

FORAMINIFERAL EVIDENCE OF A LATE HOLOCENE WESTWARD SHIFT OF THE ALEUTIAN LOW PRESSURE SYSTEM

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ABSTRACT

The late Holocene distribution of agglutinated foraminifera and freshwater thecamoebians was documented within a 12.26-m piston core (VEC02A04) deposited between 1090 to ~4560 cal. yr BP, collected from the glacier-carved Frederick Sound, Seymour-Belize Inlet Complex (SBIC), British Columbia. Core sediments contained unevenly distributed, massive and laminated intervals interrupted by occasional slumps and turbidites. The microfauna was characterized by low diversity and low abundances of agglutinated foraminifera (Shannon Diversity Index ≤ 1.36) with rare allochthonous freshwater thecamoebians. The predominance of low-oxygen-tolerant agglutinated foraminifera, and absence of calcareous species indicate that dysoxia was the main environmental stressor. Abundant organic matter in the core sediments provides additional evidence of low-oxygen conditions that excluded most organisms that might have utilized this rich food resource.

A moderate up-core increase in the abundance of glaciomarine indicator species (e.g., *Spiroplectammina biformis*, *Recurvoides turbinatus*, *Portatrochammina bipolaris*, and *Cribr stomoides jeffreysii*) after 3125 cal. yr BP (above 7.19 m) indicates a subtle shift to progressively cooler bottom-water conditions. The presence of varying proportions of thecamoebians through this upper core interval was likely related to increased spring snowmelt or early summer precipitation, resulting in increased terrestrial erosion (e.g., reworking of marsh sediments into the fjord). Development of relatively cooler/drier climate conditions in the SBIC during the late Holocene corresponds to the neoglacial advances in the NE Pacific, which is directly linked to a weakened and/or westward shift in the center of action of the Aleutian Low Pressure System.

INTRODUCTION

The Seymour-Belize Inlet Complex (SBIC), located on the central coastal mainland of British Columbia, is comprised of a series of deep, steep-sided, glacial-carved fjords (Pickard, 1961; Vázquez-Riveiros and others, 2007). The configuration of the underwater topography and elevated primary production in fjords within the SBIC has led to development of anoxic bottom waters and resultant preservation of annually deposited laminated couplets (varves; Patterson and others, 2007). Paleoenvironmental proxies derived from annually laminated sediments such as preserved in Frederick Sound (FS) within the SBIC have

been found elsewhere to be very useful for investigating paleoceanographic and paleoclimatic variability at high temporal resolution (e.g., Chang and others, 2003; Jensen and others, 2004; Cockburn and Lamoureaux, 2008). In this paper, down-core changes in foraminiferal and allochthonous freshwater thecamoebian distributional patterns archived in piston core VEC02A04 from FS (Fig. 1) are used to assess late Holocene variations in bottom-water circulation within the SBIC in the context of regional climate variability.

PREVIOUS WORK

A few studies have been carried out on modern foraminifera found in fjord environments along the British Columbia coast. Schafer and others (1989) studied the foraminiferal and thecamoebian biofacies distribution within Bute and Knight inlets to characterize the microfaunal paleoenvironments within these fjords. Elsewhere within the SBIC, Vázquez-Riveiros and Patterson (2008, 2009) used the distribution of modern foraminifera and thecamoebians from sediment-water interface grab samples and core samples in Alison Sound (ALS) and Belize Inlet (BI) to determine regional variations in paleoceanography and paleoclimate as influenced by the Aleutian Low (AL). Foraminifera and thecamoebians studied from transects in marshes near the heads of ALS and FS have also been examined to quantify changes in paleo sea level in this region (Vázquez-Riveiros and others, 2007).

Related research in the SBIC includes cyclostratigraphic analysis of late Holocene laminated sedimentary sequences to identify changes in regional climate (Patterson and others, 2007). Pollen and diatom assemblages observed in adjacent lakes and coastal-marsh transects have also been utilized to assess paleovegetation and paleoclimate variability (Wigston, 2005; Galloway and others, 2007, 2008, 2010; Stolze and others, 2007) and regional changes in sea level (Roe and others, 2009, 2013).

FORAMINIFERA IN LOW-OXYGEN SETTINGS

Higher latitude dysoxic estuarine and fjord environments, such as found in the SBIC, typically contain a low diversity of agglutinated benthic fauna, mainly comprised of one or a few species (Alve, 1991a, b; Schafer and others, 1991; Patterson and others, 2000; Scott and others, 2001; Sen Gupta, 2002). Many foraminiferal species are not only tolerant of dysoxic conditions but can temporarily survive under anoxic conditions (Bernhard, 1989, 1993; Moodley, 1990; Moodley and Hess, 1992; Alve and Bernhard, 1995; Bernhard and Alve, 1996; Moodley and others, 1997). Rhoads and Morse (1971) and subsequent researchers (e.g., Tyson and Pearson, 1991; Bernhard and Sen Gupta, 2002) have proposed classifications of marine microfaunal

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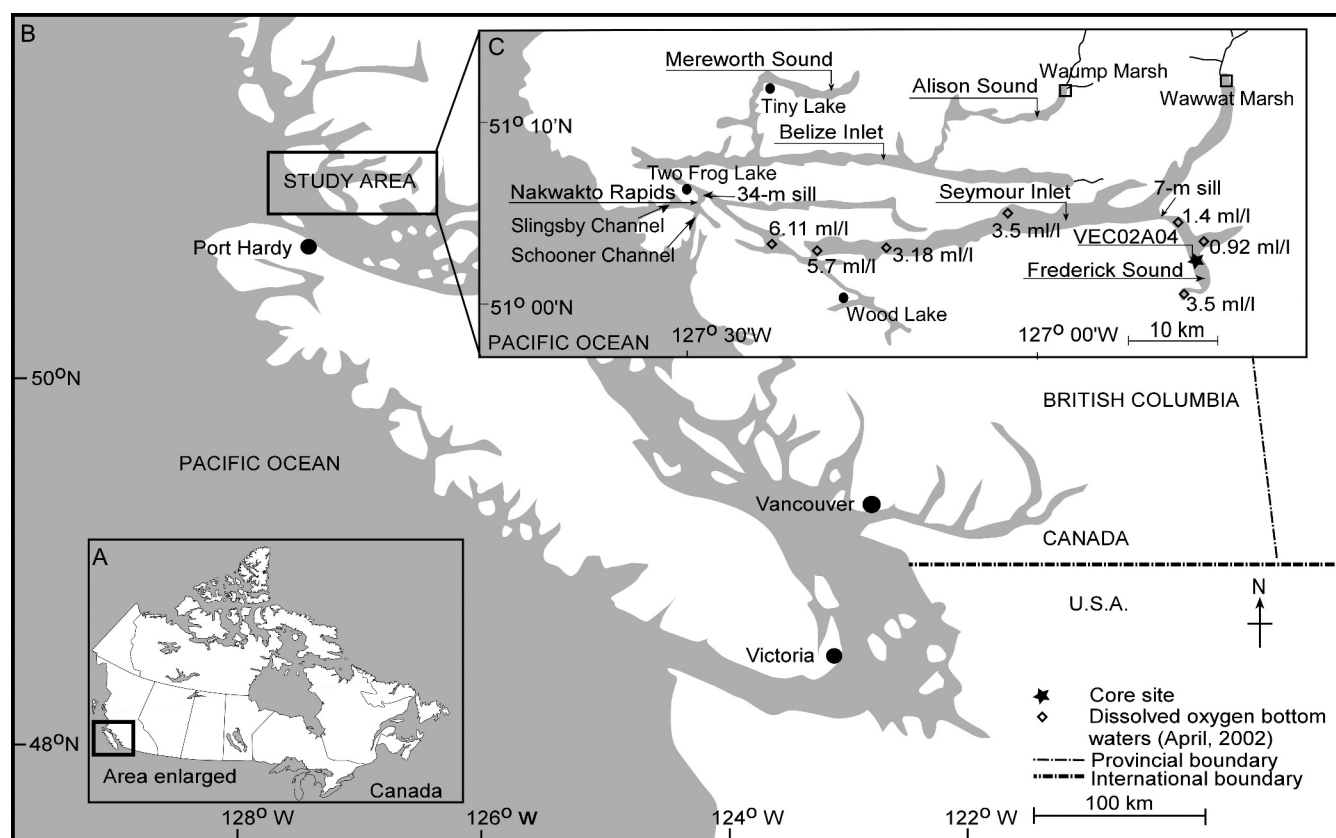


FIGURE 1. Map showing the location of the Seymour-Belize Inlet Complex (SBIC) and adjacent regions in British Columbia. SBIC is located between latitudes $51^{\circ}50.2'N$ – $51^{\circ}10.6'N$; and longitudes $126^{\circ}30.2'W$ – $127^{\circ}40.5'W$. A Map of Canada showing Vancouver Island, B map of southwest British Columbia showing study area, and C map of SBIC showing the locations of Frederick Sound, sills, and the VEC02A04 core site (star; after Galloway and others, 2010). Dissolved-oxygen concentrations within the inlet range from 3.5–0.92 ml/l near the core site.

environments based on variations in dissolved-oxygen content. Foraminiferal distribution patterns have similarly been used to characterize dysoxic and oxic environments (e.g., Blackwelder and others, 1996; Sen Gupta and others, 1996). For example, Kaiho (1994) subdivided microfaunal environments into high oxic (>3 ml/l), low oxic (1.5–3 ml/l), suboxic (0.3–1.5 ml/l), dysoxic (0.1–0.3 ml/l), and anoxic (0–0.1 ml/l) ranges, based on benthic foraminiferal tolerance. Kaminski (2012) also found that Kaiho's index accurately reproduced bottom-water dissolved-oxygen values in the Marmara Sea.

