped together as Cupressaceae. *Larix* Mill. (larch) and *P. menziesii* pollen are morphologically similar but because *Larix* is uncommon in coastal BC (Duhamel, 1963) this pollen type is attributed to *P. menziesii*. Pteropsida (monolete) spores include all monolete members of the class Pteridophyta except Polypodiaceae, the only family where the perine is commonly preserved. In this case, spores were identified as *Polypodium vulgare* L.-type. Fossil *L. clavatum* spores were differentiated from exotic spores by differential preservation and safranin stain acceptance following Stanley (1966) and Heusser (1983). Six core sub-samples had a pollen sum <300 (420, 460, 607, 684, 704 and 744 cm). A minimum count of 171 occurred at 420 cm. The main pollen sum includes all terrestrial pollen and spores from ferns and mosses because they are an important component of coastal forest ecosystems (cf. Brown and Hebda, 2002; Lacourse, 2005; Galloway et al., 2007, 2009). Calculation of pollen concentration followed Stockmarr (1971). Pollen accumulation rates (PARs; grains cm^{-2} yr^{-1}) were calculated from pollen concentrations (grains cm^{-3}) of each sample and the average sedimentation rate (cm yr^{-1}). Accumulation rates were calculated based on calibrated radiocarbon ages so that the temporal variation of radiocarbon production was not incorporated. Pollen percentage data were graphed using Tilia version 2.0 (Grimm, 1993) and the CONISS program for stratigraphically constrained cluster analysis (square root

Table 1
Conventional and calibrated radiocarbon ages measured by atomic mass spectrometry from the Frederick Sound sediment core.

Laboratory number	Depth (cm)	Sedimentology	Material dated	Conventional age (^{14}C yr BP)[a]	Calibrated age (cal. yr BP)[b,c]	Median calibrated age (cal. yr BP)[d]
TO-10788	97	Laminated	Wood fragment	1510 ± 60	1306–1523	1414.5 ± 108
TO-11082	313	Massive	Wood fragment	3070 ± 70	3076–3412	3244 ± 168[e]
TO-10789	457	Laminated	Wood fragment	2560 ± 80	2362–2784	2573 ± 211
TO-10790	457	Laminated	Wood fragment	3050 ± 60	3076–3383	3229.5 ± 153.5[e]
TO-11084	734	Woody layer	Pine cone	2540 ± 70	2432–2759	2595.5 ± 163.5
UBA-13359	945	Laminated	Wood fragment	3318 ± 32	3469–3633	3551 ± 82
TO-10791	1051	Laminated	Twig	4350 ± 80	4816–5093	4954.5 ± 138.5
UBA-13360	1060	Laminated	Wood fragment	3710 ± 22	3981–4094	4037.5 ± 56.5
TO-10793	1182	Massive	Wood fragment	3770 ± 60	3973–4300	4136.5 ± 163.5

[a] ± 90% confidence interval.
[b] Range represents 95% confidence interval.
[c] Calibrated using Calib6.0 (Stuiver et al., 2009) and the IntCal09 dataset (Stuiver and Reimer, 1993; Reimer et al., 2009).
[d] ± 95% confidence interval.
[e] Date omitted from Frederick Sound core age–depth model.

data transformation) was used to aid pollen diagram zonation (Grimm, 1987). Changes in pollen to spore ratios, that have the potential to detect oxidative corrosion due to the greater resistance of spores to oxidation (Havinga, 1964), were investigated using the PAR dataset.

Methods for the preparation and analysis of foraminifera preserved in the Frederick Sound core are presented in Babalola (2009). Briefly, 211 sub-samples were collected at approximate 5-cm intervals and were wet sieved with a 63 μm mesh and dried at 45 °C.

4. Results

4.1. Sedimentology

Visual inspection of core sediments and X-ray negative images of slabs of the Frederick Sound core indicate that sediments are largely composed of organic-rich dark olive-grey mud and silt with occasional intervals of fine sand (Fig. 4). Three dominant sedimentary facies occur: (1) graded layers (5% of measured facies thickness); laminated sediments (41%); and (3) massive sediments (sediments that lack internal structure; 44%). The remaining ten percent of the core is slumped (~3%) or missing (~7%). Graded intervals are rare, only occur between 905 cm and 730 cm of the core, and show a succession commencing with sand fining up to mud topped by a diatom-rich layer, and in one instance, a woody layer. We interpret graded sediments to have been deposited by sediment gravity flows. Sediment gravity flows may have been initiated by localized failure of a build up of loose sediments on the walls of the fjord (cf. Patterson et al., 2007).

Laminated sedimentary units range in thickness from 1 cm to 45 cm and laminae range in thickness from <0.05 mm to 3 mm. We interpret laminae to be composed of alternating seasonally deposited light-coloured diatom-rich layers deposited during spring and summer and dark-coloured mineral material deposited during autumn and winter, as has been observed elsewhere along the Northeast Pacific coast (Sancetta, 1989; McQuoid and Hobson, 1997; Chang et al., 2003; Patterson et al., 2007). Laminae are also composed of fecal pellets and organic debris with minor quartz and mica grains in some instances.

Massive sedimentary units range in thickness from a few millimeters to 20 cm and are determined by visual inspection to be composed of organic matter with occasional silt, fine sandy mud, fine sand, fecal pellets, and in one instance, woody debris. Sandy units compose ~1.2% of total massive sedimentary unit thickness and occur as lenses that range in thickness from 1 cm to 5 cm, with the thickest interval between 635 cm and 640 cm of the Frederick Sound core. The sand lenses are composed of quartz, mica, and clay, as well as plant debris. We interpret massive sedimentary units to have been deposited by re-suspension, homogenization, and deposition of basin sediments.

There is no indication of bioturbation, macrobenthos, or other evidence of sea-floor oxygenation events or evidence of tectonically-derived deposits, such as large slumps (>20 cm) or major disconformities, in the Frederick Sound core (cf. Dallimore et al., 2005;

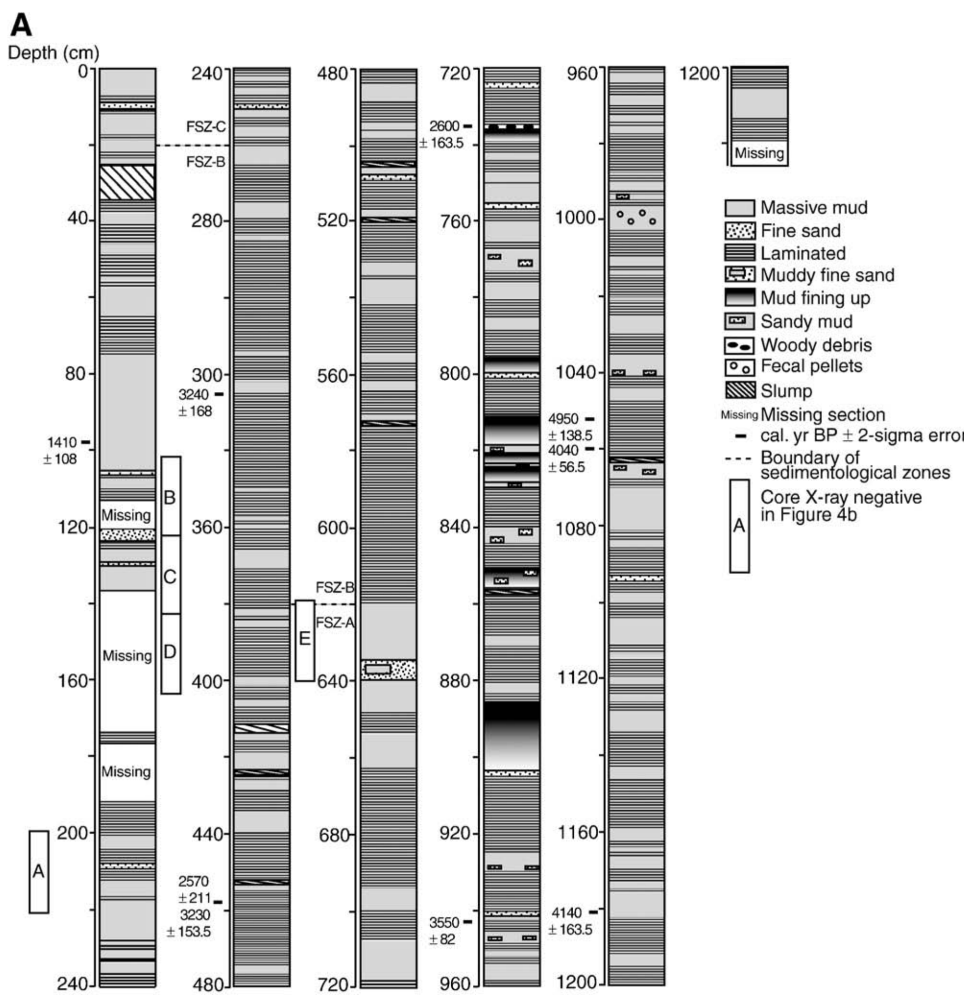

Fig. 4. Sedimentology of the Frederick Sound core. The chronology is from Table 1 and is in calendar years before present (cal. yr BP) rounded to nearest 10 years ±2-sigma ranges.

