Late Holocene paleoceanographic evidence of the influence of the Aleutian Low and North Pacific High on circulation in the Seymour-Belize Inlet Complex, British Columbia, Canada

Natalia Vázquez Riveiros, R. Timothy Patterson*

Department of Earth Sciences, Carleton University and Ottawa-Carleton Geoscience Centre, 1125 Colonel By Drive, Ottawa, Ontario K1S5B6, Canada

ABSTRACT

Foraminiferal and thecamoebian faunas from the Seymour-Belize Inlet Complex (SBIC), a fjord network situated on the mainland coast of British Columbia, were studied to assess climatic cycles and trends impacting the area through the ∼ AD 850–AD 2002 interval. Ocean circulation patterns prevalent in the SBIC are strongly linked to precipitation, which is closely linked to the relative strength and position (center of action; COA) of the seasonally developed Aleutian Low (AL) and North Pacific High (NPH) atmospheric circulation gyres.

Through interpretation of cluster analysis and ordination methods, a period of weak estuarine circulation was recognized to have impacted the SBIC area between ∼ AD 850 and AD 1500. During this time waters in the SBIC were dysoxic to anoxic and the sediment–water interface was comprised of a depauperate foraminiferal fauna consisting of low diversity agglutinated forms. These reduced oxygen conditions came about as a result of diminished precipitation in the SBIC catchment as the COA of the AL progressively migrated westward over time, resulting in greatly reduced estuarine circulation and only infrequent and feeble incursions of well oxygenated open ocean water into the SBIC basin. By ∼AD 1575, following a gradual transition period of ∼75 years when circulation patterns in the inlet were unstable, very strong estuarine circulation developed in the SBIC, concomitant with the onset of the Little Ice Age (LIA) in western Canada. In the SBIC this interval was characterized by higher levels of precipitation, which greatly enhanced estuarine circulation resulting in frequent incursions of cold, well oxygenated ocean currents into the bottom waters of the SBIC and the development of a diverse calcareous foraminiferal fauna. This circulation pattern began to break down in the late 19th century AD and by ∼AD 1940 conditions similar to those that existed in the inlet prior to ∼AD 1500 had redeveloped, a process that continues at present.

1. Introduction

Coastal mainland British Columbia (BC) is a vast and geographically complex area, characterized by a mountainous terrain punctuated by numerous fjords that reach far inland. The Seymour-Belize Inlet Complex (SBIC) is one of these fjord systems. Although some research on the foraminiferal distribution in shelf and fjord environments in coastal BC has been carried out (Cushman, 1925; Cockbain, 1963; McCulloch, 1977; Jones and Ross, 1979; Schafer et al., 1989; Patterson et al., 1998; Guilbault et al., 2003; Vázquez Riveiros et al., 2007; Vázquez Riveiros and Patterson, 2008), more baseline foraminiferal distributional data needs to be collected from this geographically vast region if a detailed understanding of the paleoceanographic history is to be developed. Therefore, the purpose of the research presented here is to:

1) document and characterize the modern distribution of foraminiferal faunas from the SBIC;
2) use the foraminiferal distributional data to interpret environmental constraints on the observed foraminiferal faunas recovered from a freeze core that was collected near the mouth of the SBIC and deposited over the last ∼1100 years; and
3) provide baseline data that will be used by other researchers to interpret additional cores deposited through the Holocene in the SBIC and elsewhere in the region.

* Corresponding author. Tel.: +1 613 520 2600x4425; fax: +1 613 520 2569.
E-mail addresses: nvazquezriveiros@gmail.com (N. Vázquez Riveiros), tpatters@earthsci.carleton.ca (R.T. Patterson).

2. Geographic setting

The SBIC is a network of long and deep steep-sided fjords on the central coast of mainland British Columbia (Fig. 1), about 40 km northeast of Port Hardy, Vancouver Island. The complex lies between latitudes 50°50.2′ N and 51°10.6′ N, and longitudes 126° 30.2′ W and 127°40.5′ W, and opens to Queen Charlotte Sound in the Pacific Ocean via Slingby and Schooner Channels.

The main arms of the complex are the east-west trending Seymour and Belize inlets, which reach inland about 70 and 50 km respectively. Alison Sound is a smaller inlet that extends 20 km off the northern margin of Belize Inlet, and it is oriented in a northeasterly direction before turning towards the east. Small rivers and creeks provide freshwater to the heads of all inlets in the SBIC. The freshwater input of these rivers, together with numerous waterfalls along the inlets, peaks during the snow-melt period that starts in May, and plays an important role in circulation in the SBIC (Thomson, 1981).

3. Regional climate

The climate of coastal British Columbia is mild, with generally rainy winters when temperatures typically remain above the freezing point and warm days punctuated by cool nights in summer (Hare and Thomas, 1979). Mean annual precipitation averages 3120 mm (range of 2009–3943 mm) in the SBIC, with an average annual temperature of 9.1 °C (range of 5.4°–9.4 °C) (Green and Klinka, 1994).

Weather systems are seasonally dominated by the counterclockwise circulating winds that accompany the Aleutian Low (AL) in winter and clockwise circulating winds that occur with the North Pacific High (NPH) in summer. The relative position of these pressure systems is in turn influenced by shifts in the positioning of planetary waves like the jet stream (Ware and Thomson, 2000). The mouth of the SBIC is situated at the northern boundary of the Coastal Upwelling Domain (CUD) (Ware and McFarlane, 1989), where from May through September the northwesterly winds of
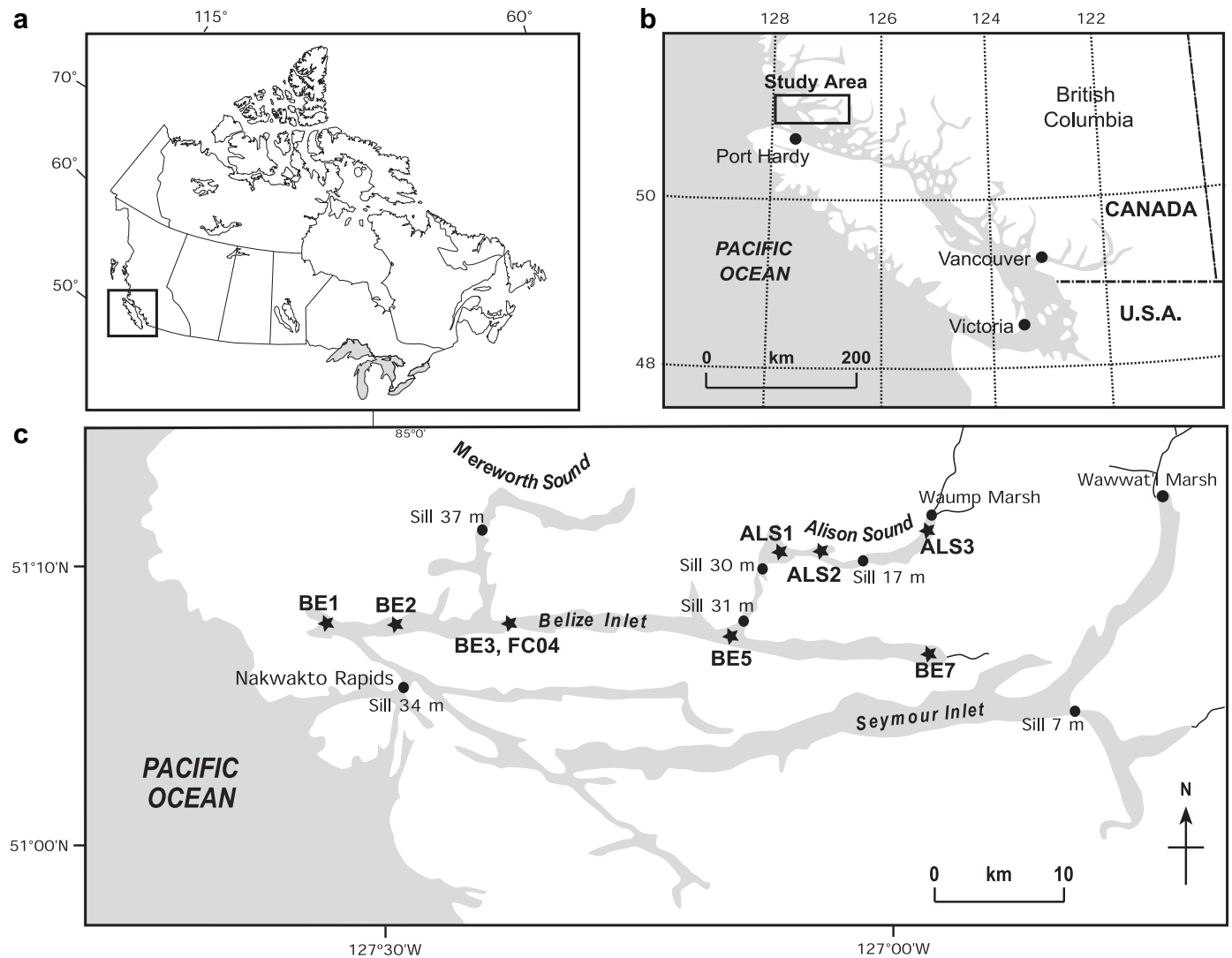
Fig. 1. location of study area and sampling site. (a) Map of Canada. (b) Map of Vancouver Island and mainland coastal British Columbia. (c) Map of the Seymour-Belize Inlet Complex, with sampling sites marked with stars.

the NPH tend to displace warm water from the surface, promoting the upwelling of cold, nutrient-rich deep water that greatly enhances productivity in the surface layers. However, because the SBIC is at the extreme northern boundary of the CUD and opens to Queen Charlotte Sound instead of the open ocean, the influence of upwelling within the SBIC is virtually nil when compared to more exposed inlets on the west coast of Vancouver Island (e.g., Patterson et al., 2004a). However, there is another type of upwelling that occurs when a deep current encounters an underwater ridge, which will then deflect it towards the surface (Thomson, 1981). This localized effect can have a very important influence on circulation in fjord systems such as the SBIC, which have pronounced sills at their entrances.