Foraminiferal studies have been previously conducted within many fjords and basins with seasonal anoxia along the west coast of North America (e.g., Cushman, 1925; Cushman and Todd, 1947; McCulloch, 1977; Gallagher, 1979; Jones and Ross, 1979). Several studies carried out in the Santa Barbara Basin, California, for example, linked distinctive foraminiferal faunas to dissolved-oxygen levels (Douglas and others, 1976, 1979; Kaminski and others, 1995; Bernhard and others, 1997). Similarly Patterson and others (2000) studied the effects of variations in oxygen concentrations on foraminiferal biofacies distribution in Effingham inlet, on the west side of Vancouver Island, British Columbia. On the east coast of Vancouver Island, foraminiferal biofacies have also been linked to paleoceanographic fluctuations in seasonally anoxic Saanich Inlet (Blais-Steven and Patterson, 1998; Patterson and Kumar, 2002a).

REGIONAL SETTING

GEOGRAPHY

The coastline of British Columbia is one of the most incised in the world, with numerous rocky fjords (Pickard and Giovando, 1960; Patterson and others, 2007). The SBIC (Fig. 1), located 40 km northeast of Port Hardy, is typical of fjords in the region, containing 1600 km of steep-walled glacier-carved coastline. Frederick Sound opens to the 70-km long Seymour Inlet, one of the two main arms of the SBIC.

CLIMATE

The SBIC lies within the Coastal Western Hemlock (CWH) biogeoclimatic zone, rising from sea level to 900 m (Allen and others, 1999; Rollerson and others, 2001; Haggarty and others, 2003). The CWH with a mean annual precipitation of 2228 mm (range: 1000–4400 mm; Pojar and others, 1991; Rollerson and others, 2001) is the wettest and most productive forest zone in British Columbia. This biogeoclimatic zone is usually characterized by cool summers and mild winters with a mean annual temperature of $8^{\circ}C$ (Haggarty and others, 2003; Pojar and others, 1991).

Climate along the British Columbia coast is primarily controlled by seasonal variability of the two main pressure systems in the northeast Pacific region; the Aleutian Low

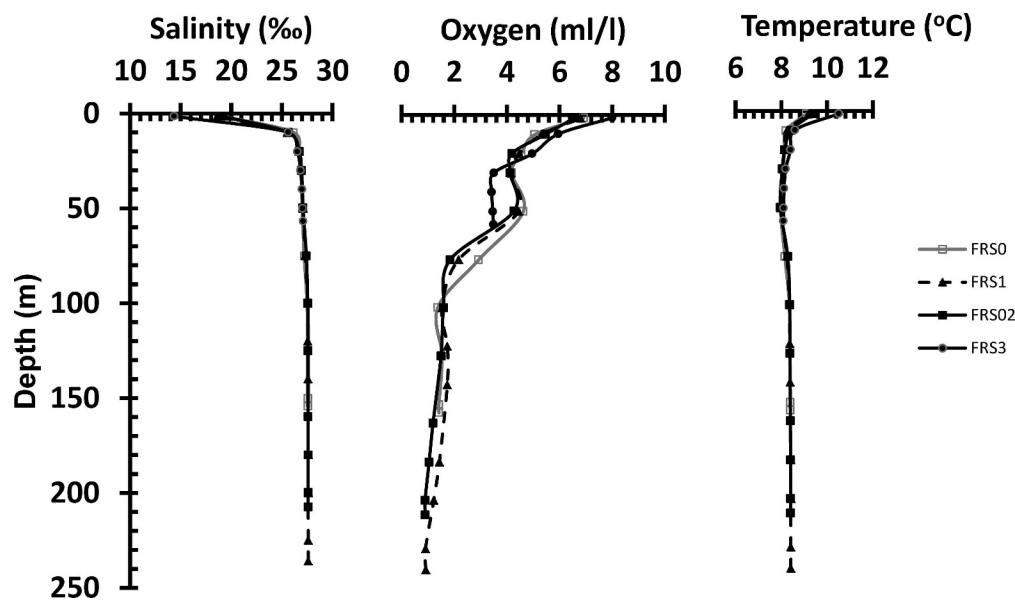


FIGURE 2. Bottom water profiles, measured at the water-sediment interface in Frederick Sound in April 2002. Salinity, dissolved oxygen, and water temperature come from close to the head, middle, and mouth of the inlet (data from Thomson, written communication, 2003).

(AL) and North Pacific High (NPH; Thomson, 1981; Kumar and Patterson, 2002). Seasonal shifts in dominance of the AL and NPH also influence oceanic circulation. In winter, winds associated with the anticlockwise circulation of the AL cause the North Pacific Coastal Current to flow northwest (Thomson, 1981; Thomson and Gower, 1998), while in the summer the current direction shifts southeast as the shelf current responds to winds associated with the clockwise circulation of the NPH (Thomson and Gower, 1998).

OCEANOGRAPHY

The SBIC opens to the southern end of Queen Charlotte Sound through Slingsby and Schooner channels, which merge to a single narrow passage (34-m deep and 400-m wide) at the Nakwakto Rapids (Thomson, 1981; Hemingway and Douglas, 1999; Fig. 1C). The constriction formed by this channel makes the tides at the entrances of Seymour and Belize inlets one of the swiftest in the world, ranging from 8–10 m/s (16–20 knots) on a spring ebb tide to 7 m/s (14 knots) during the maximum flood current (Thomson, 1981; Hemingway and Douglas, 1999). Despite the high currents within the Nakwakto Rapids, the narrowness of the channel prevents sea levels within the SBIC complex and Queen Charlotte Sound from equilibrating with each other across the turn of a tide. As a result, the tidal range within the SBIC is only ~1.3 m while that in Queen Charlotte Sound is >3 m (Canadian Department of Fisheries and Oceans, 2003).

The presence of shallow topographic sills, which restrict circulation, results in a highly stratified water column in the majority of SBIC fjords throughout most of the year (Haggarty and others, 2003). The stratification of the water column results in dysoxic–anoxic bottom-water conditions suitable for formation and preservation of organic matter and rhythmically laminated sediments (varves). These varved sediments deposited in glacier-formed fjords create

optimal conditions for archiving proxy records, which can be used to reconstruct paleoceanographic histories (Baumgartner and others, 1985; Schimmelmann and others, 1990; Schimmelmann and Lange, 1996; Kemp, 2003).

Frederick Sound is ~10-km long and ~0.5-km wide at its entrance into Seymour Inlet, and ~1.5-km wide at its opening to the adjoining Salmon Sound (Pickard, 1961). In addition to the main sill at the Nakwakto Rapids, a secondary 7-m deep sill at the mouth of FS further restricts circulation, resulting in the development of permanent stratification.

Bottom-water profiles measured during research cruises of the Canadian Coast Guard Ship (CCGS) *Vector* in April 2002 indicate that FS has a well-developed estuarine circulation. Salinities in FS increase from about 15‰ at the surface to 27.6‰ at the bottom of the sound (Fig. 2a). Dissolved-oxygen concentrations within FS also vary considerably, ranging from ~8 ml/l at the surface to 0.9 ml/l at depth (Fig. 2b). Water temperature variation is less pronounced; it decreases from ~10.5°C at the surface to 8.5°C at the bottom (Fig. 2c).

MATERIALS AND METHODS

SAMPLE COLLECTION

The 12.26-m VEC02A04 piston core studied here was collected in FS from 240-m water depth during the April 2002 research cruise of the CCGS *Vector*. The recovered core was longitudinally split and the sedimentary sequence was described at the Pacific Geoscience Center in Sydney, British Columbia. One split was sampled for various proxies including micropaleontological analysis. The other half was subdivided into 62 short core intervals measuring 20-cm long \times 3 cm thick. The short cores were subsequently X-rayed to facilitate recognition of their internal sedimentological structures, and preserved as an archive.