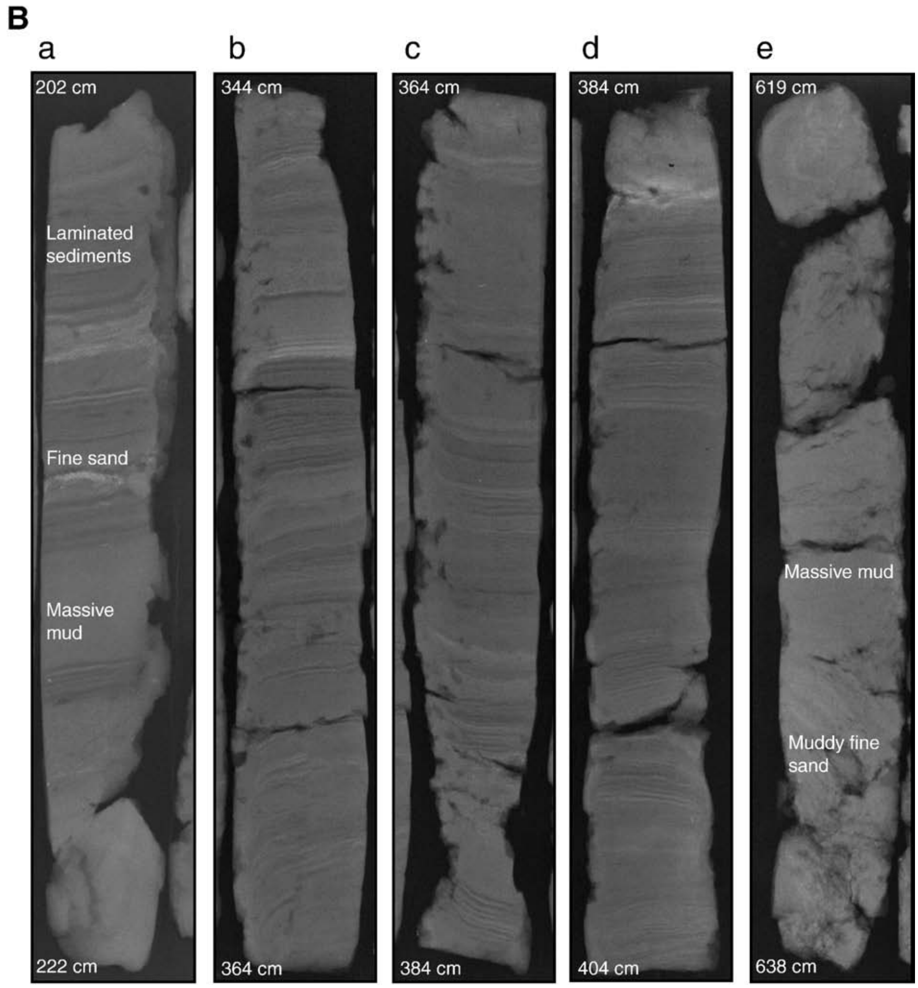

Fig. 4 (*continued*).

Ivanochko et al., 2008). Bioturbation following incursions of oxygenated waters into the inner basin of Frederick Sound is unlikely because dysoxia in coastal fjords is often restored within months (cf. Dallimore et al., 2005). Thus, oxic conditions are likely to have been too brief in Frederick Sound to permit colonization by a macrobenthos community (cf. Svarda et al., 1991; Behl and Kennett, 1996).

Stratigraphically constrained cluster analysis of binary data for the presence or absence of each facies type shows that laminated intervals are less frequently interrupted by other facies types between 620 cm and 260 cm (Fig. 5). Based on the results of cluster analysis, three main depositional regimes are identified in the Frederick Sound core and labeled as Sedimentological Zones FSZ-A through FSZ-C (Figs. 4 and 5).

4.2. Chronology

Nine conventional radiocarbon dates were reported (Table 1; one sample was not datable). An age–depth model was generated based on linear regression (cf. Hay et al., 2007; Dallimore et al., 2008; Ivanochko et al., 2008) of calibrated radiocarbon dates because calibration removes the wiggle of radiocarbon dates, and thus enhances the precision of the model (Fig. 6; Bartlein et al., 1995). The youngest dates that occur in stratigraphic order in the Frederick Sound core are considered to most likely approximate the age of sediment deposition because all of the material used for dating was detrital, and therefore, transported from source to basin for an unknown length of time. In addition, in-built age effects can occur in woody fragments from long-lived plants where old tissues remain (McFadgen, 1982) and can result in ages that are several hundreds of years older than sediments in which they are found (McFadgen, 1982; Oswald et al., 2005). For example, dates obtained from two plant macrofossils recovered from the woody layer deposited at 457 cm in the Frederick Sound core yield ages that differ by 560 cal. years, representing either or both sources of error. Error derived from in-built age effects may be especially important in the SBIC, and elsewhere in the CHWvm1, where trees are long-lived (>1000 years). The exclusion of two radiocarbon dates that occur out of chronostratigraphic sequence thereby minimizes in-built age effects and/or the error associated with delayed deposition on the accuracy of the age–depth model. A radiocarbon date from a twig at 1051 cm was included in the model despite its occurrence out of chronostratigraphic order because the twig is not likely to have substantial in-built age effects (a lack of old heartwood), survived decomposition during delayed deposition over hundreds of years, or to have been reworked as it occurs in a laminated interval of the core. The age–depth model is based on seven radiocarbon ages and yields an average sedimentation rate of 0.35 cm year^{-1} from a close spread of ages ($r^2 = 0.85$). The modeled average sedimentation rate is similar to a well-dated sediment core (VEC02A07) collected from Alison Sound, located immediately north of Frederick Sound (9 radiocarbon dates; 4th order polynomial age–depth model; average sediment rate 0.3 cm year^{-1}; Patterson et al., 2007), providing additional confidence that the Frederick Sound core age–depth model is reliable and accurate. Age ranges of Sedimentological Zones, Pollen Zones, and other points of interest are estimated from the age–depth model and rounded to the nearest 10 years. The top of the Frederick Sound core has a modeled age of ca. 1090 cal. yr BP. We did not expect to

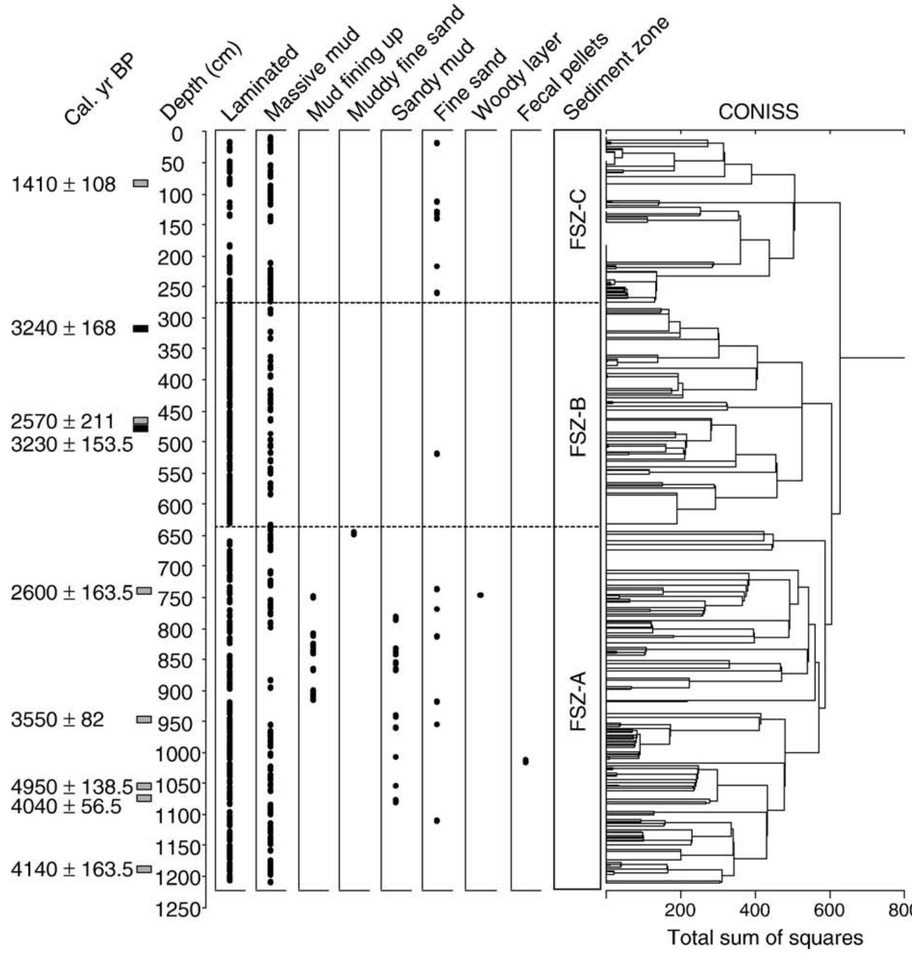

Fig. 5. Stratigraphically constrained cluster analysis (Grimm, 1987) of binary data representing the presence (shown by a black circle) or absence of a sedimentological facies in the Frederick Sound core. Chronology is from Table 1 and is in calendar years before present (cal. yr BP) rounded to nearest 10 years ±2-sigma ranges. Shaded bars indicate ages used in the Frederick Sound core age–depth model.

capture the uppermost sediments because over-penetration of coring equipment is common in marine sediments in coastal BC, where suspended sediment layers of up to 0.5 m can exist (cf. Dallimore et al., 2008). The base of the core has a modeled age of ca. 4540 cal. yr BP, thus the Frederick Sound core represents ca. 3450 cal. years of late Holocene deposition. The 10-cm interval sampling resolution used for microfossil analysis represents ca. 28 cal. years and the 0.5-cm^3 sub-sample size used for pollen analysis represents ca. 1 cal. yr of deposition.