The AL is also responsible for the frequency and intensity of winter storms that promote cold weather and precipitation at this time of the year (Miller et al., 1994; Beamish et al., 1999; Chang and Patterson, 2005). Storms that form in the ocean on the southern edge of the AL travel northeast towards southern BC and northern Washington. At the same time, storms that form in the Gulf of Alaska move southeastward towards the coast, due to the clockwise circulation of the Alaska Gyre. Therefore, the coast of BC receives the highest amount of precipitation when the AL dominates circulation patterns in the North Pacific (Cayan and Peterson, 1989; Trenberth and Hurrel, 1995). During the spring and summer, when the NPH moves northward and the AL dissipates, less precipitation and clear skies are the dominant features in the area (Thomson, 1981; Chang and Patterson, 2005). Although the position and strength of the AL is characterized by great inter-annual variability, there have been periods where a strong westward position dominated at longer time scales (Spooner et al., 2003). Cycles of 2, 11, 20–30, 50–70, 150 and 200–500 years have been observed in the region that may in part be accounted for by the varying influence of the AL and NPH (Hu et al., 2003; Chang and Patterson, 2005).

4. Oceanographic setting

Maximum depths within the SBIC are greater than 300 m in Belize Sound, and 150 m in Alison Sound. Oxygen concentrations in the bottom waters of the SBIC range from high oxic (>6 mL/L) in main arms such as Belize Inlet to anoxic conditions in Alison Sound.

An important characteristic of these bathymetrically U-shaped basins is the presence of sills in most of them, formed by crushed rock and silt that were deposited as moraines by advancing glaciers. The sills reduce the input of oxygen-rich ocean water into the inlets, which together with a low-salinity wedge caused by riverine input at the surface, results in reduced mixing between surface and bottom waters, forming a stratified water column. It is also typical in these partially mixed estuaries to have the salinity of the surface layer increase down-inlet away from freshwater sources, and the salinity of bottom waters to increase slightly towards the head of the inlet (Pickard and Stanton, 1980; Thomson, 1981). The brackish layer at the surface of Belize Inlet (Fig. 2) has a minimum value of 26‰ close to the head of the inlet. This layer is restricted to the top 25 m of the water column, with deeper areas of the inlet being characterized by salinities of 30‰. The restricted circulation in these systems enhances the trapping of organic and inorganic material borne by runoff, making these environments effective nutrient traps. Disturbance at the sediment–water interface is minimized due to the high residence time and slow circulation of the bottom water, thus creating an ideal setting for paleoenvironmental research.

The main sill at the mouth of the SBIC, the Nakwakto Rapids, is only 34 m deep and 300 m wide, and forms a major bottleneck during tidal cycles (Department of Energy, 1979) (Fig. 1). During the ebb tide, current flow through Nakwakto Rapids can reach velocities of 8 m/s, making it one of the strongest tidal currents in the world (Thomson, 1981). This tidal constriction at the Nakwakto Rapids is so restrictive that it is impossible for sea level with the SBIC to equalize with that of Queen Charlotte Sound during ebb tidal flow, resulting in a tidal range of more than 2 m in Queen Charlotte Sound and a maximum of only 1.3 m in the interior of the SBIC (Fisheries and Oceans, 2003).

Despite the restriction of the Nakwakto Rapids, the physics of estuarine circulation results in some cold oceanic waters penetrating into the SBIC (Pickard, 1961; Thomson, 1981), which in this case is strongly influenced by the seasonal variability in local precipitation patterns. Rainfall acts as a source of low density water to the surface layer, stabilizing the stratification and increasing the horizontal flux of the river runoff as the freshwater moves towards the sea (e.g., Gibbs et al., 2000). The net motion of the surface layer in these environments (80 m³/s through Belize Inlet) is always directed towards the ocean as an immediate consequence of the discharge of freshwater into the heads of the inlets. This freshwater creates a low salinity surface layer, enhanced at the head and more diluted towards the mouth, that gains volume and velocity as it entrains saline water from below on its movement towards the sill. This unidirectional flow is superimposed on the tidal current, increasing the speed of the flood tide and decreasing that of the ebb (Pickard, 1961).

There are three additional sills in Alison Sound (Fig. 1), which further restrict circulation into this inlet. The outermost one, located at the juncture of Alison Sound with Belize Inlet, is 31 m deep; the second, just inside the mouth of Alison Sound, is 30 m deep, while the last sill, located near the head of the inlet, is only 17 m deep. As a result of this restriction, oceanographic conditions in Alison Sound are quite different from those observed in open areas of the SBIC, such as Belize Inlet (Figs. 2 and 3). The low salinity surface plume (26.5‰–28‰) is present above a bottom water layer characterized by a constant salinity of 28.5‰. The reduced salinity levels at depth relative to those measured in Belize Inlet reflect the reduced oceanic influence within Alison Sound, although a small tongue of colder oceanic water was observed to penetrate a short distance into the sound in April 2002 (Fig. 3). In contrast, temperature profiles measured in Alison Sound tend to be more homogeneous than those observed in Belize Inlet, which may in part be related to the shallower depth of the sound.

Oxygen concentration values in excess of 4 mL/L characterize the surface water mass of Alison Sound, which easily penetrates from Belize Inlet past both the first and second sills located at the mouth of the sound. These sills impact the circulation of deeper water masses, though. Despite there being a lower salinity variation between surface and bottom waters in Alison Sound than observed in Belize Inlet, bottom water oxygen levels of <2 mL/L prevail. At station ALS3, which is beyond the third and shallowest sill in Alison Sound (17 m; Fig. 1) circulation is further restricted, resulting in an additional reduction in bottom-water oxygen values to 0.06 mL/L.