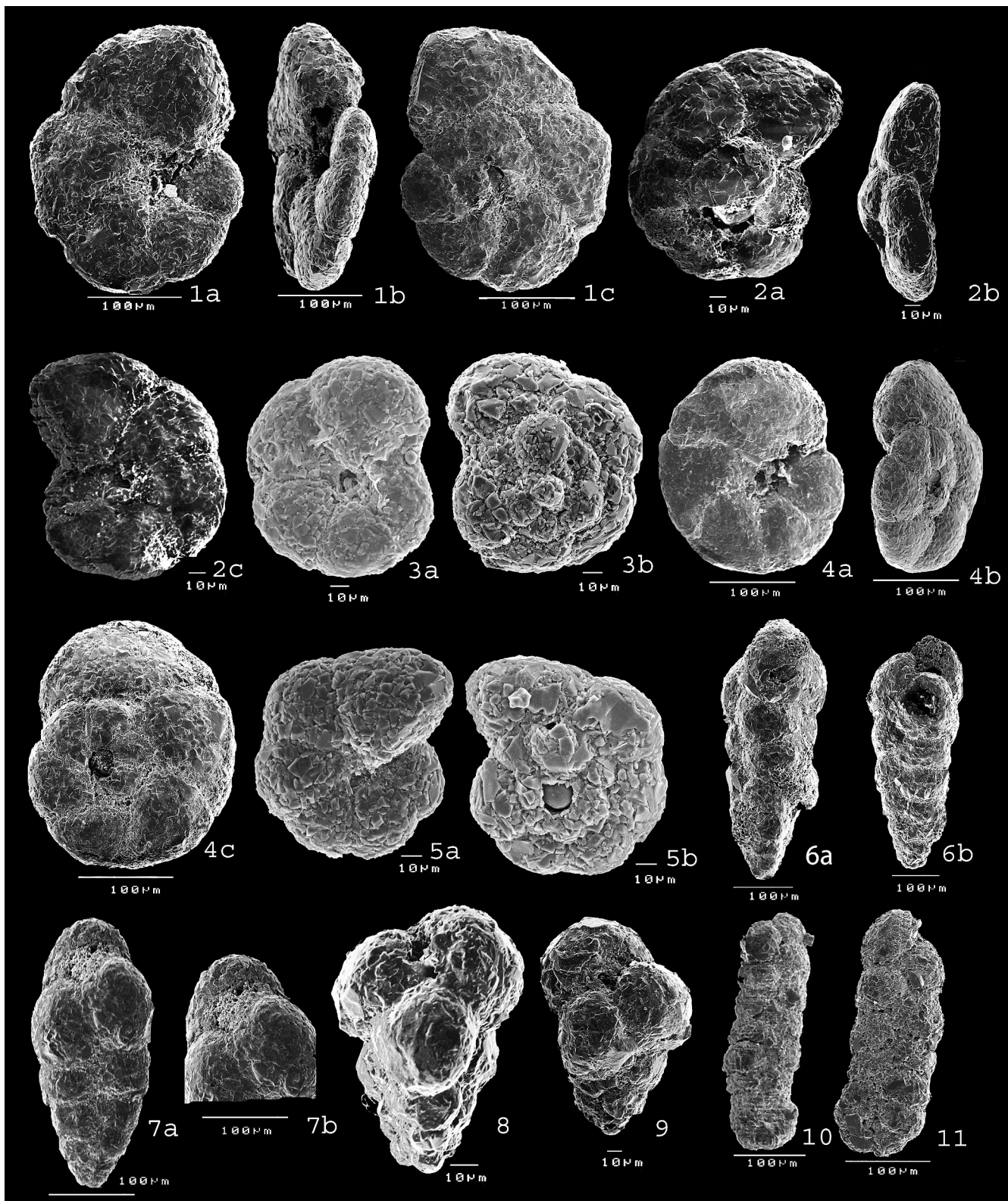


FIGURE 3. All specimens from the Frederick Sound core VEC02A04. **1** *Lepidoparatrochammina charlottensis* (Cushman), sample S1_35–40; a, umbilical side; b, side view; c, dorsal view. **2** *Zavodovskina nana* (Brady), sample S1_50–55; a, dorsal side; b, side view; c, umbilical view, showing slightly depressed umbilicus. **3** *Portatrochammina bipolaris* (Brönnimann and Whittaker), sample S7_0–5; a, umbilical view; b, dorsal view. **4** *Trochammina squamata* (Jones and Parker), sample S1_60–65; a, umbilical view; b, oblique view of the spiral side showing coiling and apertural slit; c, spiral view. **5** *Deuterammina grisea* (Earland), sample S6_0–5; a, umbilical view; b, spiral view. **6, 7** *Eggerella advena* (Cushman): 6, sample S1_95–100; a, side view; b, apertural face; 7, sample S1_120–125; a, apertural view; b, enlarged apertural slit. **8, 9** *Eggerella* sp. of Vázquez-Riveiros and Patterson (2008, pl. 5, fig. 5): 8, sample S1_15–20, side view; 9, sample S3_80–85, side view. **10, 11** *Spiroplectammina bififormis* (Parker and Jones): 10, sample S1_35–40, side view; 11, sample S1_35–40, side view.

LABORATORY ANALYSES

Two hundred and eleven samples, taken at 5-cm intervals from FS core VEC02A04, were processed for micropaleontological analysis. All samples were wet-sieved with a 63- μ mesh and dried in an oven at low temperature. Foraminiferal and thecamoebian specimens were identified and counted using an Olympus SZH10 stereomicroscope, and photographed with a JEOL 6400 Scanning Electron Microscope at Carleton University (Figs. 3, 4). They are archived in the Micropaleontological Research Laboratory at Carleton University. Foraminiferal identification and classification followed Loeblich and Tappan (1987) and Patterson and others (1998). Although thecamoebians (Fig. 4) were identified to individual species and strains (e.g., Patterson and others, 1996; Kumar and Dalby, 1998; Roe and others, 2010), in this study they were collectively used only to indicate terrestrial runoff. Radiocarbon analysis was obtained using Accelerator Mass Spectrometry (AMS) at IsoTrace Laboratories at the University of Toronto, Ontario, and CHRONO Center at Queens University, Belfast, Northern Ireland. Dated materials consisted of seven wood fragments, one pine cone, and one twig (Table 1). The radiocarbon dates were calibrated using CALIB REV. 5.1 for Windows with reference to the Intcal04 data set (Reimer and others, 2009; Stuiver and others, 2005). The program converts radiocarbon ages to calibrated calendar years (Stuiver and others, 2005).

MULTIVARIATE ANALYSES

Of the 211 samples processed and analyzed for microfossils, 20 were barren. In order to identify statistically significant samples, the probable error (*pe*) for total counts in each of the remaining 191 samples was calculated using the following equation:

$$pe = 1.96 \left(\frac{S}{\sqrt{X_i}} \right)$$

where *S* is the standard deviation of the specimen population counts and *X_i* is the number of specimen counts per sample. A sample is statistically significant if its total faunal count is greater than the probable error (Boudreau and others, 2005; Vázquez-Riveiros and others, 2007). Due to the low abundances relative to the probable errors of the samples, some adjacent samples were combined for subsequent multivariate analyses. The lowermost 22 cm (12.04–12.26 m) of the core contained a very sparse fauna and was excluded from further analyses. One hundred and one composite samples were obtained through this process and utilized in subsequent multivariate analysis.

The relative fractional abundance (*F_i*) of each species in each of the statistically significant samples was determined using the following equation:

$$F_i = \frac{C_i}{N_i},$$

where *C_i* is the species count and *N_i* is the total of all species counts in a given sample.

The standard error (*S_{xi}*) at 95% confidence level (Patterson and Fishbein, 1989; Fishbein and Patterson, 1993) was determined from the fractional abundance using

the following formula:

$$S_{xi} = 1.96 \sqrt{\frac{F_i(1 - F_i)}{N_i}}.$$

Species with standard errors greater than their fractional abundances in all the samples were discarded from subsequent multivariate analysis.

Species proportions and faunal diversity in a sample measure the relative health of the depositional environments of the sediments in which they occur. Environmental stability is commonly assessed using the Shannon Diversity Index (*SDI*; Shannon, 1948; Fishbein and Patterson, 1993). This index is calculated using the following equation:

$$SDI = - \sum_1^S \left(\frac{F_i}{N_i} \right) \times \ln \left(\frac{F_i}{N_i} \right),$$

where *S* is the species richness of the sample, *F_i* is the fractional abundance of each species, *N_i* is the total abundance (counts) of the sample, and ln is the natural logarithm (log_e).

In healthy and stable environments where faunal abundances are ≥ 500 specimens/cm³ (Patterson and Kumar 2002b), *SDI* commonly ranges from 2.5–3.5 (e.g., Magurran, 1988; Legendre and Legendre, 1998). The index ranges from 1.5–2.5 in transitional environments, and its values generally vary from 0.1–1.5 in highly stressed environments such as in the SBIC fjords (Kumar and Patterson, 2002). Faunal abundances in stressed environments are commonly between 30–150 specimens/cm³ and are usually dominated by one or two taxa with other associated species occurring rarely (Patterson and Kumar, 2002b).