4.3. Pollen

Stratigraphically constrained cluster analysis (CONISS; Grimm, 1987) of relative abundance pollen and spore data aided the identification of three pollen assemblage zones (Pollen Zones FPZ-A, FPZ-B, FPZ-C; Fig. 7) in the Frederick Sound core. Stratigraphically constrained cluster analysis shows similar clustering of pollen accumulation rate data (Pollen Accumulation Rate Zones FParZ-A through FParZ-C; Fig. 8). Clustering of relative pollen data is also broadly coherent with clustering of facies-types in the Frederick Sound core (Fig. 9). Taxa with >2% relative abundance in one or more levels are shown in Figs. 7 and 8 and listed in Table 2. The pollen spectrum is dominated by Cupressaceae pollen (core maximum 71%). *Tsuga heterophylla* pollen is also relatively abundant (core maximum 40%) and *Alnus* pollen maintains a consistent presence between 4% and 21%. Total PARs range from 37,782 grains cm^{-2} yr^{-1} to 235,259 grains cm^{-2} yr^{-1}. The most prominent feature of the Frederick Sound pollen record is a decline in Cupressaceae pollen mid-record (Pollen Zone FPZ-B) by ~10% in relative abundance and by ~8975 grains cm^{-2} yr^{-1} (~50% decline in PAR). Although the majority of paleoecological and paleoclimatological interpretations are based on large (~40% to 60%) changes in relative pollen abundance, small changes in paleontological records may also deserve treatment. For example, Lacourse et al. (2007) describe a ~10% decline in Cupressaceae pollen relative abundance (up to 300 grains cm^{-2} yr^{-1} decline in PAR) during the late Holocene at SGang Gwaay Pond, Anthony Island, that is related to anthropogenic disturbance.

4.3.1. Pollen Zone FPZ-A (1219 cm to 744 cm; ca. 4540 cal. yr BP to ca. 3190 cal. yr BP)

The sediments of Pollen Zone FPZ-A are characterized by numerous (53 in total) units of sandy mud, fine sand, and fining upwards mud layers inter-bedded with laminated sequences (Fig. 4). This Pollen Zone occurs within Sedimentological Zone FSZ-A that ranges from 1219 cm to 620 cm (Fig. 5). Pollen Zone FPZ-A is characterized by Cupressaceae pollen frequencies of 20% to 64%. *Tsuga heterophylla* pollen ranges from 7% to 39% in relative abundance, *Alnus* pollen is present between 7% and 21%, and *Abies* Mill. (fir) and *Picea* A. Dietr. (spruce) pollen occur near 3%. *Pseudotsuga menziesii* pollen reaches ~2% in relative abundance. Pteropsida (monolete) spores are relatively high (range 8% to 36%) and other spore types present include *P. vulgare*-type and *Polytrichum* Hedw. (haricap moss)-type (~2%). Median Cupressaceae PARs in this zone are 51,274 grains cm^{-2} yr^{-1} (range 18,023 grains cm^{-2} yr^{-1} to 100,538 grains cm^{-2} yr^{-1}) and median *Alnus* PARs are 13,824 grains cm^{-2} yr^{-1} (range 3267 grains cm $^{-2}$ yr^{-1} to 30,413 grains cm^{-2} yr^{-1}). Median total PARs are 107,827 grains cm^{-2} yr^{-1} (range 36,265 grains cm^{-2} yr^{-1} to 194,833 grains cm^{-2} yr^{-1}). The median P:S ratio in this zone is 5.65.

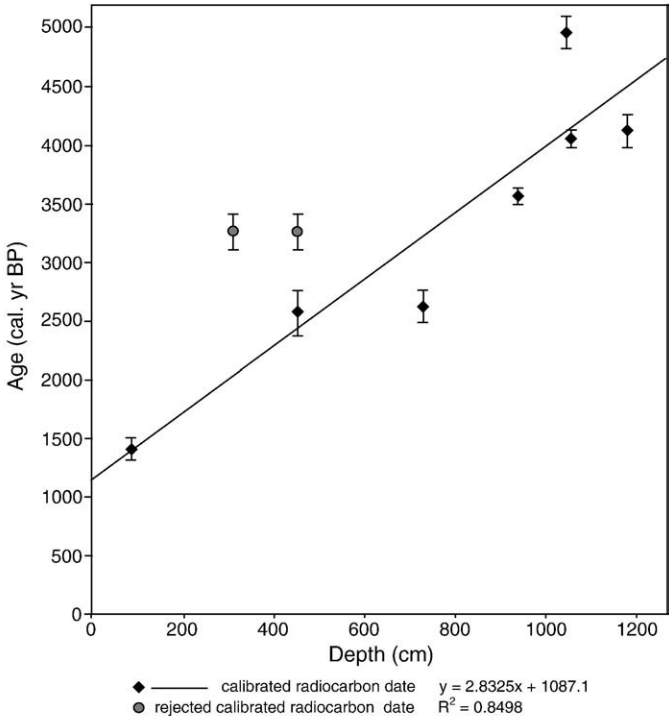

Fig. 6. The Frederick Sound core age–depth model is based on linear regression of seven calibrated radiocarbon ages measured by atomic mass spectrometry with depth (cm) as the independent variable. Bars represent ±2-sigma ranges. The chronology is also shown in Table 1.

4.3.2. Pollen Zone FPZ-B (744 cm to 410 cm; ca. 3190 cal. yr BP to ca. 2250 cal. yr BP)

The sediments of Pollen Zone FPZ-B are dominated by laminated units with some (27 in total) massive intervals (Fig. 4). Few sandy units occur and a single graded bed is present (735 cm to 740 cm). This Pollen Zone spans the latter part of Sedimentological Zone FSZ-A and the majority of Sedimentological Zone FSZ-B (620 cm to 260 cm; Fig. 5). Cupressaceae pollen frequencies decline to between ~20% and 61%. *Tsuga heterophylla* pollen frequencies increase marginally relative to Pollen Zone FPZ-A, and range from 9% to 40%. *Alnus* pollen is present between 5% and 17% and *Abies*, *Picea*, and *P. menziesii* pollen are present at ~0% to 4%, ~0% to 3%, and ~1%, respectively. Pteropsida (monolete) spores occur between 9% and 21% and *P. vulgare*-type and *Polytrichum*-type spores are present up to ~4%. Median Cupressaceae PARs are lower in this zone than in Pollen Zone FPZ-A (median 25,706 grains cm^{-2} yr^{-1}; range 9048 grains cm^{-2} yr^{-1} to 51,274 grains cm^{-2} yr^{-1}). *Alnus* PARs also decrease in this zone relative to Pollen Zone FPZ-A (median 6557 grains cm^{-2} yr^{-1}; range 2580 grains cm^{-2} $yr^{-1}$to 16,337 grains cm^{-2} yr^{-1}). Median total PARs for Pollen Zone FPZ-B are 64,847 grains cm^{-2} yr^{-1} (range 37,782 grains cm^{-2} yr^{-1} to 117,629 grains cm^{-2} yr^{-1}). The median P:S ratio for Pollen Zone FPZ-B is 5.35. The similarity of this ratio to the P:S ratio of Pollen Zone FPZ-A suggests that little change in palynomorph preservation occurred across the zone boundary.