5. Methods and materials

5.1. Sampling

Sampling took place during a research cruise to the SBIC by the CCGS *Vector* in April 2002. Eight sediment–water interface samples were collected using a Smith-Mac grab sampler in Belize Inlet (BE1, BE2, BE3, BE5, BE7) and Alison Sound (ALS1, ALS2 and ALS3; Fig. 1; Table 1). In addition, one 145 cm freeze core, FC04, was collected in Belize Inlet at a water depth of 274 m (Fig. 1). Water property data profiles of pressure, temperature and transmissivity were measured at each grab and freeze core station (with the exception of BE3), following standard techniques (Vázquez Riveiros, 2006).
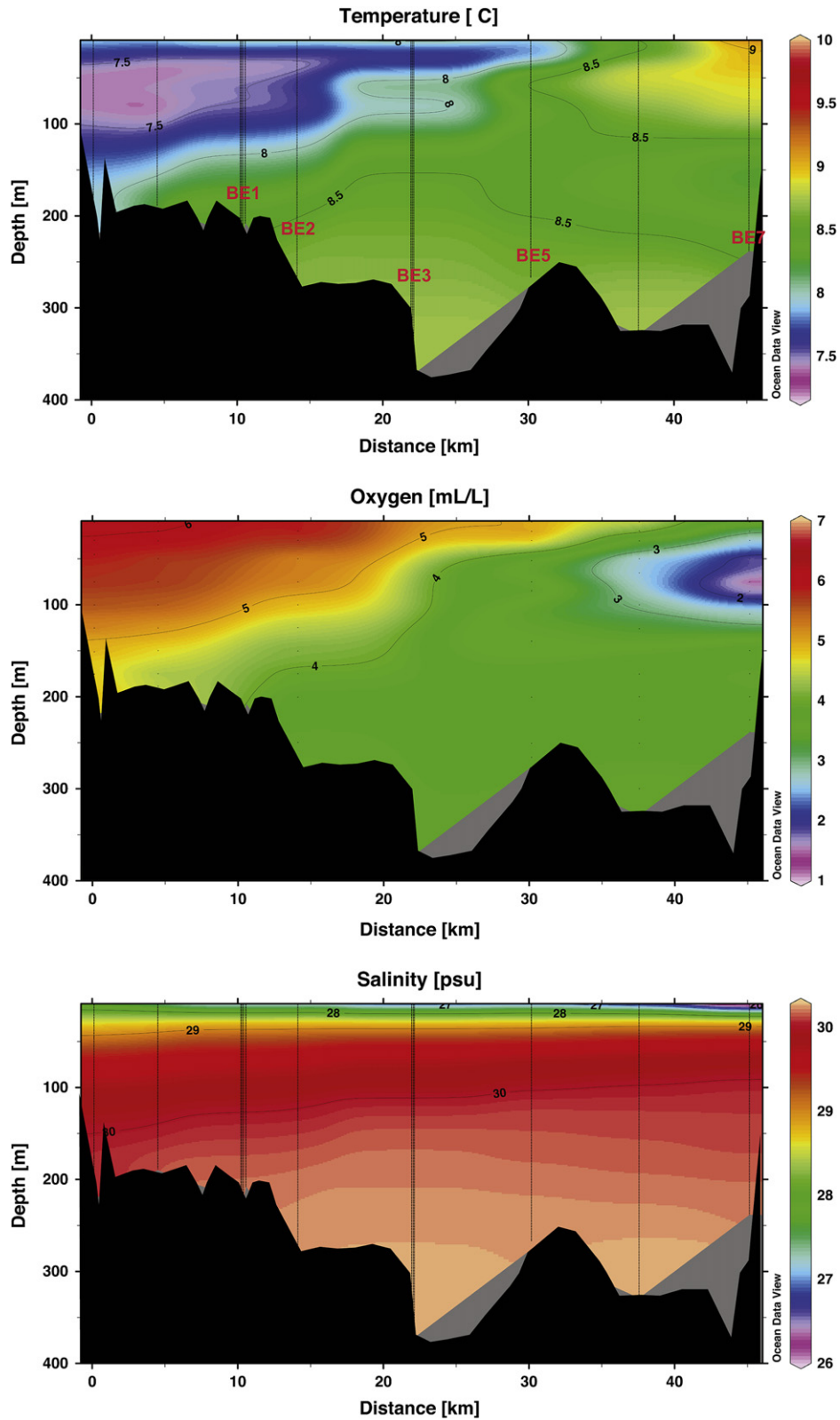
Fig. 2. Longitudinal profiles of Belize Inlet, with bathymetric contour. Top, temperature in °C. Middle, dissolved oxygen concentration, in mL/L. Bottom, salinity, in practical salinity units (psu). *Y*-axis is depth, in m. *X*-axis is distance from the mouth of the inlet, in km. Vertical lines represent sampling stations. Color scale for each unit at the right side of each profile. Position of stations is indicated.
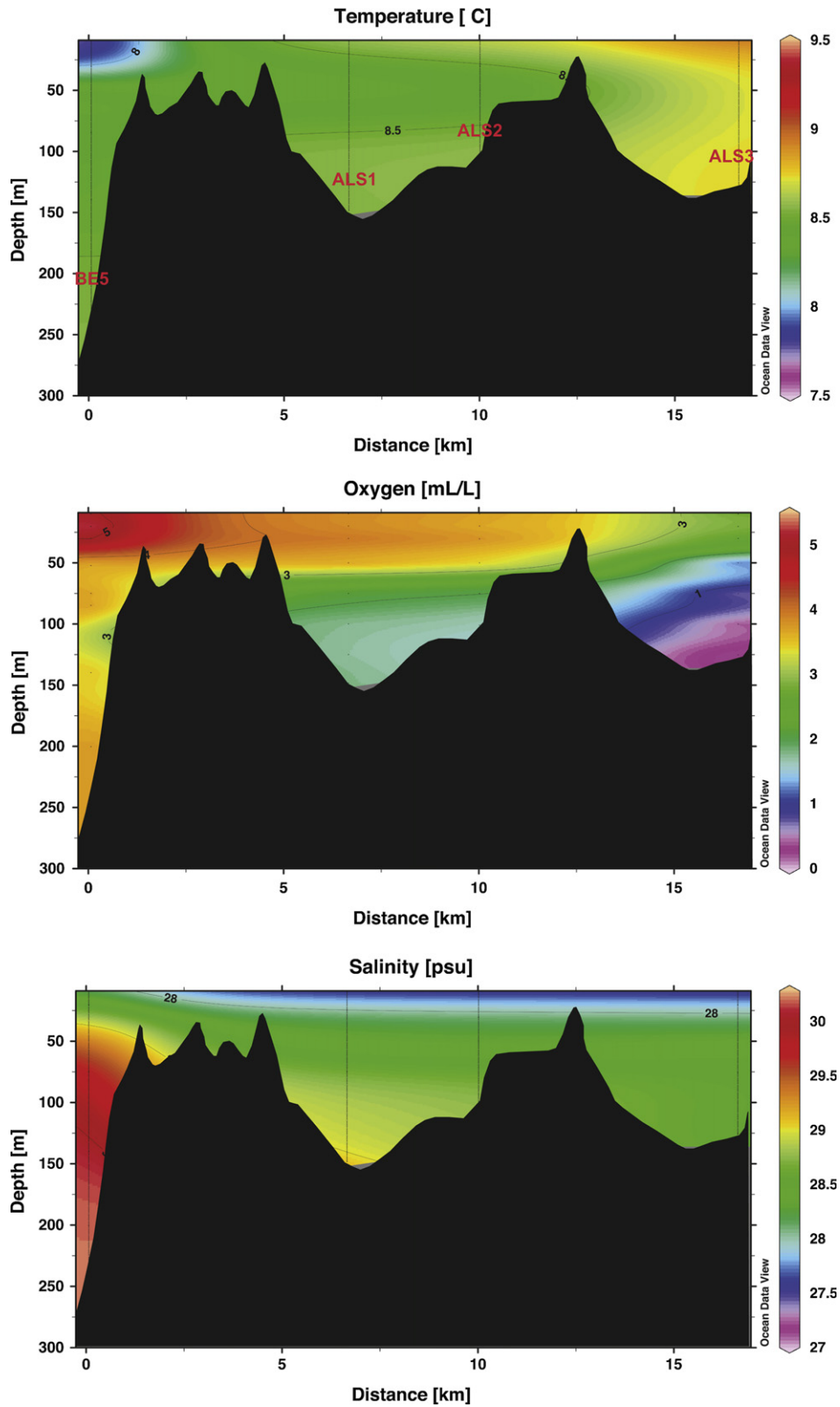
Fig. 3. Longitudinal profiles of Alison Sound, with bathymetric contour. Top, temperature in °C. Middle, dissolved oxygen concentration, in mL/L. Bottom, salinity, in practical salinity units (psu). *Y*-axis is depth, in m. *X*-axis is distance from the mouth of the inlet, in km. Vertical lines represent sampling stations. Color scale for each unit at the right side of each profile. Position of stations is indicated; station BE5 in Belize Sound is included at the left side of each diagram.

Table 1
Water depth, latitude and longitude of sediment–water interface samples and freeze core FC04 used on this study.

	Depth (m)	Latitude (°′)	Longitude (°′)
BE1	225	51°7.79′ N	127°34.19′ W
BE2	190	51°7.94′ N	127°30.38′ W
BE3	290	51°7.78′ N	127°21.95′ W
BE5	276	51°7.10′ N	127°8.82′ W
BE7	245	51°6.50′ N	126°55.72′ W
ALS1	152	51°10.0 0′ N	127°5.13′ W
ALS2	135	51°10.16′ N	126°2.48′ W
ALS3	135	51°10.02′ N	126°56.79′ W
FC04	274	51°7.90′ N	127°9.02′ W

5.2. Laboratory analysis

Examination of the grab samples, collected in 2002 and refrigerated, in 2004 revealed no discernable deterioration. Samples from Alison Sound, where dysoxic conditions prevailed, were characterized by a slight sulfurous smell, as well as darker color. Ten cm³ aliquots were taken from each grab sample and wet sieved through a 63 μm screen to retain foraminifera and a 500 μm screen to remove coarse organic material.

Freeze core FC04 was comprised of very fine-grained and soupy sediments that would have been impossible to recover using conventional coring methods. The organic content of the core increased significantly below 75 cm, and was characterized by an increasing proportion of fecal pellets down core. The core was x-rayed so that any internal sedimentary structures or laminations could be detected. Visual examination of the x-rays revealed two sections, 80–85 cm, and 93–104 cm, which were comprised of clearly visible laminations. Based on the results of the visual core examination, the 0–138 cm portion of the core was subdivided using a ceramic knife into 121, 1 cm thick samples for foraminiferal analysis. The laminated 93–104 cm interval of the core was not subsampled. Based on analysis of the laminated 80 - 85 cm horizon of this core as well as laminated intervals from other cores in the area, it was concluded that this interval was deposited under anoxic conditions and would therefore be barren of foraminifera.