Using the “error weighted maximum likelihood” clustering method of Fishbein and Patterson (1993), Q-mode cluster analysis was carried out on 101 samples. The cluster methodology employed was Ward’s minimum variance method, which uses the Squared Euclidean Distance as a linkage between groups of samples. The results were displayed in hierarchical diagrams using SPSS version 15 for Windows. R-mode cluster analysis was performed using the same technique as in the Q-mode analysis to determine the similarities between species and characterize the assemblages represented by the Q-mode sample groupings.

RESULTS AND DISCUSSION

CHRONOLOGY

Calibrated radiocarbon dates (Table 1), including six that are in stratigraphic order and a seventh derived from a twig fragment, were utilized to construct an age model for FS core VEC02A04 (Fig. 5). To reduce any potential errors in the accuracy of the age/depth model associated with delayed deposition, two anomalous old dates from 3.13 m and 4.57 m were excluded from the model (e.g., Galloway and others, 2010). The radiocarbon date at 10.51 m, which is much older than the date obtained at 11.82 m, was included in the age model because the twig fragment from which the former date was derived lacks old hardwood and would not likely have a substantial built-in aging effect (Galloway and others, 2010). Twig fragments also resist

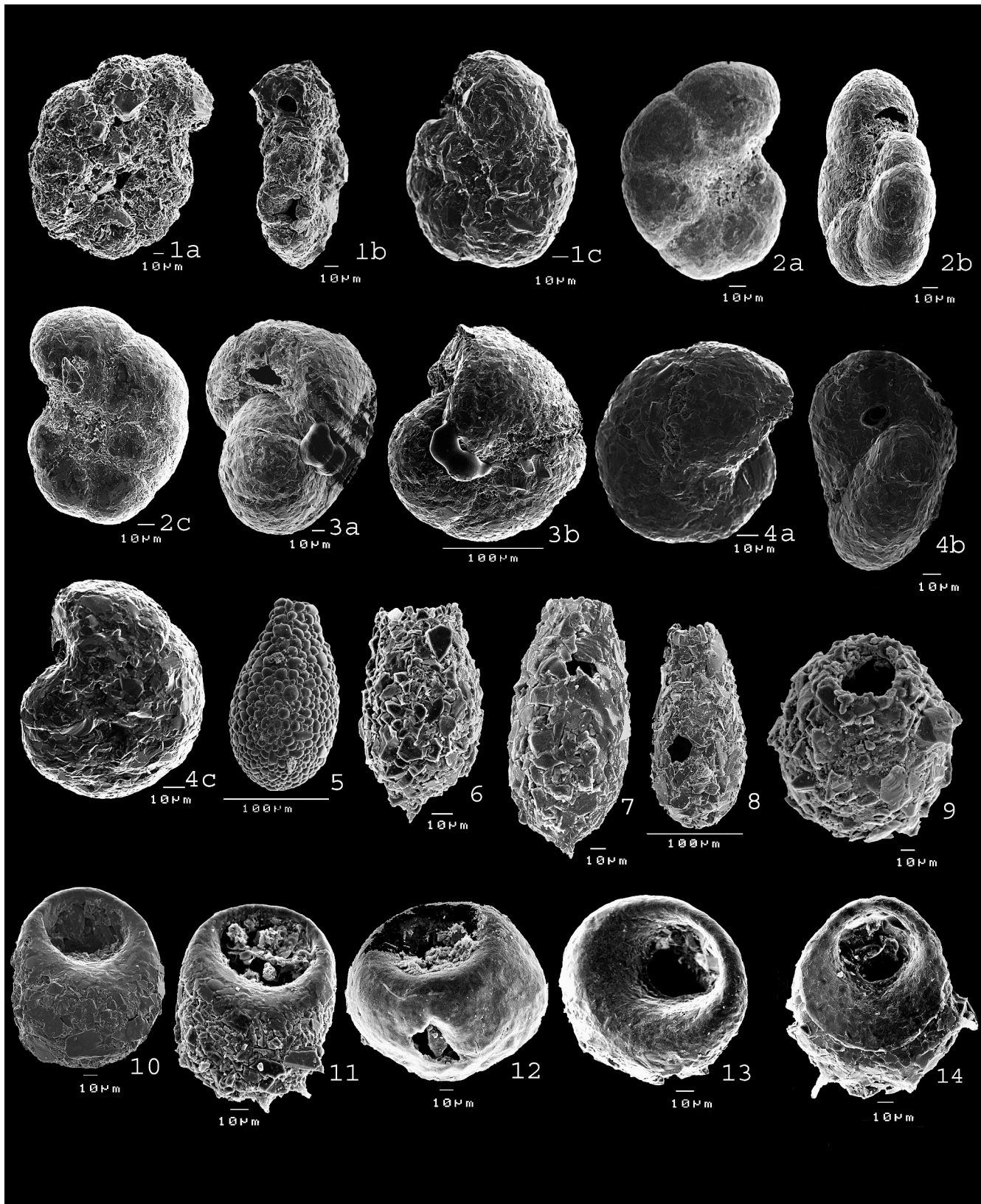


FIGURE 4. All specimens from the Frederick Sound core VEC02A04. 1 *Cribrostomoides crassimargo* (Norman), sample S3_35–40; a, umbilical view showing depressed umbilicus; b, apertural view showing arched aperture; c, dorsal view. 2 *Cribrostomoides jeffreysii* (Williamson), specimen from sample S1_35–40; a, umbilical view; b, apertural view with lipped, slit-like aperture; c, dorsal view. 3 *Cribrostomoides subglobosus* (Cushman), sample S1_15–20; a, apertural view showing typical thick-lipped apertural slit; b, side view. 4 *Recurvoides turbinatus* (Brady), sample S1_35–40; a, side view; b, apertural view showing asymmetrical test and inclined aperture; c, side view. 5 *Diffflugia oblonga* strain “oblonga” (Reinhardt and others) showing

TABLE 1. Radiocarbon and calendar ages from Frederick Sound core VEC02A04; a = Conventional radiocarbon date $^{13}\text{C}/^{12}\text{C}$ corrected using $\delta^{13}\text{C}$ = -25‰; b = Calibrated using CALIB REV 5.1 (Stuiver and others, 2005) with INTCAL09 dataset (Reimer and others, 2009); BP denotes before 1950; * indicates date rejected from Frederick Sound age-depth model.

Sample ID	Lab Number	Depth (cm)	Lithology	Material Dated	^{14}C Radiocarbon Age (cal. yr AD/BC) ^a		Calibrated Age (cal. yr BP) ^b	
					Corrected	Calibrated	Probability Median	Probability Median
VEC02A04-1-97	TO-10788	97	Laminated	Wood Fragment	1510±60	427–644 AD	535	1306–1523
VEC02A04-2/3-16	TO-11082	313	Massive	Wood Fragment	3070±70	1127–1463 BC	1295	3077–3413
VEC02A04-3-132a	TO-10789	457	Laminated	Wood Fragment	2560±80	413–835 AD	624	2363–2785
VEC02A04-132b	TO-10790	457	Laminated	Wood Fragment	3050±60	1127–1434 BC	1280	3077–3384
VEC02A04-5-115	TO-11084	734	Woody layer	Pine Cone	2540±70	483–810 AD	646	2433–2760
VEC02A04-7-126	TO-10791	1051	Laminated	Twig	4350±80	2867–3144 BC	3006	4817–5094
VEC02A04S7-20-25	UBA-13359	945	Laminated	Wood Fragment	3318±32	1520–1684 BC	1602	3470–3634
VEC02A04S7-130-135	UBA-13360	1060	Massive	Wood Fragment	3710±22	2032–2145 BC	2089	3982–4095
VEC02A04-8-103	TO-10793	1182	Massive	Wood Fragment	3770±60	2024–2351 BC	2188	3974–4301
								4138±327

decomposition during delayed deposition. In addition, since the dated material was sampled from a laminated core interval, it was likely deposited contemporaneously with the sediments and not reworked. A linear regression method used to model the age of the entire core interval yielded an r^2 of 0.84 and 0.353 cm/yr sedimentation rate. Based on this rate, the core was determined to have been deposited from 1090 to ~4560 cal. yr BP.

SEDIMENTOLOGY

Almost the top meter of sediment in the FS core was lost due to over-penetration by the piston corer. This unrecovered section represents ~1000 yr of sedimentation. In addition, ~6.7% of the total 12.26-m long core was not recovered due to caving (Fig. 6).

The core is composed of organic-rich mud and silt with occasional sand intervals, which were deposited as massive (44%), annually laminated (41%), graded (5%), and slump (3%) units (Fig. 6). Laminated intervals are unevenly distributed throughout the core and are comprised of alternating olive to dark-gray organic-rich clay and silt couplets representing seasonal variation in deposition (Fig. 6). Variable thicknesses of light-olive to yellow diatom-rich laminae indicate spring and summer diatom productivity. In contrast, variable dark terrigenous laminae record variation in winter precipitation and spring melt-water runoff (McQuoid and Hobson, 1997; Kemp, 2003).