4.3.3. Pollen Zone FPZ-C (410 cm to 0 cm; ca. 2250 cal. yr BP to ca. 1090 cal. yr BP)

The sediments of Pollen Zone FPZ-C are dominated by laminated intervals until 260 cm (ca. 1820 cal. yr BP), above which the majority of sediments are massive with some laminated and sandy units (Fig. 4). In total, 44 massive sedimentary units occur within Pollen Zone FPZ-C, which spans the latter part of Sedimentological Zone FSZ-B and all of

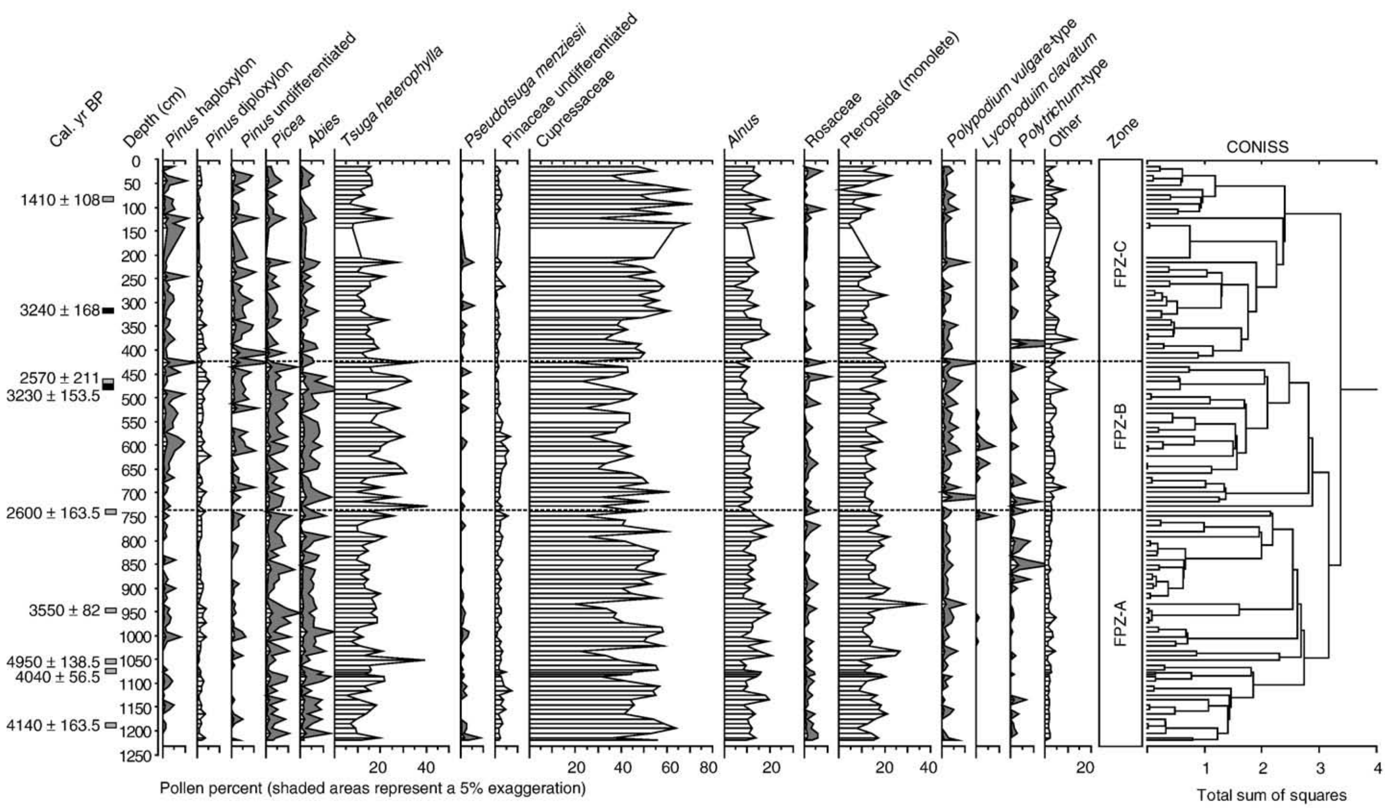

Fig. 7. Relative abundances of pollen and spores preserved in the Frederick Sound core. Zonation is based on stratigraphically constrained cluster analysis of the relative abundance of all terrestrial pollen and spore taxa (Grimm, 1987) but only taxa present >2% at at least one level are shown. The chronology is from Table 1 and is in calendar years before present (cal. yr BP) rounded to nearest 10 years ±2-sigma ranges. Shaded bars represent ages used in the Frederick Sound core age–depth model (Fig. 6).

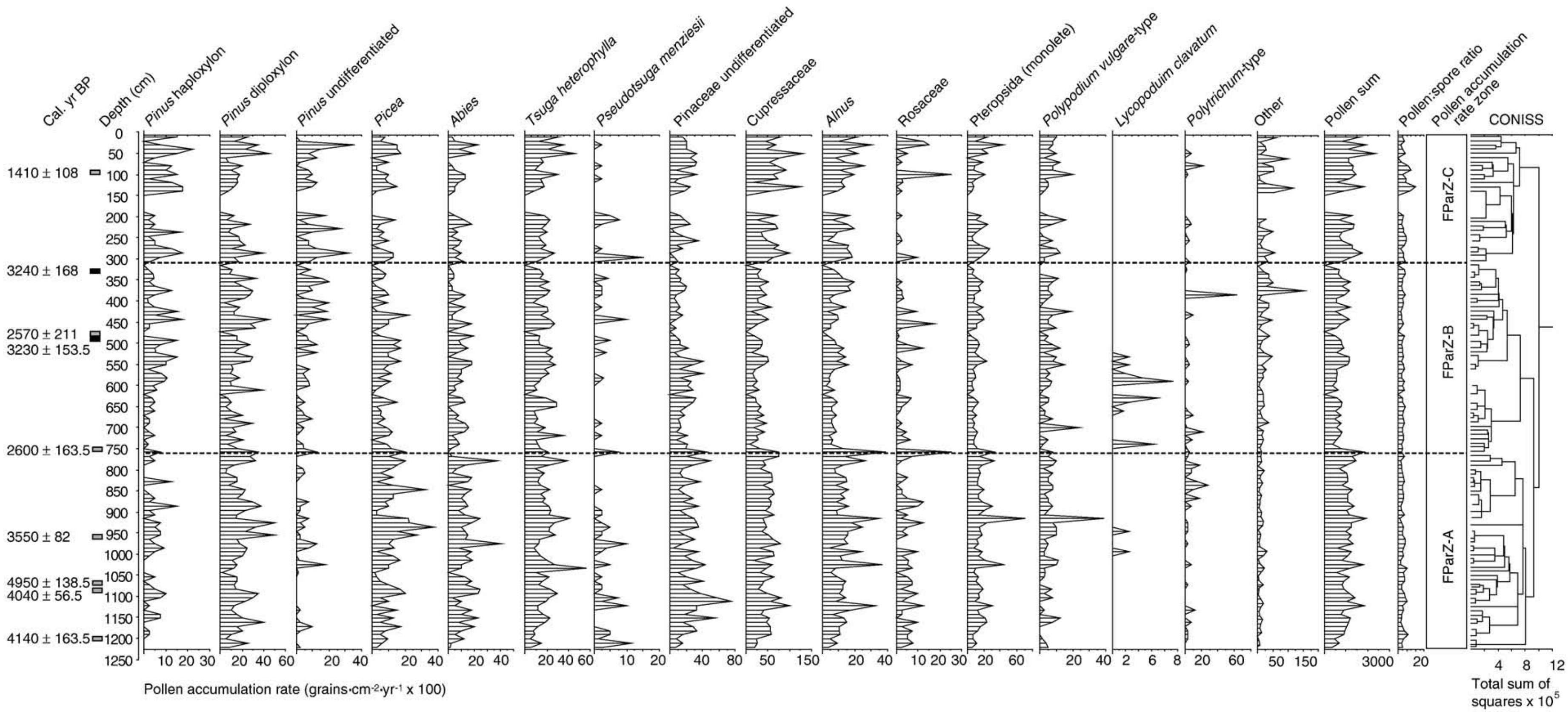

Fig. 8. Pollen and spore accumulation rates (grains cm^{-2} yr^{-1}) of the Frederick Sound core. Note changes in scale. Pollen:spore ratios are shown with an outlier of 202 removed at 55 cm. Stratigraphically constrained cluster analysis was performed on the accumulation rate of all terrestrial pollen and spores (Grimm, 1987) although only taxa present >2% at one or more level are shown. The chronology is from Table 1 and is in calendar years before present (cal. yr BP) rounded to nearest 10 years ±2-sigma ranges. Shaded bars represent ages used in the Frederick Sound core age depth model (Fig. 6).