With the exception of small portions of 15 aliquot samples that were removed for ^{210}Pb dating (see below) all freeze core samples were subsequently sieved and processed using the same method as described above for the grab samples. Samples were not stained with Rose Bengal as the time that had elapsed between collection and laboratory analysis was deemed too long to expect an accurate assessment of the living – dead foraminifera ratio. The sediment–water interface grab and freeze core samples were quantitatively analyzed for foraminifera; all specimens were picked and identified following the classification of Loeblich and Tappan, 1987 (Vázquez Riveiros and Patterson, 2008). Scanning electron photomicrographs were obtained at the Carleton University Research Facility for Electron Microscopy (CURFEM) (Plate 1).

5.3. Chronology

The ^{210}Pb dating method is routinely used for the high resolution dating of marine sediments. Due to the short half-life of ^{210}Pb, the methodology is limited to sediments deposited during the last 150 years (Sorgente et al., 1999; Appleby, 2001). However, as the method involves the dating of several samples over many centimeters of core, it is possible to determine sedimentation rates, which may permit the estimation of ages in older sediments, particularly if corroborating ^{14}C dates are available down core, as was the case here. Fifteen subsamples were removed from FC04 for ^{210}Pb dating using alpha ray spectroscopy.

Two additional subsamples from FC04 were submitted for accelerated mass spectrometry (AMS) ^{14}C analysis. The first sample from FC04, at 89 cm depth, was a wood fragment, while the second sample, at 128 cm was comprised of bulk sediment, as no other dateable wood or shell fragments were available lower in the core.

5.4. Statistical analysis

One hundred and one samples, eight from surface grabs and 93 from the freeze core were utilized in the statistical analysis of this study. All eight surface grab samples were found to contain foraminifera. Of the samples obtained from core FC04, 97 samples contained foraminifera, and four were found to be barren. Twenty-three samples interspersed through the basal part of the core were not quantified for foraminifera. As it was found that there was very little biostratigraphic variability in fossil content in that part of the core assemblage, continuity was assumed. Many samples were found to have low foraminiferal abundances, so an important first step was to determine which samples contained statistically significant populations. The probable error (pe) for each of the samples was calculated using the following formula (c.f. Boudreau et al., 2005):

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

where s is the standard deviation of the population counts and X_i is the number of counts at each sample i. A sample was judged to have a statistically significant population if the total counts for each sample were greater than the probable error. Fifty-seven samples were found to have statistically significant populations, although 44 other samples, all from FC04 and representing more than 43% of the total, were rejected. To reduce the rate of sample rejection, and since the primary purpose of this study was to determine the major faunal changes down core and compare them with the different assemblages present in surface samples, the combination of adjacent and faunally similar samples was deemed to be a better solution than the rejection of such a significant portion of freeze core samples.

A first attempt at merging contiguous samples, with the subsequent calculation of pe, resulted in a reduced number of 17 samples being rejected as not being statistically significant. Visual inspection of the faunal makeup of these samples revealed that most of them contained low numbers of specimens of well-defined assemblages and that none of them were stratigraphically close to any major faunal shifts. Therefore, it was deemed that an amalgamation of some adjacent samples should be carried out to minimize the loss of information due to the discarding of samples. Following amalgamation only one group of five samples was not utilized in the statistical analysis (between 81 and 85 cm of depth).

In these samples, 100 benthic foraminiferal species, four planktic foraminiferal species and ten freshwater thecamoebian species were identified (Vázquez Riveiros and Patterson, 2008). The standard error (S_{xi}) at the 95% confidence level associated with each species was calculated using the following formula (Patterson and Fishbein, 1989):

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

where F_i is the fractional abundance and N_i is the total of all the specimens counted.

If the calculated standard error was greater than the fractional abundance for a particular species in all samples then that species was not included in successive multivariate analysis. Following this
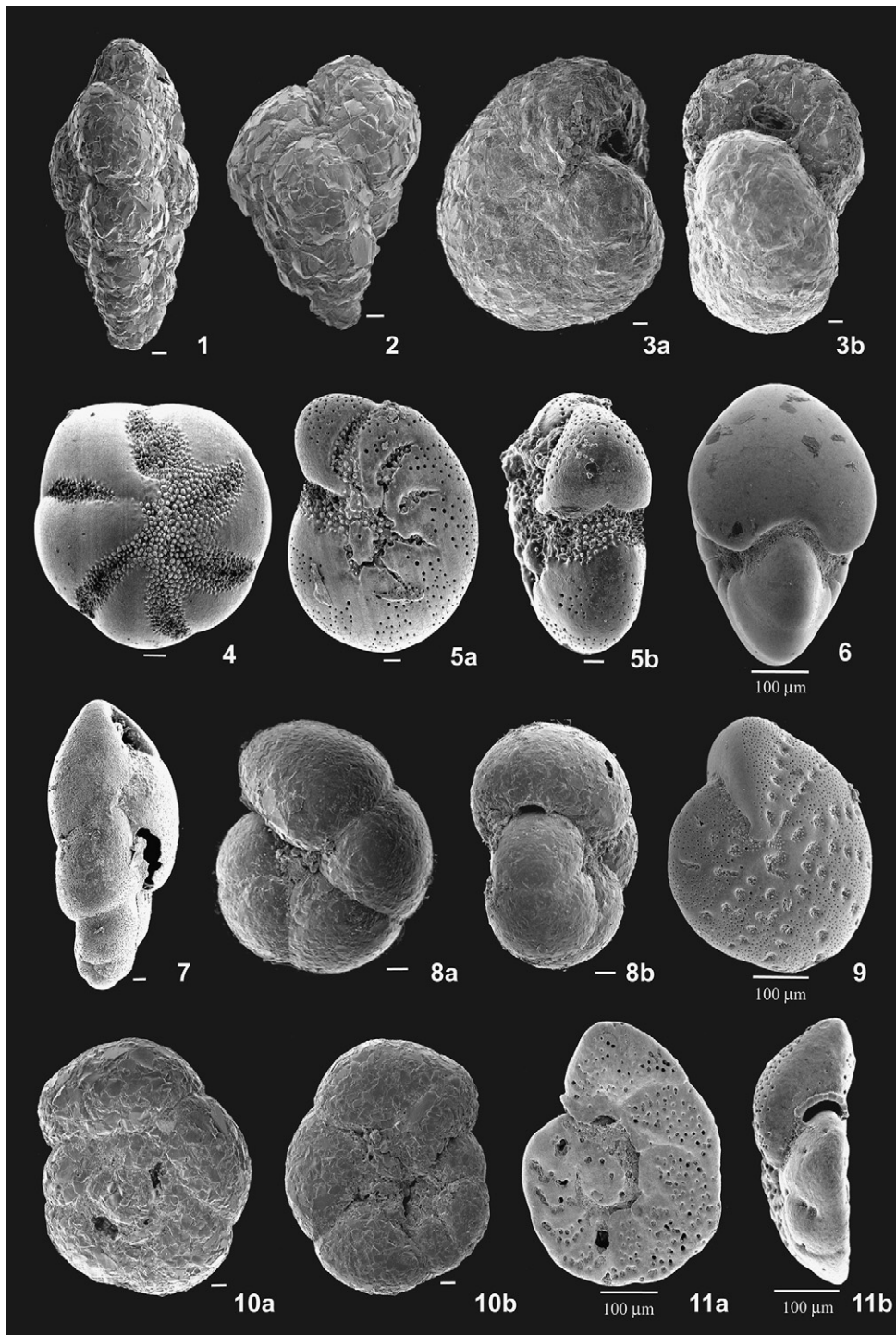
Plate 1. 1. *Eggerella advena* Cushman, from sample ALS3, side view. 2. *Eggerella* sp., from sample ALS2, side view. 3. *Recurvoides turbinatus* (Brady), from sample ALS1; 3a, side view; 3b, apertural view showing asymmetry of test and angled aperture. 4. *Buccella frigida* (Cushman) from sample BE1, ventral view showing pustules along sutures. 5. *Cribroelphidium excavatum* forma *clavata* Cushman, from sample BE1; 5a, side view showing umbilical boss and backwards-curved sutures; 5b, apertural view. 6. *Nonionella labradorica* (Dawson) from sample BE1, apertural view showing broad flat apertural face. 7. *Stainforthia feylingi* Knudsen and Seidenkrantz (1994), from sample BE1, side view showing smooth, fusiform, finely perforated test. 8. *Haplophragmoides bradyi* (Brady), from sample BE3; 8a, side view showing very smooth test; 8b, apertural view showing characteristic interiomarginal aperture. 9. *Cribroelphidium foraminosum* (Cushman), from sample BE1, side view showing coarse perforation, sutural pores and sutural bridges. 10. *Portatrochammina bipolaris* Brönnimann and Whitaker, from sample BE7; 10a, dorsal view; 10b, umbilical view, showing characteristic umbilical flap. 11. *Lobatula lobatula* (Walker and Jacob), from sample BE1, 11a, ventral view showing aperture extending on the last few chambers and coarse perforation; 11b, side view showing lipped aperture Scale bars are 10 μm unless otherwise indicated.

criterion, 67 species were rejected from further consideration because they were not present in statistically significant numbers in any sample. This number included four planktic foraminiferal species and seven species of thecamoebians. Since all planktic

foraminifera and freshwater thecamoebian species were considered allochtonous, it was deemed that their presence or absence might provide some information on transport mechanisms during deposition of the core. The planktic species were therefore grouped

together under the generic heading "planktic species", and the ten species of thecamoebians were similarly grouped under "thecamoebian species". A recalculation of fractional abundances and standard errors resulted in 51 species, which included the supraspecific groupings "planktic species" and "thecamoebian species", being present in statistically significant numbers (Appendix A).