Homogenous units in the FS core are mostly concentrated in the lowermost section (2.26–8.03 m), becoming unevenly intermingled with laminated intervals in other parts of the core. Approximately 1.2% of these massive sediments are composed of very fine- to fine-grained sands, ranging in thickness from 1–5 cm. Slump deposits are concentrated within the 3.80–5.40-m core interval (Fig. 6). The thickness of these typically fining-up units ranges from

2–7 cm. They are generally comprised of basal sand bodies which first grade to dark hemipelagic mud and are topped with diatom-rich layers (Patterson and others 2007; Babalola, 2009; Galloway and others, 2010).

The similarity between the microfaunal composition found in both the laminated and homogeneous sediments and the absence of bioturbation or evidence of any other benthic activities within the massive units suggest that both sediment types were deposited under similar anoxic to dysoxic conditions. As discussed previously, in some detail for this core (Patterson and others, 2007; Galloway and others, 2010) and from similar depositional environments known elsewhere along the British Columbia coast (e.g., Russell and Morford, 2001), the massive sediments were likely initially deposited as laminated sediments, and then reworked and homogenized by turbidity currents, slump, and mass movements (mud avalanche) as a result of failures of the steep, forested fjord slopes during heavy rainfalls. The presence of graded beds and slump sediments in the core provides considerable support for this interpretation. The absence of thick slump deposits suggests that massive sediments were not derived from seismic-related disturbances or any other form of tectonic activity (e.g., Dallimore and others, 2005; Galloway and others, 2010).

FORAMINIFERAL DISTRIBUTION

Species diversity and abundances were generally low in the FS core with only 24 foraminiferal and 13 thecamoebian species identified (Appendices 1, 2). Shannon Diversity Index values (0–1.36) were also generally low, although these values and the number of foraminiferal species identified gradually increased above 6.79 m (Figs. 7, 8). Agglutinated foraminifera, especially *Eggerella advena*, which accounted for 50–93% of the foraminiferal assemblages (Figs. 3, 7) dominated the entire FS core. *Spiroplectammina biformis*,

reticulate ornamentation, sample S1_95–100. **6** *Diffflugia protaeformis* strain “*claviformis*” (Reinhardt and others), sample S3_35–40, side view. **7** *Diffflugia protaeformis* strain “*acuminata*” (Reinhardt and others), sample S3_35–40, side view. **8** *Diffflugia oblonga* strain “*lanceolata*” (Reinhardt and others), sample S1_130–135, side view. **9** *Diffflugia oblonga* strain “*glans*” (Reinhardt and others), sample S3_105–110, side view. **10** *Centropyxis constricta* strain “*aerophila*” (Reinhardt and others), S3_35–40, side view. **11** *Centropyxis constricta* strain “*constricta*” (Reinhardt and others), sample S2_120–125; side view, **12** *Centropyxis aculeata* strain “*aculeata*” (Reinhardt and others), sample S2_80–85, side view. **13, 14** *Centropyxis aculeata* strain “*discoidea*” (Reinhardt and others), sample S1_130–135, side view.

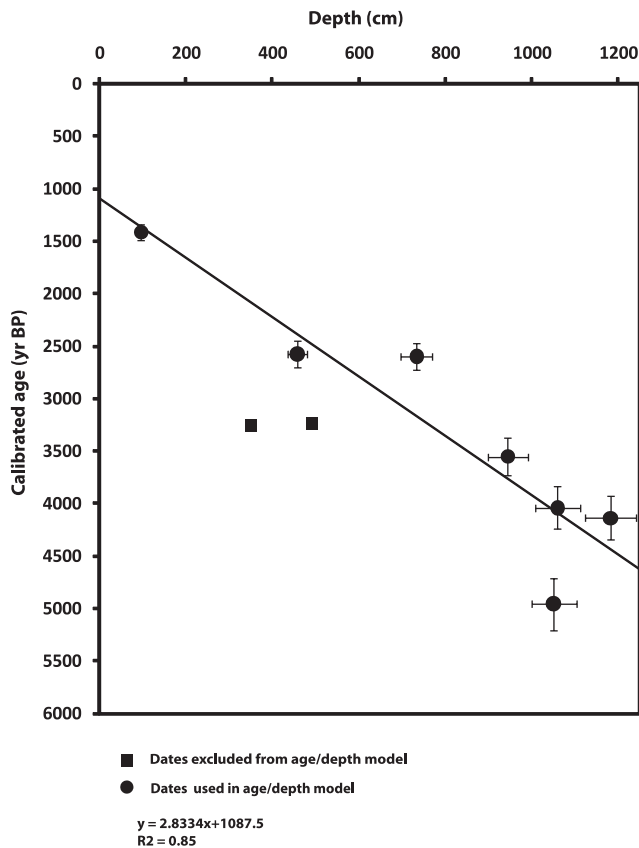


FIGURE 5. Chronology of the Frederick Sound core. The age/depth model is based on linear regression of seven calibrated radiocarbon dates. Error bars indicate the 2- σ ranges of the calibrated dates.

Recurvoides turbinatus, *Portatrochammina bipolaris*, and a number of *Trochammina* and *Cribrostomoides* species were subordinate but widely distributed throughout the core (Figs. 3, 4, 7).

Freshwater thecamoebians, primarily represented by centropxyid and diffligid taxa (Fig. 4; Appendix 2), occur as a minor component of the core faunal assemblages. With the exception of some centropxyid taxa that can withstand brackish conditions (<5‰ salinities; Scott and others, 2001) living thecamoebians are restricted to freshwater. Their association with agglutinated foraminifera in the FS core thus indicates that they are allochthonous, as salinities required to support the foraminifera were too high for thecamoebians. Due to their low absolute counts in the examined samples, the thecamoebian species were combined and utilized as a single “terrestrial run-off” proxy (Fig. 7). Since freshwater thecamoebians, which do not inhabit marine environments, were washed into FS inlet via streams and runoff, they were not included in the statistical analyses but treated as a complementary proxy to the foraminiferal data.

As there were no distinctive changes in foraminiferal distributions in the core, foraminiferal biofacies were identified by subtle changes in the distribution frequencies and abundances of only three species: *E. advena*, *R. turbinatus*, and *S. bififormis*. A Q-mode cluster analysis carried out on 101 samples from the core yielded three biofacies: an *Eggerella advena* Biofacies, an *Eggerella advena-Spiroplectammina bififormis* Biofacies, and a *Recurvoides*

turbinatus-Spiroplectammina bififormis Biofacies (Table 2; Fig. 8). These biofacies were unevenly distributed throughout the core with the *Eggerella advena* Biofacies dominating the lowermost 6.79–12.04 m of the core (Table 2; Fig. 9). This biofacies, with an 83% mean occurrence of *E. advena*, also occurs in the 4.45–5.62 m and 1.2–1.37 m core intervals (Table 2; Fig. 9). The *Eggerella advena-Spiroplectammina bififormis* Biofacies, delineated by a slight reduction in *E. advena* (74.2% mean occurrence) and an increase in *S. bififormis* (11.4% mean occurrence; Table 2), was found mostly within the 5.62–6.79 m and 3.9–4.45 m core intervals. The *Recurvoides turbinatus-Spiroplectammina bififormis* Biofacies, defined by substantially increased abundances of *R. turbinatus* (14.2% mean), moderately abundant *S. bififormis* (8.5% mean), and a much reduced *E. advena* (64.7% mean), was primarily restricted to the topmost (0.1–1.2 and 3.25–3.87 m) intervals of the core (Table 2; Fig. 9).

PALEOENVIRONMENTAL INTERPRETATION

As discussed above, the organic-matter-rich, homogeneous and laminated sediments of the FS core are comprised of sparse populations of low diversity ($SDI \leq 1.36$) agglutinated foraminiferal species that are tolerant to dysoxic bottom-water conditions. The predominance of these low-oxygen-indicator agglutinated foraminifera and the absence of calcareous foraminiferal species are an indication that the late Holocene bottom waters in SBIC had low oxygen. This interpretation is supported by the low concentrations of dissolved oxygen measured in modern FS bottom waters (0–0.92 ml/l) and the presence of significant intervals of laminated sediments in the core.

Eggerella advena, the most dominant species in the inlet (accounting for >50% of the foraminifera in all samples) is a shallow-water species found mainly in lagoons and nearshore Arctic-boreal environments (Vilks, 1969; Vilks and Deonarine, 1988; Lloyd, 2006; Murray, 2006). This species is also tolerant of low-oxygen conditions (Patterson and others, 2000), and has also been recognized as an important pollution-indicator species that can thrive in highly contaminated, oxygen-depleted, organic-rich environments close to sewage dump sites in coastal areas of eastern Canada and along the Pacific coast of North America (e.g., Schafer, 1982; Schafer and others, 1991; Alve, 1993, 1995; Alve and Nagy, 1986, 1990; Blais-Stevens and Patterson, 1998). As the SBIC is located in a remote area lacking any settlements, industry, or agricultural activity, the dominance of *E. advena* and other organic-matter tolerant species is related to the natural accumulation of organic matter under dysoxic to anoxic bottom-water conditions.