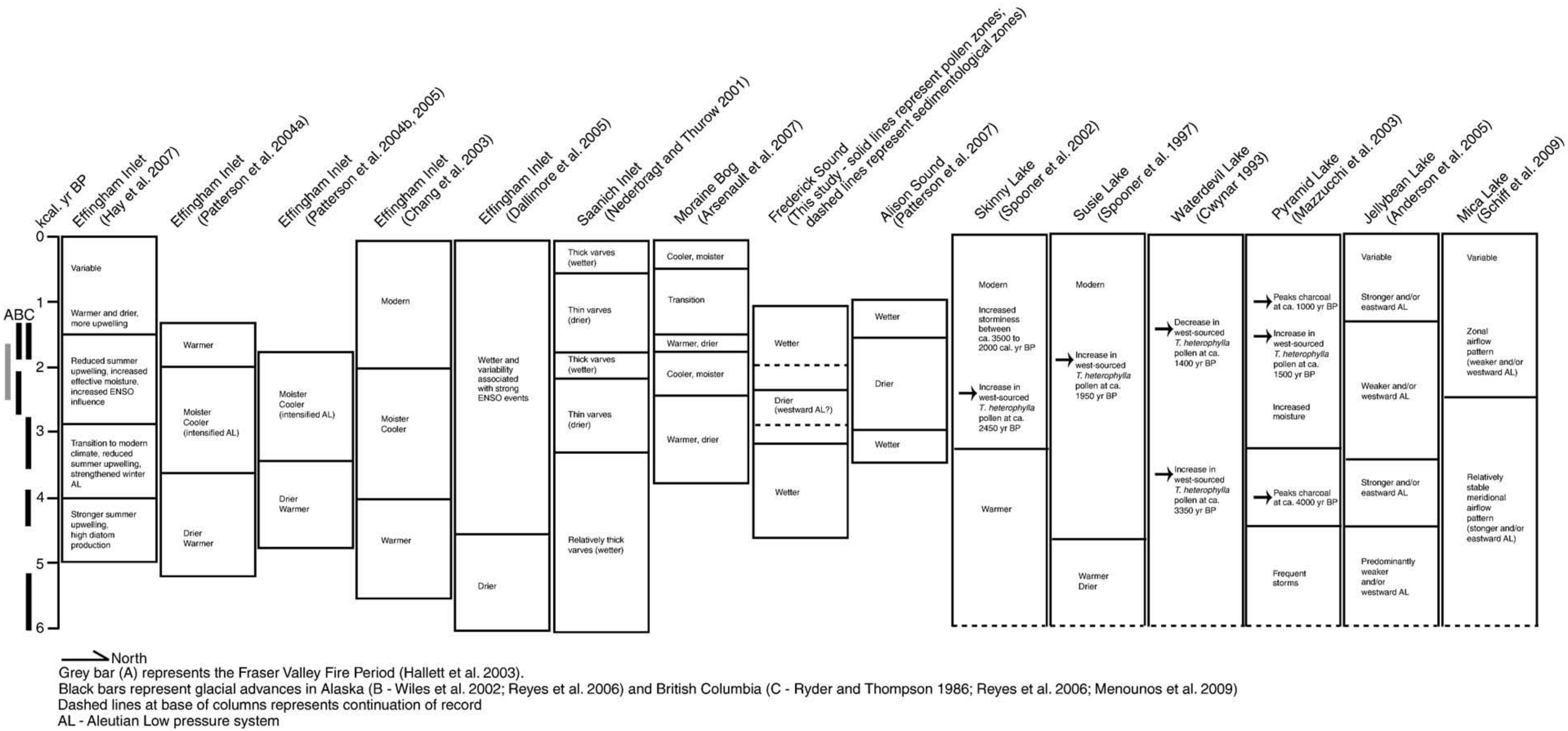

Fig. 9. Summary diagram showing late Holocene climate histories interpreted from this study and selected sites in northwestern North America. Changes in late Holocene atmospheric circulation interpreted from pollen records in northern British Columbia (by increases or decreases in exotic Tsuga heterophylla pollen) and $\delta^{18}O$ values of lacustrine carbonates from a lake in the Yukon territory (Anderson et al., 2005) and of diatom valves from a lake in Alaska (Schiff et al., 2009) are also shown. Neoglacial advances in British Columbia and Alaska are shown by black bars.

Table 2
Common names of plant taxa mentioned in the text or shown in Figs. 7 and 8.

Latin name and taxonomic reference	Common name
Abies Mill.	Fir
Abies amabilis (Dougl.) Forb.	Amabilis fir
Acer glabrum Torr. var. *douglasii* (Hook) Dipp.	Douglas maple
Alnus rubra Bong.	Red alder
Alnus sinuata (Regel) Rydb.	Sitka alder
Alnus crispa (Ait.) Pursh ssp. *sinuata* (Regel) Hulten	Green alder
Blechnum spicant (L.) Sm.	Deer fern
Callitropsis nootkatensis (D. Don) Örsted	Yellow-cedar
Chamaecyparis nootkatensis (D.Don) Spach	Yellow-cedar
Juniperus L.	Juniper
Larix Mill.	Larch
Lycopodium clavatum L.	Clubmoss
Picea A. Dietr.	Spruce
Pinus L.	Pine
Pinus haploxylon	Soft pines (e.g., *Pinus monticola* Dougl. western whitepine)
Pinus diploxylon	Hard pines (e.g., *Pinus contorta* Dougl. Ex. Loud lodgepole pine)
Polypodium vulgare L.	Common polypody
Polystichum munitum (Kaulf.) C. Presl	Western sword fern
Polytrichum Hedw.	Haircap moss
Pseudotsuga menziesii (Mirb.) Franco	Douglas-fir
Pteropsida (monolete)	Class Pteridopsida
Rosaceae	Rose family
Taxus brevifolia Nutt.	Western yew
Thuja plicata Donn ex. D. Don	Western redcedar
Tsuga mertensiana (Bong.) Carr.	Mountain hemlock
Tsuga heterophylla (Raf.) Sarg.	Western hemlock
Vaccinium L.	Cranberry, blueberry, and others

Sedimentological Zone FSZ-C (260 cm to 0 cm; Fig. 5). Sediments are missing between 195 cm and 178 cm, 175 cm and 135 cm, and 120 cm and 115 cm where sections of the core were lost on recovery. A slump is present between 35 cm and 25 cm. Cupressaceae pollen increases to a core maximum of 71%. *Alnus* pollen occurs in this zone at frequencies between 4% and 21% and *Abies* and *Picea* pollen remain present near 2%. Pteropsida (monolete) spores occur between 0% and 23% and *P. vulgare*-type spores and *Polytrichum*-type spores occur near 2%. Median Cupressaceae PARs are higher than in Pollen Zone FPZ-B at 55,296 grains $cm^{-2}\,yr^{-1}$ (range 16,525 grains $cm^{-2}\,yr^{-1}$ to 131,453 grains $cm^{-2}\,yr^{-1}$). *Alnus* PARs are also higher in Pollen Zone FPZ-C than in the previous zone (median 12,892 grains $cm^{-2}\,yr^{-1}$; range 3471 grains $cm^{-2}\,yr^{-1}$ to 38,707 grains $cm^{-2}\,yr^{-1}$). Median total PARs for Pollen Zone FPZ-C are 113,105 grains $cm^{-2}\,yr^{-1}$ and increase from 56,552 grains $cm^{-2}\,yr^{-1}$ to 235,259 grains $cm^{-2}\,yr^{-1}$ mid zone. The median P:S ratio for Pollen Zone FPZ-C is 6.24. This higher value may reflect greater preservation of pollen in Pollen Zone FPZ-C relative to Pollen Zones FPZ-A and FPZ-B or may reflect enhanced pollen production by trees in the latest Holocene in the SBIC.

4.4. Foraminifera

Two hundred and eleven sub-samples from the Frederick Sound core were processed and examined for foraminifera (Babalola, 2009). Foraminifera were present in both laminated and massive sedimentary units of the Frederick Sound core and only twenty samples were barren. Twenty six species were observed and enumerated, and sample abundances ranged from 10 to 289 specimens. All intervals of Frederick Sound core examined for foraminifera were dominated by agglutinated species. Calcareous taxa were totally absent. *Eggerella advena* (Hardwicke) dominates faunal assemblages, accounting for between >50% and 93% of foraminifera species. *Spiroplectammina biformis* (Parker and Jones), *Recurvoides turbinatus* (Brady), *Portatrochammina bipolaris* Brönnimann and Whitaker, and a number of *Trochammina* Parker and Jones, 1859, and *Cribrostomoides* Cushman, species were also present.

5. Discussion

5.1. Massive sedimentary units in the Frederick Sound core

Massive sedimentary units present in the Frederick Sound core are interpreted to have been formed by re-suspension, homogenization, and deposition of basin sediments when slope stability in the steep sided walls of the fjord basin failed. Massive sedimentary units are most common in portions of Frederick Sound core deposited between 1219 cm and 620 cm (ca. 4540 cal. yr BP to ca. 2840 cal. yr BP) and between 260 cm and 0 cm (ca. 1820 cal. yr BP to 1090 cal. yr BP; Fig. 5).

Several processes can reduce slope stability, and thus promote the re-deposition on basin sediments, in fjords in coastal BC. For example, incursions of dense, oxygen-rich water into the inner basin of fjords can reduce slope stability. Deep water renewal events may be associated with enhanced upwelling, especially in fjords in the Coastal Upwelling Domain (cf. Dallimore et al., 2005). In the SBIC, deep water renewal events may be related to precipitation (cf. Vázquez Riveiros and Patterson, 2009). Increased precipitation results in increased freshwater river input that enhances the strength of estuarine-type circulation. Stronger seaward flow at the mouth of the SBIC could promote frequent incursions of dense, oxygen-rich waters over the sill at Nakwakto Rapids (cf. Vázquez Riveiros and Patterson, 2009). The occurrence of diverse calcareous foraminifera fauna (e.g., *Stainforthia feylingi* (Knudsen and Seidenkrantz)) in massive sediments deposited in Belize Inlet between ca. 1575 A.D. and 1940 A.D. suggest that this scenario prevailed for approximately three centuries in the SBIC during the latest Holocene (Vázquez Riveiros and Patterson, 2009).