The Shannon diversity index (SDI) was used to assess environmental stability based on the proportion and diversity of species found at each sample station. This index was calculated using:

$$SDI = -\sum_{1}^{S}\left(\frac{F_i}{N_i}\right) \times \ln\left(\frac{F_i}{N_i}\right)$$

where S is equal to the species richness of the sample (Shannon, 1948a,b). The SDI in natural environments normally ranges between 1 and 3.5, with high values corresponding to stable climax ecosystems, and low values indicating environmentally stressed environments. Ecosystems that are in a pioneering or arrested successional state are also characterized by low SDI values (Magurran, 1988).

5.4.1. Cluster analysis

Once the reduced number of statistically significant samples and species were determined, cluster analysis was carried out on the resulting matrix. Cluster analysis is a commonly used multivariate analytical technique in foraminiferal research which classifies entities (samples or species) into "naturally occurring" groups, and quantifies the relation between groups (Parker and Arnold, 1999). R-mode and Q-mode cluster analyses were carried out on the reduced dataset, the former to group samples with significantly similar variables (i.e., species), using a proximity matrix with Ward's minimum variance method measured as Square Euclidean Distances (cf. Fishbein and Patterson, 1993), and the latter to determine which species were most closely related to others, and thus best characterized a particular assemblage.

5.4.2. Ordination

Ordination methods represent species distributions related to gradients of environmental change. If data for environmental variables affecting the population are known, a constrained ordination analysis is used, where the variability of the population is represented with respect to the environmental variables measured. If no measured environmental data are accessible, unconstrained analysis will show any variation within the species data along axes that represent gradients of environmental change. The determination of which variables correlate best with the axes is left to the researcher.

For this study, a dataset comprised of the surface grab samples and the environmental variables measured for each (depth, temperature, salinity, oxygen content, nitrate + nitrite, silicate and phosphate) was available, although for sample BE3 only the water depth was measured. In order not to lose the valuable ecological information that the species composition of this sample contained, the values for the other variables were synthesized by building a multiple regression model, using the samples with no missing values as predictors (Leps and Smilauer, 2003). The procedure was also utilized for sample ALS3 to simulate missing values for nitrate + nitrite, silicate and phosphate. The synthetic predictors developed for these two samples were derived from similar samples within the same inlet, to minimize error (Table 2).

Ordination analysis commenced with a dataset containing the fractional abundances of statistically significant species for the surface samples, and the environmental variables dataset, using the computer program CANOCO 4 (ter Braak and Smilauer, 1998a). The parameter "Depth" was chosen to be interpreted as a covariable in view of its high correlation to the other physical parameters, so the derived ordination diagram showed the relationship between the response variables (species) and environmental variables after acknowledging the effect of depth on the sample composition (partial correspondence analysis) (ter Braak and Prentice, 1988).

In order to determine if the response of a species to environmental variables was unimodal or linear, a preliminary test run was carried out, utilizing Detrended Correspondence Analysis (DCA) on all the response and predictor variables, with depth as a covariable. The gradient length on the first axis showed a value of 4.089, indicating that there was large beta diversity in community composition along the individual independent gradients. Use of a linear method was therefore not appropriate for the present analysis, as too many species deviate from the assumed model of linear response to the variable (Leps and Smilauer, 2003). The unimodal response method assumes that the species has an optimum on the environmental gradient, with a symmetric bell-shaped response around it. Therefore, the chosen method of analysis was partial Canonical Correspondence Analysis (constrained unimodal ordination with covariables).

A problem arose when the Variance Inflation Factors associated with the environmental variables of the DCA log were considered. These factors are related to the (partial) multiple correlations between one environmental variable and the others in the analysis. All of these values were extremely high, indicating that the variables were almost perfectly correlated with each other. They therefore did not provide a unique contribution to the utilized regression equation (ter Braak and Smilauer, 1998b). In order to ascertain any influence that the environmental variables had on each other, the correlations between them were calculated using a two-tailed bivariate correlation with Pearson's coefficient. The result showed that there was a high degree of correlation between several of the variables (Table 3). Based on these results "Temperature", "oxygen" and "silicate" were the variables subsequently retained in the analysis, even though there was a degree of correlation between oxygen and silicate. Partial Canonical Correspondence Analysis was then applied to a dataset

Table 2
Values of environmental variables measured at the sediment–water interface samples. The values marked with * represent values imputed with linear regression using the values for the rest of the stations in the same inlet.

Sample	Depth (m)	Temperature (°C)	Salinity (psu)	Oxygen (mL/L)	Nitrate + Nitrite (mmol/L)	Silicate (mmol/L)	Phosphate (mmol/L)
BE1	225	7.84	30.05	4.95	20.9	44	2.2
BE2	190	8.38	30.16	4.16	23	46.1	2.51
BE3	290	8.57*	30.23*	3.70*	22.5*	51.0*	2.43*
BE5	276	8.61	30.23	3.71	23	51.8	2.45
BE7	245	8.52	30.21	3.74	22.3	46.7	2.52
ALS1	152	8.55	28.83	1.67	23.3	61.9	3.23
ALS2	135	8.56	28.8	1.72	23.6	61.2	3.24
ALS3	135	8.76	28.52	0.06	23.6*	61.2*	3.24*

Table 3
Values for the Pearson correlation coefficient for the environmental variables.

		Depth	Temp	Salin	Oxygen	Nitr	Silicate	Phosph
DEPTH	Pearson Correlation	1	−0.18	0.889**	0.741*	−0.55	−0.681	−0.844**
	Sig. (2-tailed)		0.67	0.003	0.036	0.158	0.063	0.008
	N	8	8	8	8	8	8	8
TEMP	Pearson Correlation	−0.18	1	−0.406	−0.693	0.866**	0.655	0.604
	Sig. (2-tailed)	0.67		0.318	0.057	0.005	0.078	0.113
	N	8	8	8	8	8	8	8
SALIN	Pearson Correlation	0.889**	−0.406	1	0.928**	−0.633	−0.908**	−0.951**
	Sig. (2-tailed)	0.003	0.318		0.001	0.092	0.002	0
	N	8	8	8	8	8	8	8
OXYGEN	Pearson Correlation	0.741*	−0.693	0.928**	1	−0.781*	−0.926**	−0.942**
	Sig. (2-tailed)	0.036	0.057	0.001		0.022	0.001	0
	N	8	8	8	8	8	8	8
NITR	Pearson Correlation	−0.55	0.866**	−0.633	−0.781*	1	0.793*	0.805*
	Sig. (2-tailed)	0.158	0.005	0.092	0.022		0.019	0.016
	N	8	8	8	8	8	8	8
SILICATE	Pearson Correlation	−0.681	0.655	−0.908**	−0.926**	0.793*	1	0.947**
	Sig. (2-tailed)	0.063	0.078	0.002	0.001	0.019		0
	N	8	8	8	8	8	8	8
PHOSPH	Pearson Correlation	−0.844**	0.604	−0.951**	−0.942**	0.805*	0.947**	1
	Sig. (2-tailed)	0.008	0.113	0	0	0.016	0	
	N	8	8	8	8	8	8	8

*Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

composed of fractional abundances of statistically significant species from the surface samples, and the environmental variables "temperature", "oxygen" and "silicate", with "depth" as a covariable.

6. Results

6.1. Chronology

The ^{210}Pb dates were calculated using the constant rate of supply (CRS) method, which assumes that the rate of supply of ^{210}Pb to the sediments is constant, regardless of changes in the sedimentation rate (Appleby et al., 1979) (Table 4). The calculated value for the sedimentation rate with this method was 1.52 mm/yr.

The obtained radiocarbon dates were the average of two separate analyses, and were corrected for ^{13}C/^{12}C isotope fractionation.

Table 4
Results of the ^{210}Pb analysis, showing the ages at different depths on the top section of FC04, and their standard deviation. The sedimentation rate calculated from these dates is 1.52 mm/yr.