The association of *E. advena* throughout the FS core with other low-oxygen tolerant species [e.g., *R. turbinatus*, *S. bififormis*, *Cribrostomoides jeffreysii* and *P. bipolaris* (e.g., Patterson and others, 2000)] in the FS core is similar to an exclusively agglutinated fauna reported by Vázquez-Riveiros and Patterson (2009) from low-oxygen (<1.0 ml/l) environments in Belize Inlet. The presence of this association throughout the FS core indicates that similar dysoxic bottom-water conditions prevailed throughout the entire depositional record. The relative abundances of these

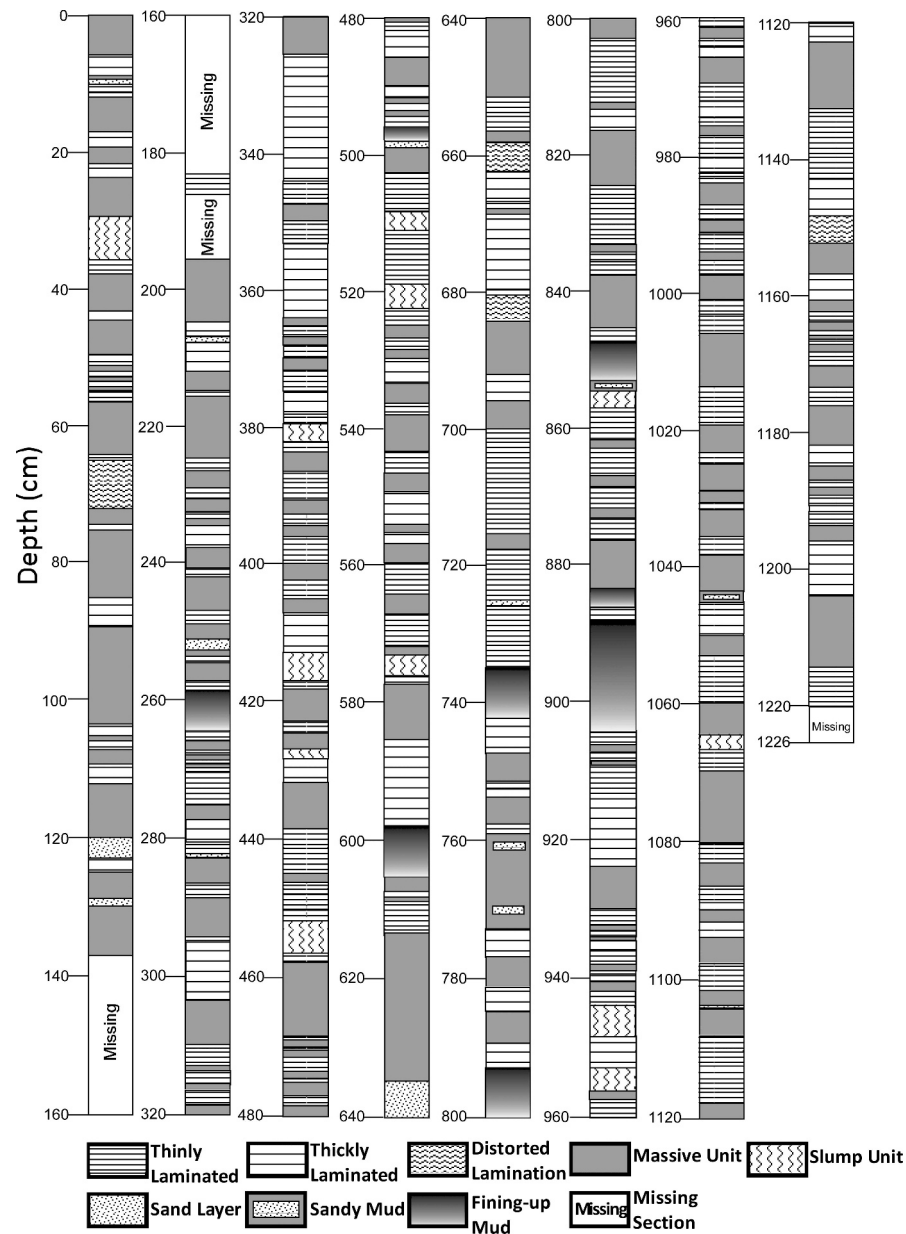


FIGURE 6. Stratigraphic column of the Frederick Sound core. Laminated and massive sediments alternate unevenly in the core, predominantly comprised of organic-rich mud/silt with minor sand occurrences. A wood layer occurs at 734 cm.

and other taxa change periodically throughout the core, providing evidence that additional factors besides low oxygen (e.g., water temperature, precipitation, and related runoff) influenced the faunal makeup. For example, *Portatrochammina bipolaris*, which appears frequently throughout the core, is dominant in cool deeper waters throughout the Canadian Arctic (e.g., Vilks, 1989; Murray, 2006) and Scoresby Sound, eastern Greenland (Madsen and Knudsen, 1994). Further evidence of cold-water conditions is provided by the presence of *S. biformis*, typical in cold glaciomarine environments (Schafer and Cole, 1986; Madsen and Knudsen, 1994; Hald and Korsun, 1997; Korsun and Hald, 1998). This species is among the first foraminiferal taxa to colonize proximal glaciomarine environments in Arctic regions (Korsun and Hald, 2000).

Cribrostomoides jeffreysii, a common species in the upper (3.50–6.79 m and 0.1–1.37 m) intervals of the FS core, is also a typical cold-water Arctic indicator (Vilks, 1969; Lagoe, 1979), which can tolerate near bottom-water anoxic (<0.1 ml/l) conditions (Bernhard, 1989; Sen Gupta and Machain-Castillo, 1993). In contrast, *Zavodovskina nana*, moderately abundant within the basal portion of the core, has been reported in high abundances from a warm pocket in the Canadian Arctic (Lagoe, 1979). The relative shift in abundance from *Z. nana* to an increased proportion of *C. jeffreysii* is interpreted to indicate the development of progressively cooler bottom-water conditions. An increase in the abundance of allochthonous thecamoebians, particularly through the upper 7.83 m of the core, suggests an increase in freshwater runoff into the fjord.