Sub-fossil foraminiferal assemblages preserved in the Frederick Sound core analyzed at approximate 5-cm intervals (~14 years) were found to be composed almost exclusively of species indicative of low oxygen levels (e.g., *Eggerella advena*, *Spiroplectammina biformis*; Babalola, 2009). Dysoxic estuarine environments in high latitude fjords are typically characterized by a low diversity of agglutinated benthic foraminifera that are dominated by one or few species, whereas highly diverse assemblages that include calcareous foraminifera are typical of well ventilated marine environments (Sen Gupta, 1999). The complete absence of calcareous foraminifera and the relatively high abundance of taxa indicative of poorly oxygenated environments in the Frederick Sound core do not support the hypothesis that incursions of oxygenated seawater into Frederick Sound were frequent between ca. 4540 cal. yr BP and ca. 1090 cal. yr BP. Instead, foraminifera fauna suggest that deep water renewal events into Frederick Sound were uncommon and weak during the deposition of the Frederick Sound core, similar to modern conditions in Belize Inlet where agglutinated foraminifera occur (Vázquez Riveiros and Patterson, 2009).

Climate variability may have been a predominant influence on sedimentation in Frederick Sound between ca. 4540 cal. yr BP and ca. 1090 cal. yr BP by affecting marine productivity and terrestrial clastic input to the basin (cf. Patterson et al., 2007). Warm and wet climates are expected to result in higher clastic input into marine basins by increasing the weathering rate of catchment soils and rocks, terrestrial erosion rates, and sediment delivery during periods of enhanced freshet and surface runoff (cf. Patterson et al., 2007). Clastic input can in turn reduce submarine slope stability and thus, the potential for wall failure and re-deposition of marine sediments to form the massive sedimentary units that are common in Sedimentological Zones FSZ-A and FSZ-C (Fig. 5). In contrast, cooler and drier climates associated with sunnier conditions promote marine productivity and result in higher rates of diatom frustules raining to the fjord bottom. Less terrestrial mineral material is deposited during dry climate intervals due to a decrease in coastal erosion and freshet volume, and consequently, slope stability and the preservation potential of laminae may increase, as is observed for Sedimentological Zone FSZ-B (cf. Patterson et al., 2007).

5.2. Integrity of the pollen record

Frederick Sound is a marine inlet that provides a unique sedimentary environment in which to study late Holocene ecology and climate because some of the problems associated with marine palynology in more open settings may be considered negligible in this restricted site. A series of sills in the SBIC are thought to restrict the incursion of ocean currents and the associated extra-regional pollen components into Frederick Sound, which is indicated by a relatively low amount of *Pinus* L. (pine) pollen in the Frederick Sound core, that is comparable to, or lower than, *Pinus* pollen frequencies in late Holocene lake sediments in the SBIC (Stolze et al., 2007; Galloway et al., 2007, 2009). The inclusion of non-contemporaneous pollen through down-slope transport of reworked sediments may have occurred in this record, particularly where there is indication of sediment gravity flows (Fig. 4). However, the confinement of fining upward sequences to Sedimentological Zone FSZ-A suggests this it is unlikely that this taphonomic process influenced the preservation of the pollen signal throughout the majority of the record (Fig. 5). Changes in sedimentation rate can affect pollen spectra. For example, relatively slow sedimentation rates associated with the deposition of laminated sediments may promote selective oxidation of pollen and spores. However, the absence of foraminifera indicative of well oxygenated environments throughout the Frederick Sound core suggests that the incursion of oxygenated waters into Frederick Sound was uncommon during the late Holocene. Further, the deposition and preservation of laminated sediments, that increase in proportion in Sedimentological Zone FSZ-B, are associated with dysoxic and quiescent bottom water conditions (cf. Dallimore et al., 2005; Patterson et al., 2007). Lastly, the P:S ratio changes little between Pollen Zones FPZ-A and FPZ-B, suggesting that the decrease of Cupressaceae pollen in the latter zone relative to Pollen Zone FPZ-A is not an artifact of differential preservation associated with changes in sedimentation rate or oxygen levels.

5.3. The early-late Holocene (ca. 4540 cal. yr BP to ca. 3190 cal. yr BP)

Fining upward mud, sandy mud, and fine sand layers occur more frequently between ca. 4540 cal. yr BP and ca. 2840 cal. yr BP than anywhere else in the Frederick Sound core (Fig. 5). These units are probably gravity-flow deposits that formed when the slopes of Frederick Sound destabilized, in contrast to the fine grained massive sedimentary units that are also common in this portion of the Frederick Sound core. The massive sedimentary units are most likely derived from debris-flows in relatively deep portions of the basin (cf. Patterson et al., 2007). Slope stability is regulated by sediment particle size, geometry, and density, water content, deep water movement, and the flux of allochthonous sediment that may be related to prevailing climate conditions (cf. Patterson et al., 2007; Vázquez Riveiros and Patterson, 2009). Increased allochthonous sediment supply from increased rates of terrestrial weathering and erosion of catchment rocks and soils and enhanced river and terrestrial runoff associated with relatively warm and wet climate regimes can reduce slope stability in marine inlets, and thus promote re-deposition of basin sediments and decrease the potential for laminae preservation (cf. Patterson et al., 2007). Alternatively, deep water renewal events associated with higher precipitation that strengthens estuarine-type circulation and thus water exchange (cf. Vázquez Riveiros and Patterson, 2009), or enhanced upwelling (cf. Dallimore et al., 2005), can also affect slope stability. However, deep water renewal events were likely infrequent in the SBIC during the deposition of the Frederick Sound core. Relative sea level change in a narrowly constricted fjord such as Frederick Sound could also have affected submarine slope gradient, and thus stability, but diatom stratigraphies from isolation basins in the SBIC indicate that relative sea level was stable or rising very slowly between ca. 7800 cal. yr BP and ca. 2450 cal. yr BP, when relative sea level rose 1.49 m (Doherty, 2005).

Cupressaceae pollen, likely attributable to *T. plicata* and *C. nootkatensis* based on modern biogeography and macrofossil evidence from the Fraser Lowlands and nearby Woods Lake (Wainman and Mathewes, 1987; Pojar and MacKinnon, 1994; Stolze et al., 2007), dominates the base of the Frederick Sound core. Cupressaceae pollen percentages range from 20% to 63% in Pollen Zone FPZ-A, and PARs are relatively high, indicating that *T. plicata* and/or *C. nootkatensis* were well established at Frederick Sound by ca. 4540 cal. yr BP (Hebda and Allen, 1993). Both species thrive in cool and wet climates today, so the predominance of Cupressaceae pollen in the lowermost section of the Frederick Sound core, and in correlative chronostratigraphic levels in sediment cores from lakes in the SBIC (Stolze et al., 2007; Galloway et al., 2007, 2009), suggests that cool and wet climate conditions were established in the SBIC by the late Holocene. This interpretation is consistent with other pollen records in coastal BC that document the development of a cool and wet climate between ca. 8200 cal. yr BP and ca. 7000 cal. yr BP (Mathewes, 1973; Pellatt and Mathewes, 1997; Brown and Hebda, 2002; Lacourse, 2005; Stolze et al., 2007; Galloway et al., 2007, 2009).

5.4. The mid-late Holocene (ca. 3190 cal. yr BP to ca. 2250 cal. yr BP)

The increased preservation of laminated sediments between ca. 2840 cal. yr BP and ca. 1820 cal. yr BP suggests that slope stability in Frederick Sound increased in the mid-late Holocene (Fig. 5). Factors that could have increased slope stability include a fall in relative sea level, but this hypothesis is not supported by the diatom-based sea level record for the SBIC (Doherty, 2005). A reduction of the incursion of dense, oxygen-rich currents into the inner basin of the fjord may also have led to an increase in slope stability, but foraminifera evidence for persistent dysoxia suggests that reduced terrestrial sediment input and/or increased light incidence associated with drier, less cloudy conditions and reduced marine fog that promoted marine productivity was probably the predominant control on Late Holocene sedimentation in Frederick Sound (cf. Patterson et al., 2007).

A decline in Cupressaceae and *Alnus* pollen relative abundance and PARs in Pollen Zone FPZ-B, relative to preceding Pollen Zone FPZ-A, at ca. 3190 cal. yr BP is broadly coincident with changes in the sedimentology of the Frederick Sound core (Fig. 9). However, it is unlikely that a change in sedimentation, and thus delayed burial and possible oxidative corrosion, played a role in the reduction of Cupressaceae pollen in Pollen Zone FPZ-B because foraminifera fauna suggest that dysoxia was persistent throughout the deposition of the Frederick Sound core.