Sample	Depth (cm)	^{210}Pb (Bq/g)	Precision 1 std (%)	Age (year AD)	STD in date (years)
FC04-1	1	0.204	4.9	2002	0
FC04-2	2			2001	
FC04-3	3	0.127	5	2000	0.7
FC04-4	4			1999	
FC04-5	5	0.214	5.6	1995	1.3
FC04-6	6			1990	
FC04-7	7	0.145	6.2	1979	6.5
FC04-8	8			1972	
FC04-9	9	0.125	3.8	1964	12.3
FC04-10	10			1956	
FC04-11	11	0.083	3.9	1943	37
FC04-12	12			1932	
FC04-16	16	0.078	5.7	1897	76.2
FC04-20	20	0.045	5.4		
FC04-23	23	0.051	8.9		
FC04-28	28	0.039	8.9		
FC04-31	31	0.051	7.5		
FC04-35	35	0.076	6.9		
FC04-40	40	0.033	5.7		
FC04-42	42	0.018	8		
FC04-81	81	0.027	9		

They were calibrated using the radiocarbon calibration program CALIB, using the Intcal.04 calibration data set (Reimer et al., 2004). CALIB makes the conversion from radiocarbon age to calibrated calendar years by calculating the probability distribution of the samples' true age (Stuiver et al., 2005). The dates are reported as calendar years AD (cal yr AD), and as a median probability of the 95.5% (2σ) confidence interval (Table 5). No marine reservoir effect was applied to the bulk sediment sample derived date, since there are no studies in the variations of reservoir effects in enclosed fjords such as the SBIC. Even though areas of strong upwelling such as the east coast of Vancouver Island tend to have strong marine reservoir effects (up to 1200 years, Hutchinson et al., 2004), values for estuaries are very much affected by freshwater inflow, especially at boundaries between different ocean circulation regimes, such as the SBIC (Ingram and Southon, 1996).

An age-depth model based on calibrated radiocarbon and ^{210}Pb dates was constructed using piece-wise linear interpolation, since this method has been demonstrated to provide the best performance when the number of dates is low (Telford et al., 2004). A depth of 0 cm was included in the linear regression as the year AD 2002, a value corroborated by the ^{210}Pb dating. As the first radiocarbon date (FC04-89) was chosen from a depth where there is a change in sedimentology, the validity of the model is strengthened (Telford et al., 2004).

The errors on the individual dates were combined to define 'maximum age" and "minimim age" models, which constrained the chronology along the core (Fig. 4). Dates are presented rounded up to the next decade on the portion of the core dated by ^{210}Pb, and to the nearest 25 yrs on the section corresponding to the radiocarbon dates.

6.2. Environmental variables

Environmental variable data (courtesy of Dr. R.E. Thomson and C. Wright, Institute of Ocean Sciences, Sydney, BC) was plotted for both Belize Inlet (Fig. 2) and Alison Sound (Fig. 3).

The profiles for Belize Inlet (Fig. 2) show a marked wedge of ocean water entering the inlet, with temperature values lower than 8 °C, and high oxygen content (>5 mL/L). Towards the head of the inlet, an oxygen minimum zone at mid-depth can be observed,

Table 5
Radiocarbon ages and calibrated ages (years AD) for the two radiocarbon samples sent to Isotrace Lab. The calibration was done using the program CALIB v. 5.0.1., with the calibration dataset Intcal.04. The calibrated results are reported at the 95.5% (2σ) confidence interval. The median probability ages are rounded to the nearest year.

Sample name	Lab number	Depth (cm)	Sample type	Radiocarbon age (yr BP)	Calibrated Calendar Date (cal yr AD)	Median Probability Date (yr AD)	Error (2σ) (yr)
FC04-89	TO-12566	89	Wood	530 ± 40	1387–1444	1415	28
FC04-128	TO-12567	128	Gyttja	1060 ± 50	875–1046	960	85

characterized by the lowest values of the profile (1 mL/L). This minimum appears to be an intermittent feature in low runoff fjords along the coast of BC. It was first supposed that high oxygen demand in the surface waters resulted in a depletion of oxygen lower in the water column, that became replenished by a steady flow of dense oxygenated ocean water sinking to the bottom (Pickard and Stanton, 1980). However, water property surveys carried out in the SBIC indicate that the oxygen minimum zone is more likely the result of the seepage of water from a salt water marsh at the head of Belize Inlet, which settles in at that density layer (C. Wright, written communication, 2006). Oxygen values in the deeper portions of Belize Inlet do not fall below ~3 mL/L.

The salinity profile is characterized by a low-salinity wedge at the surface (<30 m deep), which strengthened towards the head of the inlet. Salinity at depth remains fairly constant, with average values of 30‰. This profile is consistent with the input of freshwater from rivers and creeks up the fjord.

In Alison Sound (Fig. 3), temperature values were relatively constant. Only towards station ALS3 was an increase from 8.5 °C to 9 °C observed, probably the result of the shallower depth of the inlet. A low salinity wedge is also present in Alison Sound, although the overall salinity values are lower than those in Belize Inlet, with a maximum of 29‰.

Oxygen concentrations at depth in Alison Sound are lower than found in Belize Inlet, and are characterized by a steeply declining gradient beneath the low-salinity surface water wedge. The input of oxygenated water (>3 mL/L) coming from Belize Inlet is apparent at

Alison Sound stations ALS1 and ALS2, in sharp contrast to the close to 0 mL/L values found at the head of the inlet.

6.3. Cluster analysis

The results of the cluster analysis show a clear partition of samples into four different assemblages, some of which are represented in both core and surface samples (Fig. 5). The SDI values characterizing all assemblages ranged between 1.41 and 1.84, indicating a moderately stable environment (cf. Magurran, 1988; Patterson and Kumar, 2002a).

6.3.1. Assemblage 1
Assemblage 1 is comprised of 19 samples and includes the basal portion of core FC04 (samples FC04-77 to FC04-138) as well as samples ALS1 and ALS3. All the samples in this assemblage are dominated by agglutinated foraminifera, especially *Eggerella advena* (Cushman, 1922), with an average occurrence of 29.7% (range 15.7%–47.1%), and *Eggerella* sp. (see illustration in Vázquez Riveiros and Patterson, 2008), with an average of 24.3% (range 0.0%–34.8%). Other important species are *Cribrostomoides* cf. *subglobosum* (Cushman, 1910), *Recurvoides turbinatus* (Brady, 1881) and *Spiroplectammina biformis* (Parker and Jones, 1865).

Thecamoebians are present in 50% of the samples, with an average abundance of 5.7%, (range 1.0%–26.5%). Planktic foraminiferal species appear in a lone sample, collectively making up 1.9% of the counts in that sample. The only non-agglutinated benthic species is *Stainforthia feylingi* Knudsen and Seidenkrantz (1994) in sample FC04-138, comprising 4.8% of that sample. The SDI has a value of 1.49.

6.3.2. Assemblage 2
This assemblage is comprised of 29 samples from FC04, at a core depth of 11–64 cm, and all contained species are calcareous benthic foraminifera.

The most characteristic component of Assemblage 2 is *Buccella frigida* (Cushman, 1922), which appears in every sample, with an average concentration of 27.3% (range 52.3%–6.3%). Several other species are also abundant including: *Cribroelphidium excavatum* (Terquem, 1876) phenotype 'magna' (Miller et al., 1982), which comprises 21.6% of the population (ranging between 44.1% and 6.7%) and *C. excavatum* phenotype 'clavata' (Cushman, 1930) with an average abundance of 15.0% (range of 0.0%–27.9%). Also common are *Nonionellina labradorica* (Dawson, 1860), *Cribroelphidium foraminosum* (Cushman, 1939), *C. excavatum* phenotype 'excavatum' (Terquem, 1876) and *Cassidulina crassa* d'Orbigny, 1939.

6.3.3. Assemblage 3
This assemblage is comprised of only five samples from FC04, at core depths 65 cm through 68 cm and at 76 cm. It is a mixed assemblage, where agglutinated foraminifera make up an average of 13% of the population.