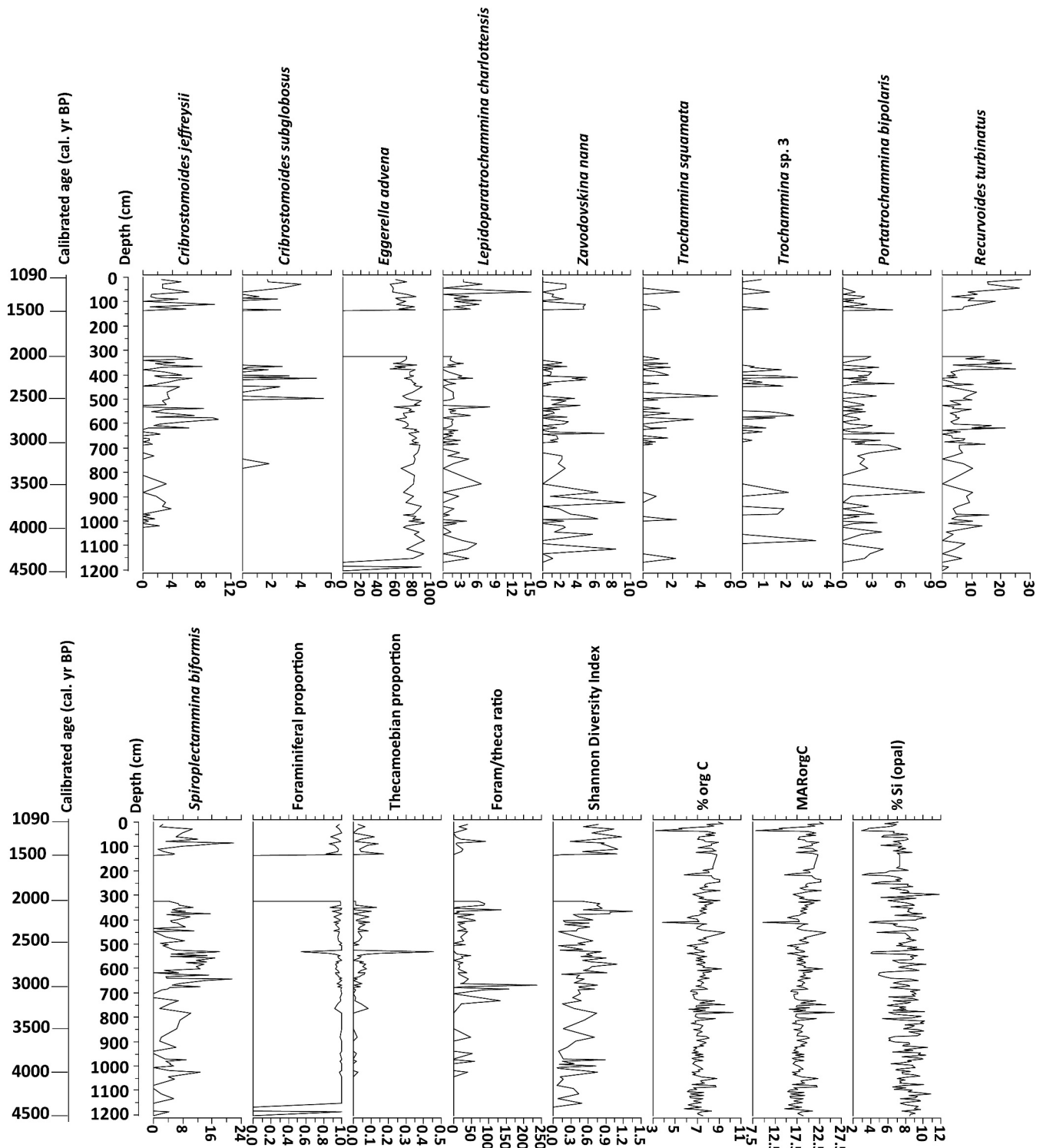


FIGURE 7. Stratigraphic distribution of foraminiferal species in the Frederick Sound core along with other distributional patterns, including foraminifera and thecamoebian proportions, foraminiferal/thecamoebian ratios, Shannon Diversity Index, organic matter (% org carbon), organic mass accumulation rate (MAR orgC) and biogenic silica (% Si, opal).

DEVELOPMENT OF DYSOXIC AND ANOXIC CONDITIONS

As previously described by Vázquez-Riveiros and Patterson (2009), development of anoxic to dysoxic conditions

in the SBIC is attributed to the presence of sills at the mouths of most of the contained U-shaped inlets and sounds. These sills, primarily comprised of crushed rock and silt, were deposited as glacial moraines. They reduce the volume of oxygen-rich oceanic water that can flow into

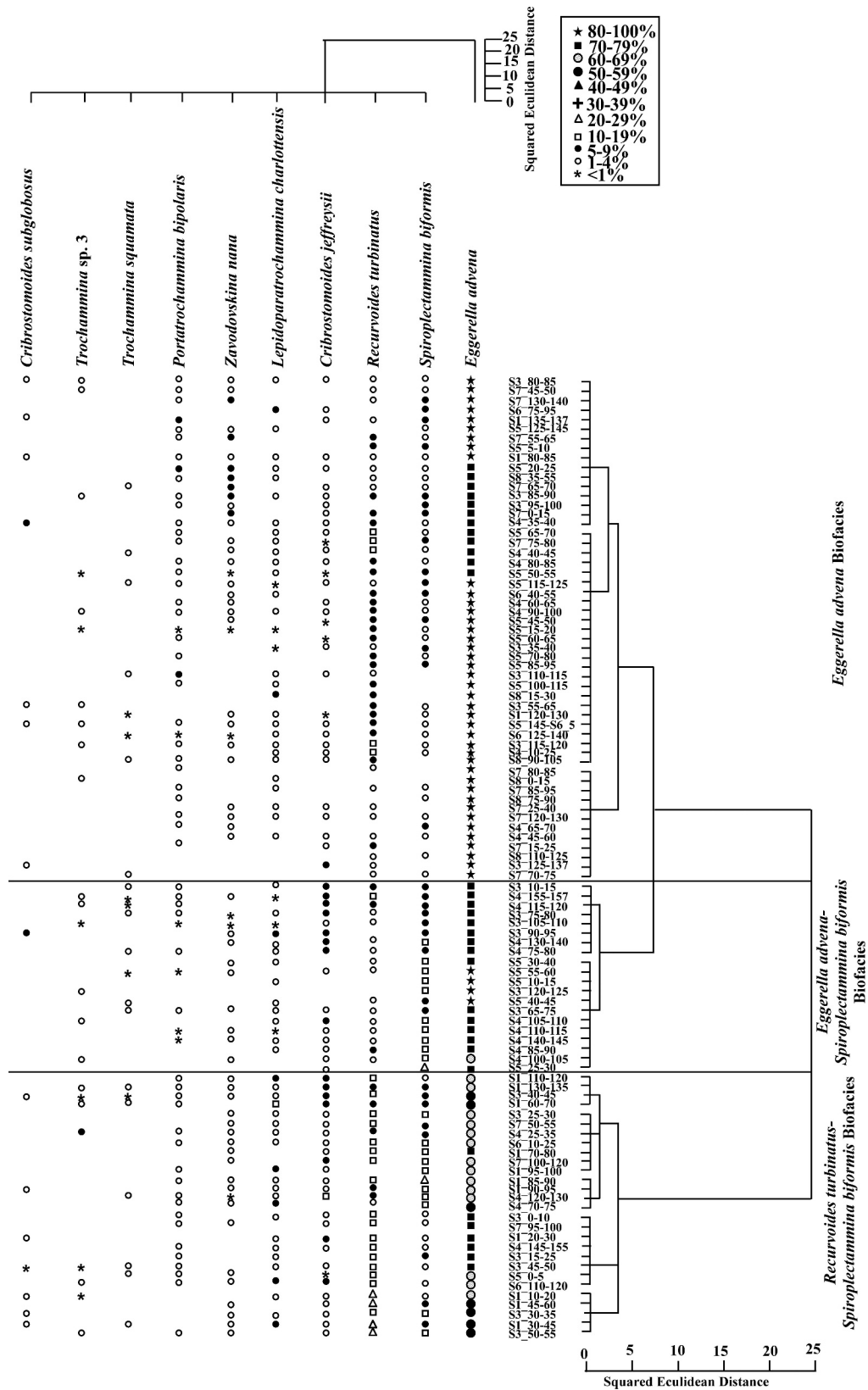


FIGURE 8. Q-mode vs. R-mode cluster dendrogram for the FS core samples. Range of abundances (%) of the foraminiferal species is indicated by symbols. The samples in the right-hand column are numbered by the core section (S) and sampling depths in cm.

TABLE 2. A summary of foraminiferal biofacies in the FS core. Each biofacies is dominant at the depths indicated.

Depth (m)	Biofacies	Dominant Species (>8% mean)	Subordinate (>2% mean)	Minor (<2% mean)
6.79–12.04				
4.45–5.62	<i>Eggerella advena</i>	<i>Eggerella advena</i> (83%)	<i>Recurvoides turbinatus</i> (5.2%)	<i>Lepidoparatrochammina charlottensis</i>
1.2–1.37			<i>Spiroplectammina biformis</i> (3.5%)	<i>Portatrochammina bipolaris</i> <i>Zavodvskina nana</i>
5.62–6.79	<i>Eggerella advena</i> - <i>Spiroplectammina</i> <i>biformis</i>	<i>Eggerella advena</i> (74.2%) <i>Spiroplectammina biformis</i> (11.4%)	<i>Recurvoides turbinatus</i> (3.5%) <i>Cribrostomoides jeffreysii</i> (3.7%)	<i>Zavodvskina nana</i> <i>Lepidoparatrochammina charlottensis</i>
3.25–3.87		<i>Eggerella advena</i> (64.7%) <i>Recurvoides turbinatus</i> (14.2%)	<i>Lepidoparatrochammina charlottensis</i> (2.6%)	<i>Zavodvskina nana</i> <i>Cribrostomoides subglobosus</i>
0.1–1.2	<i>Recurvoides turbinatus</i> - <i>Spiroplectammina</i> <i>biformis</i>	<i>Spiroplectammina biformis</i> (8.5%)	<i>Cribrostomoides jeffreysii</i> (3.1%)	<i>Trochammina squamata</i> <i>Portatrochammina bipolaris</i>

the inlets, which together with a low-salinity surface wedge caused by riverine input results in a highly stratified water column. Depending on the strength of the estuarine outflow that is controlled by shifting precipitation patterns, the amount of oceanic inflow will vary considerably, impacting oxygenation of bottom waters. The major constrictions to flow at the Nakwakto Rapids (34-m deep) and the very shallow 7-m deep sill at the mouth of FS severely restrict the inflow of oxygenated bottom water. This has resulted in permanent water-column stratification, stagnation at the base of the fjords, and anoxic conditions throughout the deposition of the entire FS core.