The relative abundance of Cupressaceae pollen in coastal lake sediments is likely representative of percent forest cover based on limited data from a modern pollen spectra study in the Bella Bella region north of the SBIC (Hebda and Allen, 1993). The 10% decrease in the relative abundance of Cupressaceae pollen in the Frederick Sound core may therefore correspond to a proportionate decrease in forest cover of *T. plicata* and/or *C. nootkatensis* through death of individuals, may represent decreased pollen production by stressed trees, or reflect a change in pollen source area. If Cupressaceae declined at Frederick Sound, a change in forest composition is not strongly recorded in the Frederick Sound pollen record. Upon removal of a dominant canopy tree it is expected that other species would be released from competition and increase in abundance, especially shade intolerant taxa such as *Alnus*, and competitive taxa such as

T. heterophylla (cf. Allison et al., 1986). However, changes in the relative abundance and PARs of Cupressaceae pollen are not accompanied by increases in *T. heterophylla* PARs; the increase in frequency of this taxon is therefore an artifact of the percentage data (Fægri and Iversen, 1989, p. 125). The de-coupling of *T. heterophylla* and Cupressaceae pollen trends in the Frederick Sound core is likely not due to differential preservation in the marine environment because pollen from these taxa also appear to change independently of each other in a lake record from the SBIC (Galloway et al., 2009). Rather, this detail may represent an individualistic species response to environmental change and suggests that the ecological variable that was disadvantageous for *T. plicata* and/or *C. nootkatensis* and caused death and/or reduced pollen production was not unfavorable for competitive taxa. This excludes fire and wind-throw as possible causes of the Cupressaceae pollen decline because *T. heterophylla* would also have been affected, probably to a greater degree than *T. plicata* whose seedlings benefit from low-intensity disturbance (Minore, 1990; Packee, 1990). Additionally, pollen of disturbance-adapted taxa, such as *Alnus*, *P. menziesii*, and/or *Polytrichum* do not increase at this time. Although a detailed fire history does not exist for the central mainland coast of BC, previous research on the Queen Charlotte Islands (Pellatt and Mathewes, 1997), Vancouver Island (Brown and Hebda, 2002), and the Fraser Lowlands of the southern mainland coast (Wainman and Mathewes, 1987) indicates that fires were rare or absent in coastal forests during the majority of the late Holocene, with few exceptions (Hallett et al., 2003).

Changes observed in the palynological and sedimentological records of the Frederick Sound core are broadly coincident with a decline in the relative abundance of ephiphytic diatom species (e.g., *Tabularia tabulata* (C.Agardh) D.M. Williams and Round) and an increase in *Skeletonema costatum* (Grev.) Cleve at ca. 3160 cal. yr BP (Wigston, 2005). Epiphytic species are washed from shallow environments to the centre of the fjord by runoff, precipitation, and/or snowmelt and *S. costatum* is a typical marine spring bloom species with relatively high light requirements (Hitchcock and Smayda, 1977; Chang and Patterson, 2005). These, and other floristic changes, suggest that sunnier spring conditions prevailed and that surface waters of Frederick Sound were more saline due to reduced freshwater input after ca. 3160 cal. yr BP (Wigston, 2005). The increased preservation of laminae and changes in the diatom stratigraphy of the Frederick Sound core are broadly concurrent with the onset of Pollen Zone FPZ-B and therefore suggest that climate change was the proximate cause of the Cupressaceae decline and/or reduced pollen production from trees near Frederick Sound.

The development of drier, cooler, and sunnier conditions could have been restrictive for *T. plicata* and *C. nootkatensis*, but not *T. heterophylla*, even though the ecologies of these species are similar (Krajina, 1969). Regions supporting populations of *C. nootkatensis* receive more than 2032 mm of annual precipitation and winter temperatures rarely fall below −7 °C (Watts, 2005). Similarly, *T. plicata* grows in mesothermal and humid climates and is geographically restricted along the North Pacific coast to regions receiving at least 890 mm of annual precipitation, and the minimum temperature this tree can withstand in coastal populations is −30 °C (Boyd, 1965; Minore, 1990). In contrast, coastal *T. heterophylla* populations can grow in regions receiving less than 380 mm of annual precipitation and survive minimum temperatures near −39 °C (Packee, 1976). It is unlikely that these limits were approached in the late Holocene in the SBIC, but interactions between temperature and precipitation are also important controls on species abundance and trade-offs between two or more climate variables can affect tolerance of extremes. For example, drier conditions at this time could have resulted in lowered cold tolerance of *T. plicata* and/or *C. nootkatensis* and resulted in stress, damage, or death of individuals during unusually cold periods. A modern analog may be the species-specific decline of *C. nootkatensis* that began in Alaska and northern BC in the mid 1900s due to a warming-mediated reduction of the snowpack layer that protects fine roots from frost damage (Hennon et al., 2006; Beier et al., 2008). It is possible that mid-late Holocene dry conditions in the SBIC could have harmed or stressed Cupressaceae in a similar way through a reduction of snowfall. A drier climate would also have affected *Alnus* growing in the SBIC because of the relatively high moisture requirements of *A. rubra* and *A. sinuata/crispa* ssp. *sinnuata*.

A broadly synchronous dry mid-late Holocene climate interval is inferred from a reduction in particle size, marine productivity, and changes in other sedimentary features (e.g., laminae thickness) in the Alison Sound sediment record between ca. 3100 cal. yr BP and ca. 1650 cal. yr BP that is related to multiple scales of climate variability that resulted in reduced precipitation, runoff, and terrestrial weathering in the mid-late Holocene (Fig. 9; Patterson et al., 2007). However, similar to the majority of pollen-based climate reconstructions in coastal BC, no evidence for a decline in Cupressaceae or a mid-late Holocene dry or cool climate interval is observed in lake sediment records in the SBIC (Stolze et al., 2007; Galloway et al., 2007, 2009). The centennial-scale sampling resolution of lake records from the SBIC and elsewhere in coastal BC may partly explain why the signal observed in the Frederick Sound core has not been previously documented in terrestrial sediment records from coastal BC. High-resolution marine sedimentary records from restricted inlets on southern Vancouver Island indicate that the mid-late Holocene was a time of climate reorganization in this region as well (Fig. 9). At Saanich Inlet, that is sheltered from west-sourced precipitation by the rainshadow effect of the mountains on southern Vancouver Island, thinner varves were deposited between ca. 3250 cal. yr BP and ca. 2100 cal. yr BP that are interpreted to represent the development of drier climate conditions that resulted in slower annual sedimentation rates and decreased terrestrial sediment input (Nederbragt and Thurow, 2001). However, a corresponding high-resolution (ca. 20 to 50 year) pollen stratigraphy from this site does not show changes at this time (Pellatt et al., 2001). At Heal Lake (~5 km away from Saanich Inlet), an abrupt change in tree growth patterns suggest that climate re-organization near ca. 4000 cal. yr BP was manifested as a decrease in precipitation at this site (Zhang and Hebda, 2005). Proxies records of climate and productivity from Effingham Inlet also show that oceanographic and climate changes were occurring in the mid-late Holocene in south coastal BC, although the direction of change appears opposite to those interpreted for the SBIC (Fig. 9). For example, a reduction in diatom productivity between ca. 4000 cal. yr BP and ca. 2800 cal. yr BP may reflect decreased nutrient input mediated by less frequent surface and intermediate-depth water incursions into the inlet and reduced summer upwelling associated with what is interpreted to be a more intense Aleutian Low pressure system (Hay et al., 2007). Similarly, moister and possibly cooler conditions are interpreted from pelagic fish scales preserved in Effingham Inlet after ca. 3400 cal. yr BP (Patterson et al., 2004a,b, 2005) and from changes in diatoms and a decrease in the preservation of laminated sedimentary successions at ca. 4500 cal. yr BP to ca. 4000 cal. yr BP (Chang et al., 2003; Dallimore et al., 2005). At inland, high elevation sites in south coastal BC, early Late Holocene climate was also cool and moist and resulted in a reduction of fire frequencies at Frozen and Mount Barr Cirque Lakes between ca. 3500 cal. yr BP and ca. 2400 cal. yr BP (Hallett et al., 2003). Neoglacial movement at the Tiedemann Glacier occurred numerous times between ca. 3550 cal. yr BP and ca. 1850 cal. yr BP and indicate that, in general, cool and moist climate conditions prevailed ~100 km south of the SBIC in the Coast Mountains of BC (Fig. 9; Ryder and Thomson, 1986; Menounos et al., 2009). A pollen and sedimentological record from Moraine Bog at the Tiedemann Glacier site also documents cool and moist conditions between ca. 2440 cal. yr BP and ca. 1830 cal. yr BP (Fig. 9; Arsenault et al., 2007). Neoglacial advances elsewhere in western Canada and Alaska show millennial-scale, and at times, higher frequency, pacing throughout the late Holocene (Reyes et al., 2006; Menounos et al., 2009). For example, in the Canadian Cordillera, advances occur between ca. 4400 cal. yr BP and ca. 3970 cal. yr BP, ca. 3540 cal. yr BP and ca. 2770 cal. yr BP, and ca. 1710 cal. yr BP and ca. 1300 cal. yr BP (Menounos et al., 2009; Fig. 9). In contrast, in southeastern Alaska, advance is documented at ca. 2700 cal. yr BP (Wiles et al., 2002).