The distinctiveness of this assemblage lies with the very high numbers of *S. feylingi*, which comprise nearly half of the sample populations (49.3%; ranging between 40.6% and 57.0%). The following most abundant species is *Haplophragmoides bradyi* (Brady, 1887), with an average of 10.4% (ranging from 8.2% to 15.7%).
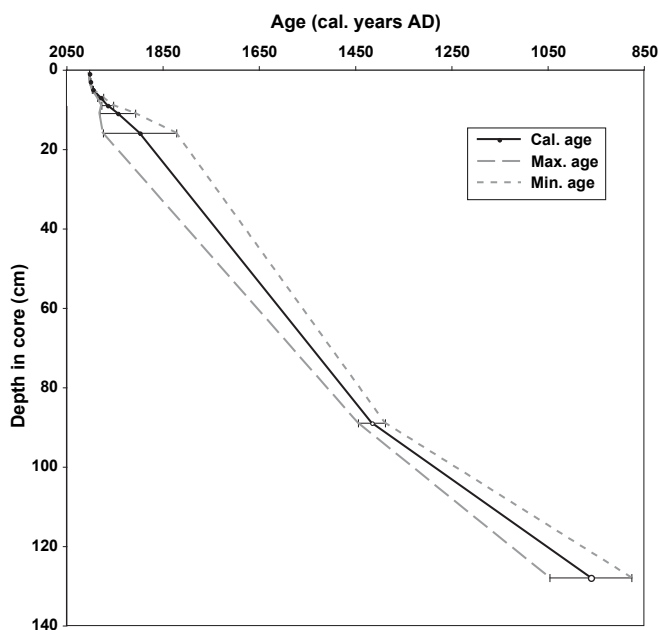
Fig. 4. Age-depth model for calibrated radiocarbon dates and ^{210}Pb dates. Horizontal error bars represent the range of ages defined by the probability distribution of the samples' true age. Dashed contours represent the maximum and minimum age-depth models, taking into account the errors on all dates. Filled circles represent ^{210}Pb dates; open circles are radiocarbon dates. Samples selected for ^{210}Pb were analyzed at MyCore Scientific Inc.; AMS ^{14}C analyses were done at IsoTrace Laboratory.
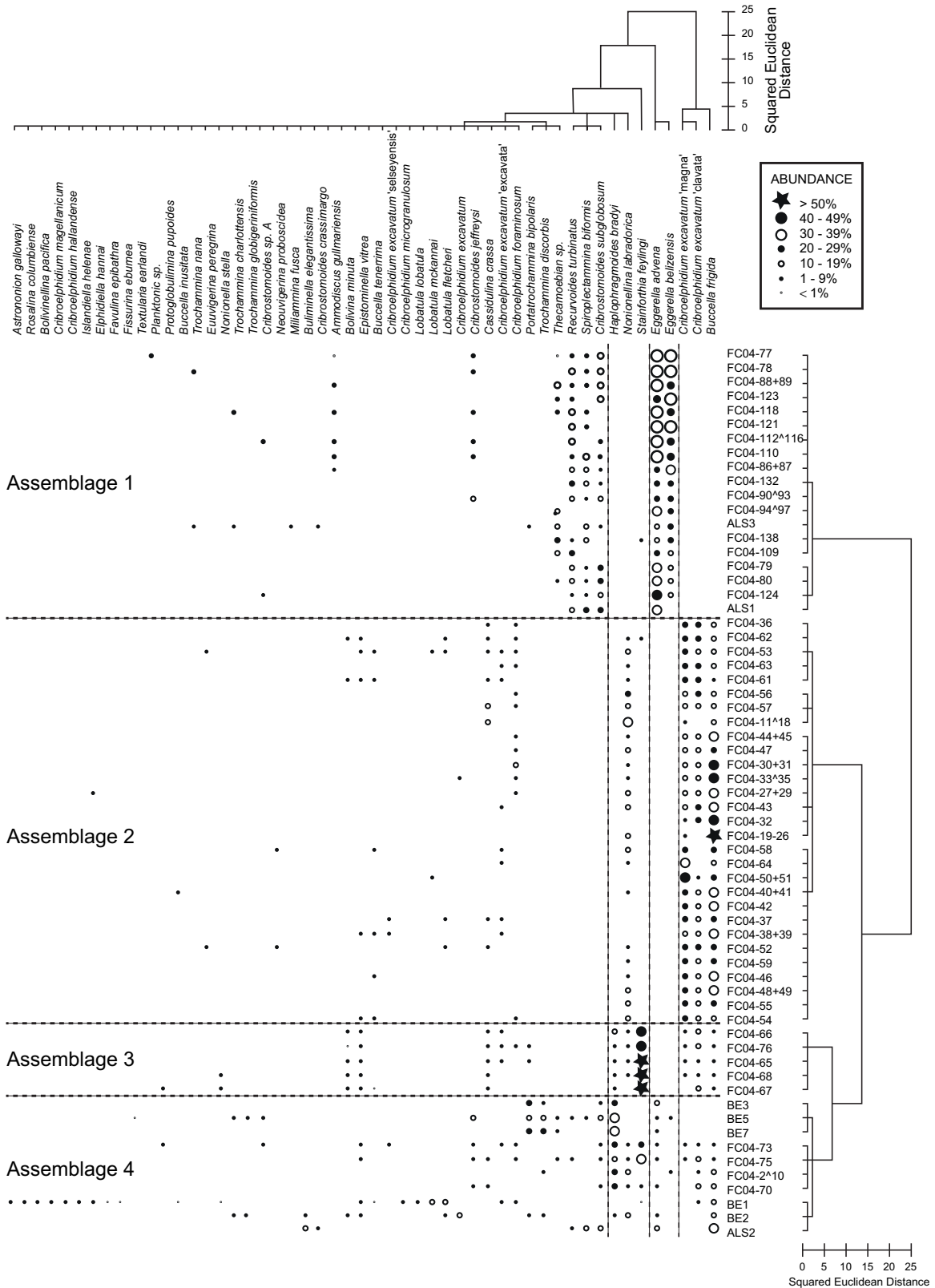
Fig. 5. Q-mode vs. R-mode cluster diagram for FC04 and surface samples, with fractional abundances of the species indicated by symbols.

C. excavatum phenotype 'clavata' characterizes 9.9% of the assemblage, with values between 4.3 and 14.3% in different samples. Other members of the *C. excavatum* family, such as *C. excavatum* phenotype 'magna' (average 2.6%; range of 0.0%–4.6%) and

C. excavatum phenotype 'excavatum' (average 2.2%; range 0.0%–5.5%) make up nearly 5% of the population when factored together. *Bucella frigida* comprises 4.9% (range of 1.2%–7.2%) of the assemblage population, *C. crassa* follows closely with an average of 4.7%

Table 6
Values for the Canonical Correspondence Analysis (CCA) of the surface samples.

Axes	1	2	3	4	Total inertia
Eigenvalues:	0.741	0.36	0.244	0.21	2.294
Species-environment correlations:	0.978	0.947	0.98	0	
Cumulative percentage variance					
Of species data :	41	60.9	74.4	86	
Of species-environment relation:	55.1	81.8	100	0	
Sum of all unconstrained eigenvalues					1.807
Sum of all canonical eigenvalues					1.344

(range of 2.1%–6.8%) and *N. labradorica* accounts for 3.2% of the population (range of 0.0%–5.6%).

6.3.4. Assemblage 4

Assemblage 4 groups together surface samples from Belize Inlet, as well as sample ALS2, and from FC04, the 2 to 10 cm and 70–75 cm intervals.

This assemblage is characterized by the most diverse fauna of all assemblages (SDI = 1.84), with *H. bradyi* (average 18.8%; range 0.0%–37.6%) and *B. frigida* (average 10.5%; range 0.0%–33.2%) being the dominant species.

Other important contributors to the fauna of this assemblage are *S. feylingi* (average 6.4%; range of 0.0–32.2%) and *E. advena* (average 5.6%; range of 0.0–15.0%). *Portatrochammina bipolaris* (Brönnimann and Whittaker, 1980) and *Trochammina discorbis* Earland, 1934 reach similar abundances, both with averages of 5.5% each (ranges of 0.0–20.5% and 0.0–23.9% respectively) while *N. labradorica* has an average abundance of 4.1% (range of 0.0–17.5%). Four percent of the assemblage is made of *C.* cf. *subglobosum* individuals (range of 0.0–14.2%) and 3.7% of *C. excavatum* phenotype 'clavata' (range of 0.0–11.8%). Thecamoebians comprise 1.2% of this assemblage (range 0.0–8.5%).

There are 32 other species with average values of less than 2% of the total population in Assemblage 4 (see Appendix A for species counts).
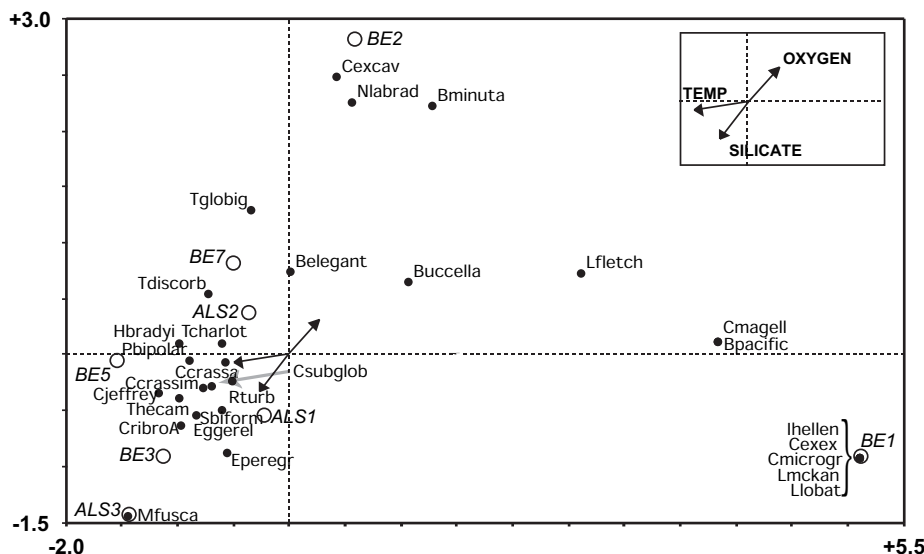
6.4. Ordination

The chosen axes of environmental variability explain 74.4% of the total variance in the species data (total inertia, 2.29, Table 6). The first axis is the most important one, explaining 41.0% of the

variance, with an eigenvalue of 0.74. This axis is very well correlated with the environmental data ($r = 0.98$). The second axis, characterized by a smaller eigenvalue (0.36), explains an additional 19.9% of the variance, and is also strongly correlated ($r = 0.95$). These correlations suggest that the data set is governed by these two dominant gradients (cf. Leps and Smilauer, 2003). The difference between the total variation explained by the axis and the total inertia of the dataset (2.29–1.81) is explained by the covariables of the analysis, in this case depth, whose effect is acknowledged on the other variables.