In addition to the effects of bottom-water stratification and restricted circulation caused by shallow sills at the mouths of the SBIC inlets, the development of bottom-water anoxia might have been further enhanced by influx of high concentrations of terrestrially derived organic matter (~7.5% mean; Babalola, 2009) during deposition in FS (Fig. 6). This likely led to the predominance of *E. advena* and *S. biformis*, as these two agglutinated foraminiferal species are very tolerant of organic-rich environments (e.g., Blais-Stevens and Patterson, 1998). Environments characterized by high organic-matter flux and low-oxygen conditions typically have low species diversity dominated by depauperate fauna (Den Dulk and others, 1998; Alve, 1990).

High diatom productivity in the inlet is indicated by the measured biogenic silica (7.71% mean, Fig. 7), high abundance of mud fecal pellets (Babalola, 2009), and high concentrations of diatom valves (Wigston, 2005) in the core sediments. High diatom productivity also likely led to biochemical-oxygen demand, contributing to the development of bottom-water anoxia.

PALEOCLIMATE

The moderate abundances of allochthonous thecamoebians within the upper 3.23–7.83 m (~2010–3305 cal. yr BP) and 0–1.37 m (~1090–1475 cal. yr BP) intervals of the FS core combined with evidence from other core proxies suggest that there was a transition from cool/wet to cooler/drier climate at ~3125 cal. yr BP. For example, Galloway and others (2010) interpreted an increase in lamination concentrations, a decline in Cupressaceae pollen, and relatively increased proportions of *Tsuga heterophylla* (Sargent) pollen as evidence that the 3190–2250 cal. yr BP

interval in the core was deposited during a period of cooler and drier climate. Similarly, Wigston (2005) interpreted a decline in the relative abundance of *Tabularia tabulata* (Williams and Round) and increased valves of *Skeletonema costatum* (Greville) Cleve at ~3160 cal. yr BP, as an indication of sunnier spring conditions and reduced precipitation. As with the thecamoebians, *T. tabulata*, a freshwater diatom, is washed into the fjords by runoff, precipitation, and/or snowmelts, while *S. costatum*, a marine spring-bloom diatom, thrives under sunnier and abundant light conditions (Hitchcock and Smayda, 1977, cited in Galloway and others, 2010). A decrease in laminae thickness and enrichment of $\delta^{13}\text{C}$ from ~3350–2020 cal. yr BP in the FS core has also been linked to dry climate conditions in the SBIC (Babalola, 2009). The reduced occurrence of massive, slump, and graded beds toward the top of the FS core suggests stabilization of the steep fjord slopes, likely as a result of drier conditions.

Given prevailing cooler/drier climate conditions, it was likely that the thecamoebian-rich sediments in the adjoining rivers (mainly the Seymour River) and marshes would likely become drier and less cohesive, and would have been more easily eroded and transported to the SBIC fjords by spring snowmelt, runoff, and/or early summer precipitation. Schafer and others (1989, 1991) and Snyder and others (1990) ascribed high thecamoebian abundances in fjords such as those in the SBIC to lower estuarine water-mass characteristics and passive transport of sediments by mass flow processes, entailing mixing and redeposition of cohesionless gravity flows. Similar to this study, Vázquez-Riveiros and others (2007) concluded that the common to moderately abundant thecamoebian species in the high-salt-marsh faunal assemblage in two marsh transects within SIBC were washed in by spring freshet.

Similar to the FS core, other regional climate records along the British Columbia coast have also indicated less precipitation in the middle late Holocene. Climate and associated precipitation in the NE Pacific region is heavily influenced by the positions and intensities of the Aleutian Low (AL) and North Pacific High Pressure systems. For example, northern British Columbia is characterized by high precipitation when the AL is intense and its center of action moves eastward (e.g., Trenberth and Hurrell, 1994; Gershunov and others, 1999; Dean and Kemp, 2004; Vázquez-Riveiros and Patterson, 2009). Therefore, a decrease in precipitation in the SBIC during the middle

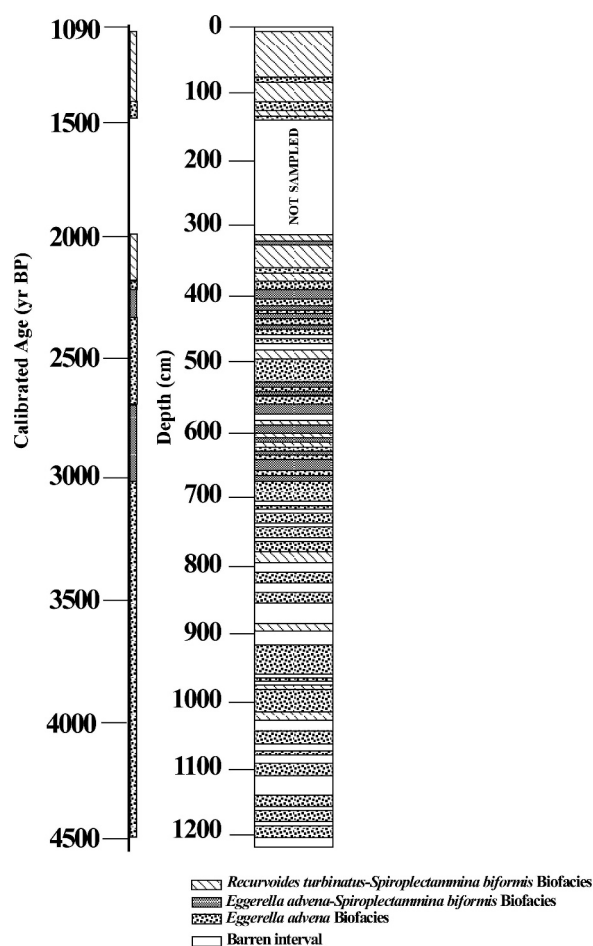


FIGURE 9. Stratigraphic distribution of foraminiferal biofacies in the Frederick Sound core.

late Holocene correlates to a period when there was a weaker or westward shift of the AL (Patterson and others, 2004). A decrease in varve thickness in ALS between 2700–2900 cal. yr BP was correlated to a period of low precipitation and cooler climate conditions (Patterson and others, 2007). Based on decreased laminae thickness, Nederbragt and Thurnow (2001) identified similar cooler/drier conditions from 3250–2100 cal. yr BP in Saanich Inlet, southern British Columbia. Anderson and others (2005a) also correlated a regime shift from wetter to drier climate conditions, as indicated by an increasing trend in $\delta^{18}\text{O}$ in Jelly Bean Lake, Yukon Territory, from 3000–2000 cal. yr BP, to a westward and/or reduced intensity of the AL. Using observed changes in pollen assemblages from Marcella Lake, Alaska, Anderson and others (2005b) also recognized a major regime shift from wet to drier conditions at 2000 cal. yr BP.

CONCLUSIONS

The Frederick Sound core intervals are characterized by an association of shallow-water, low-oxygen-tolerant agglutinated foraminifera dominated by *Eggerella advena*, with subordinate proportions of a few other shallow-water species such as *S. biformis*, *R. turbinatus*, *C. jeffreysii* and *P.*

bipolaris. The finding of a low-diversity, shallow-water, low-oxygen, and low-salinity-tolerant agglutinated foraminiferal assemblage in the core is interpreted as indicating a highly stratified estuarine environment.

Biofacies distribution patterns in the core revealed that the SBIC was characterized by dysoxic to anoxic conditions during the late Holocene, and that the regional climate was warm from ~3125 to ~4500 cal. yr BP. On the basis of increased abundances of cool-water foraminiferal species at ~3125 cal. yr BP, a subtle transition from relatively warm to cool bottom-water conditions is interpreted for the latter part of the late Holocene (1090–3125 cal. yr BP). The establishment of cooler/drier climate conditions in the SBIC after 3125 cal. yr BP corresponds to neoglaciation advances in the NE Pacific, associated with a weakened and/or westward shift in the center of action of the Aleutian Low.

A strong proximal freshwater influence is suggested by the presence of allochthonous freshwater thecamoebians in the assemblages. The thecamoebians were eroded from nearby freshwater and marsh environments at the head of the inlet, and passively transported along with sediments into the marginal-marine environment in the inlet. Near the base of the cored sequence, terrestrial sedimentary input to the fjord was dominated by massive, graded, and slump sediments produced by slope failure of saturated fjord walls during heavy rains. As the climate conditions became drier later in the Holocene, incidences of fjord-wall collapse became less frequent, and were replaced by seasonal erosion of marsh sediments during the spring freshet.

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APPENDIX 1

Foraminiferal occurrences in FS core samples. Samples were statistically analyzed and their abundances are recorded in percentages. The species marked with asterisks were those utilized for multivariate statistical analyses and paleoenvironmental interpretations. This appendix can be found on the Cushman Foundation website in the JFR Article Data Repository (<http://www.cushmanfoundation.org/jfr/index.html>) as item number JFR-DR2013004.

APPENDIX 2

Thecamoebian species occurrences in FS core samples. The species abundances are recorded as percentages. This appendix can be found on the Cushman Foundation website in the JFR Article Data Repository (<http://www.cushmanfoundation.org/jfr/index.html>) as item number JFR-DR2013004.