High-resolution microfossil records from coastal sites north of the SBIC do not exist for comparison, but the occurrence of west-sourced *T. heterophylla* pollen to inland, high elevation sites in northern BC may be indicative of atmospheric re-organization in the late Holocene (Cwynar, 1993; Spooner et al., 1997; Spooner et al., 2002; Mazzucchi et al., 2003). For example, west-sourced *T. heterophylla* pollen occurs at ca. 3350 cal. yr BP at Waterdevil Lake, northern BC, coincident with a shift in native vegetation (Cwynar, 1993) and a period of increased moisture inferred at nearby Pyramid Lake between ca. 3200 cal. yr BP and ca. 1000 cal. yr BP (Mazzucchi et al., 2003). West-sourced *T. heterophylla* pollen also occurs at Skinny Lake at ca. 2450 cal. yr BP when an increase of storminess is inferred between ca. 3500 cal. yr BP and ca. 2000 cal. yr BP (Fig. 9; Spooner et al., 2002).

The Jellybean Lake oxygen isotope record of dynamics of the position and strength of the Aleutian Low pressure system describe a steady westward shift and/or weakening of the Aleutian Low pressure system that began at ca. 3500 cal. yr BP, broadly coincident with the timing of onset of the higher rainfall phase at Effingham Inlet, the transition to drier conditions interpreted for Saanich Inlet and Frederick Sound, and the occurrence of west-sourced *T. heterophylla* pollen in the alpine of northern BC (Fig. 9). Anderson et al. (2005) describe the Aleutian Low pressure system to be on average further west and/or weaker at ca. 2000 cal. yr BP than any time during the last 7500 cal. yrs BP (Anderson et al., 2005). Similarly, Schiff et al. (2009) describe late Holocene excursions to lower δ^{18}O values in diatom valves from Mica Lake, south coastal Alaska, at ca. 2600 cal. yr BP that are interpreted to represent the development of a more zonal air flow pattern associated with a weakened Aleutian Low pressure system. A weakened and/or westward displaced Aleutian Low pressure system and associated zonal airflow in the mid-late Holocene would have translated less warm and moist maritime air to the coast of northern BC and the SBIC while a more northward positioned North Pacific High pressure system would have steered cold northeasterly winds into the region (Klein, 1949). Additionally, a more zonal airflow pattern would have reduced the number of south-to-north storm trajectories because strong temperature gradients would not be maintained over short distances and North Pacific storms that did develop would be directed to the south coast of BC (Klein, 1949; Schiff et al., 2009). Recent pollen evidence from lakes within the SBIC show a latitudinal gradient in the timing of early Holocene moisture development, suggesting that the SBIC may be located near the southern extent of immediate influence of the Aleutian Low pressure system (Stolze et al., 2007; Galloway et al., 2007, 2009), thereby possibly explaining opposing climate signals between the SBIC and more southern sites, including nearby Moraine Bog (Fig. 9).

The replacement of diverse, calcareous foraminifera by agglutinated taxa in Belize Inlet after the year 1940 suggests an infrequency of deep water renewal events into the SBIC that persists to the present (Vázquez Riveiros and Patterson, 2009). This oceanographic change is interpreted to be associated with a decrease in rainfall that is in turn related to a westward shift in the relative position of the Aleutian Low pressure system (Vázquez Riveiros and Patterson, 2009). Interestingly, a regime shift to a cool Pacific Decadal Oscillation phase, associated with relatively high sea level pressures in the Northeast Pacific, occurred near 1947 (Mantua et al., 1997). A weakened Aleutian Low pressure system would have promoted zonal airflow and steered Northeast Pacific storms south of the SBIC. Instrumental data for this period indeed show increasing precipitation in the Pacific Northwest from the year 1925 to 1976, associated with the Pacific Decadal Oscillation regime change in the late 1940 s (Hamlet et al., 2005).

5.5. The latest Holocene (ca. 2250 cal. yr BP to ca. 1090 cal. yr BP)

The palynology and sedimentology of Pollen Zone FPZ-C and Sedimentological Zone FSZ-C deposited in the upper portions of the Frederick Sound core are similar to the lowermost portions of the sediment core (Pollen Zone FPZ-A and Sedimentological Zone FSZ-A). The temporal brevity of the Cupressaceae pollen decline in the Frederick Sound core is remarkable because both *T. plicata* and *C. nootkatensis* are long-lived trees. The ca. 940-year decline of Cupressaceae pollen may therefore point to reduced pollen production from stressed trees as the dominant mode of Cupressaceae pollen reduction in the Frederick Sound core rather than death or lack of regeneration of individuals, which would be expected to occur over hundreds of years in coastal forests of BC (Lacourse, 2005). After ca. 1820 cal. yr BP, thicker and more numerous massive sedimentary units are present, suggesting a return to wetter conditions that is also reflected in the diatom record of the Frederick Sound (Wigston, 2005). At ca. 1740, a decrease in the relative abundance of *S. costatum* and increase in benthic brackish taxa (e.g., *Planothidium delicatulum* (Kütz) Round & Bukht) and *Achnanthes* Bory spp.) is interpreted to be in response to the development of a wetter climate with cloudier spring months (Wigston, 2005; Chang and Patterson, 2005). A return to wetter climate conditions is also inferred from increases in grain size and laminae thickness at Alison Sound after ca. 1650 cal. yr BP (Patterson et al., 2007). The interpretation of wetter climate conditions in the SBIC after ca. 2250 cal. yr BP is again also consistent with climate change inferred at Saanich Inlet where varves became thicker after ca. 2100 cal. yr BP (Nederbragt and Thurow, 2001). At Effingham Inlet wetter climate conditions are also inferred from sedimentological and microfossil analyses of sediments deposited after ca. 2800 cal. yr BP (Chang et al., 2003; Patterson et al., 2004a,b 2005; Hay et al., 2007). Further change is documented at Effingham Inlet when sea surface temperatures warmed at ca. 2000 cal. yr BP (Chang et al., 2003; Patterson et al., 2004a). In northern BC, increases in exotic *T. heterophylla* pollen are again documented at ca. 1950 cal. yr BP at Susie Lake (Spooner et al., 1997) and at ca. 1500 cal. yr BP at Pyramid Lake ((Mazzucchi et al., 2003; Fig. 9). The Jellybean Lake δ^{18}O record documents a rapid and high amplitude intensification and/or eastward movement of the pressure system at ca. 1200 cal. yr BP (Anderson et al., 2005) that is superimposed on a high degree of variability in position and strength of this pressure system after ca. 2000 cal. yr BP, relative to the past ca. 7500 cal. yr (Anderson et al., 2005). Similarly, Schiff et al. (2009) document a four-fold increase in variability of diatom valve δ^{18}O isotopes after ca. 2600 cal. yr BP that is postulated to represent pronounced and numerous shifts in winter precipitation, reflecting a high degree of atmospheric variability. Abrupt and high amplitude oscillations in the relative position and intensity of the Aleutian Low pressure system after ca. 2600 cal. yr BP to ca. 2000 cal. yr BP would result in climate extremes in coastal BC relative to previous millennia, and may be reflected in the SBIC beginning at ca. 1575 A.D. when deep water renewal events became frequent and/or strong enough to permit the existence of diverse calcareous foraminifera in Belize Inlet (Vázquez Riveiros and Patterson, 2009).

6. Conclusions

Pollen and sediments recovered from Frederick Sound in the Seymour–Belize Inlet Complex of central British Columbia are interpreted to document climate change between ca. 4540 cal. yr BP and ca. 1090 cal. yr BP. Late Holocene sediments deposited in Frederick Sound under primarily dysoxic conditions are dominated by laminated sediments composed of couplets of light-coloured diatom-rich layers deposited during spring and summer and dark-coloured mineral-rich layers deposited during winter between ca. 2840 cal. yr BP and ca. 1850 cal. yr BP. The increased preservation of laminae during this interval is interpreted to have resulted from an increase in slope stability associated with the development of a drier and cooler climate interval that punctuated otherwise wet and temperate late Holocene conditions in the Seymour-Belize Inlet Complex. The preservation of laminated sedimentary successions is broadly coherent with a decrease in the relative abundance and PARs of Cupressaceae pollen (likely *T. plicata* and *C. nootkatensis*) between ca. 3190 cal. yr BP and ca. 2250 cal. yr BP. Because many taphonomic factors associated with more open marine environments are reduced in Frederick Sound, the decline suggests that an excursion to relatively dry mid-late Holocene climate conditions affected Cupressaceae pollen production, survival and/or regeneration of trees in the Seymour–Belize Inlet complex. The onset of the drier climate interval is broadly correlative with the timing of climate change inferred from a sedimentary record from Alison Sound, also located in the SBIC. The occurrence of the mid-late Holocene dry climate interval documented in Frederick Sound is coherent with previously documented dynamics in the position and intensity of the Aleutian Low pressure system. High-resolution palynology in coastal British Columbia captures the ca. 940 cal. yr mid-late Holocene climate interval that would have likely been missed by a coarser resolution approach.

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