The percentage variance explained by the axes of the ordination analysis is very close to that explained by the axes of the unconstrained DCA (e.g., 41.0 in comparison with 43.3); the species-environment correlation is only slightly higher. This suggests that the measured environmental variables are the ones responsible for the variation in species composition.

The position of the environmental variable vectors in relation to the axes summarizes the relative weight of each variable in determining each axis (Fig. 6). From the triplot, it can be observed that temperature is highly negatively correlated with the first axis, whereas oxygen and silicate are both correlated with axis 1 and axis 2, oxygen positively and silicate negatively. The left side of the diagram thus shows an affinity for higher temperatures, but when values move towards the right side, the optimum temperature values for the species diminish. With regards to oxygen and silicate, the upper right quadrant is populated with species with an affinity to high oxygen concentrations and low silicate values; the opposite is true for the lower left quadrant. The fact that there are several species occupying the same point on the triplot (*Islandiella helenae* Feyling-Hanssen and Buzas (1976), Ihellen; *C. excavatum excavata*, Cexex; *C. microgranulosum*, Cmicrogr; *L. mckannai*, Lmckan; *L. lobatula*, Llobat) indicates that their relative abundances were judged to be identical using this method in different samples.

The relative position of samples and species indicates that, as shown with the cluster analysis, there is a tendency for some species to occur in certain samples. From the figure, it can be seen that the agglutinated foraminifera and thecamoebians occur in settings of higher temperature relative to the mean (samples from Alison Sound and BE3, BE5 and BE7). Most of the calcareous foraminifera appear to prefer colder temperatures. In addition, species such as *E. advena*, *Cribrostomoides crassimargo* (Norman, 1892), *C. subglobosum*, *S. biformis*, *Miliammina fusca* (Brady and Robertson,

Fig. 6. CCA ordination diagram showing the axes of the environmental gradients (temperature, oxygen and silicate), and the positions of samples and species relative to them. Filled circles represent species; open circles represent samples.

1870), *Euuvigerina peregrina* (Cushman, 1923) and thecamoebians are abundant in low-oxygen high-silicate environments. The opposite distribution is true for *Buccella* sp., *N. labradorica, Buliminella elegantissima* (d'Orbigny, 1839) as well as species and phenotypes within *Cribroelphidium* and *Lobatula*, which thrive under relatively higher oxygen conditions.

7. Discussion

7.1. Modern distribution of foraminifera in the SBIC

The distribution of foraminiferal assemblages in both Belize Inlet and Alison Sound is similar to that observed in other higher latitude estuarine environments. In these settings, a low diversity agglutinated fauna typically dominates deep-water, brackish areas where dysoxic conditions often prevail, and a higher diversity calcareous fauna is more common in areas where there is a more open marine influence (Sen Gupta, 1999).

All foraminiferal assemblages found in the modern sediment–water interface samples from Belize Inlet correspond to Assemblage 4, the most faunally diverse assemblage observed in this study. This result is not unexpected, as salinity (30‰) and oxygen concentrations (~3 mL/L) (Fig. 2) observed in the bottom waters of Belize Inlet most closely approach salinity and oxygen concentration values typical of stable open shelf environments (Schafer et al., 1989; Alve, 1995, 2000; Sen Gupta, 1999). The high abundance of *Buccella* species and *C. excavatum,* particularly in samples BE1 and BE2, provides unambiguous evidence of the open shelf nature of present-day Belize Inlet. *Buccella frigida* is a characteristic species of the open shelf in coastal British Columbia in cool, near shore environments characterized by near normal salinities (Patterson, 1993; Patterson et al., 2000). Similarly, *C. excavatum* is found in shallow waters of both polar and temperate seas where it appears in cold, normal salinity marine waters (Patterson, 1993; Sen Gupta, 1999; Patterson and Kumar, 2002b; Husum and Hald, 2004).

The most abundant species towards the head of Belize Inlet (samples BE3, BE5 and BE7) is *H. bradyi*. This generalist species normally prefers cool muddy environments characterized by low concentrations of organic matter in waters that are deeper than 50 m (Murray, 1973; Klitgaard-Kristensen and Buhl-Mortensen, 1999). Although *H. bradyi* is well adapted to dysoxic conditions (Sen Gupta and Machain-Castillo, 1993) the measured oxygen values (3 mL/L at the time of collection) and the presence of other foraminiferal species that prefer more oxygenated environments, indicates that bottom water oxygen conditions in this part of Belize Inlet consistently remain high enough to maintain the observed fauna (Fig. 2). A consistently lower bottom water oxygen concentration as measured at both stations ALS1 and ALS3 in Alison Sound is indicated by the presence of foraminiferal faunal Assemblage 1, which is characterized by a very low SDI and is comprised entirely of agglutinated forms. In the ordination triplot diagram (Fig. 6) agglutinated species group together in the lowermost left quadrant. Comparison of the observed species distribution with water property data indicates that any samples and species plotting in this quadrant are tolerant of low oxygen conditions. Conditions at station ALS3, where an oxygen concentration of 0.06 mL/L prevailed, and which plots on the farther corner of this quadrant, typifies the environmental affinity of this faunal distribution.

E. advena, the dominant species observed in Assemblage 1, is a generalist, tolerant of brackish water conditions and often found in environments contaminated by organic matter and where oxygen concentrations are frequently low (Blais-Stevens and Patterson, 1998). *E. advena* is morphologically very similar to *Eggerella scabra* (Williamson, 1858), a common species in fjords and inner shelves of Northern Europe (Alve and Nagy, 1986). *E. scabra* is

another generalist that seems to have no specific substrate preference, tolerates highly variable organic matter content, and can thrive under very low oxygen concentrations, but is most common in environments where salinity ranges from 29 to 35‰ (Alve and Nagy, 1986). Another common species found in the Assemblage 1 samples from Alison Sound is *Cribrostomoides jeffreysii*, a species typical of artic waters at depths of between 60 and 360 m (Alves Martins and Ruivo Dragão Gomes, 2004). This species is also tolerant of dysoxic environments (<0.1 mL/L), as so is *S. biformis* (<0.5 mL/L; Sen Gupta and Machain-Castillo, 1993).

The foraminiferal fauna found at station ALS 2 in Alison Sound is also comprised primarily of agglutinated species. However, it groups together with samples that comprise Assemblage 4 (Fig. 5), due to the higher proportion of *B. frigida* present. The shallower water depth of this sample station, coupled with the highest bottom water oxygen concentrations (1.7 mL/L) recorded in Alison Sound, account for this mixed assemblage.

Bottom water temperatures also play an important role in controlling the distribution of foraminifera in Belize Inlet and Alison Sound. Analysis of water property data indicates that any samples plotting in the right quadrant of the ordination triplot diagram (e.g. samples BE1 and BE2 and the dominant calcareous species found in Belize Inlet; *Buccella* sp., *C. excavatum* group, *N. labradorica, Lobatula* group, *I. helenae*) can be closely correlated with cooler water masses (Fig. 6). In contrast, samples from stations BE3, BE5, BE6, BE7, ALS1, ALS2 and ALS3, where bottom water temperatures measured in 2002, were above 8.5 °C (Figs. 2 and 3) and clustered in the left quadrant of the ordination triplot diagram.

7.2. Paleoceanographic changes in Belize inlet (~AD 850–AD 2002)

Comparison of the surface distribution of foraminifera in Belize Inlet and Alison Sound permits a generalized determination of paleoceanographic change in freeze core FC04 from Belize Inlet. As only eight sediment–water interface samples were available as a basis to construct a training set it was unfortunately not possible to develop a statistically rigorous transfer function to more precisely quantify the oceanographic changes.

The most significant transition recognized in the core was a dramatic and sudden shift from dysoxic/anoxic conditions to better-oxygenated conditions at the 76 cm (~AD 1500) horizon of the core (Fig. 7) as indicated by an abrupt change in the distribution of foraminifera from an Assemblage 1 fauna to alternating Assemblage 3 and 4 faunas from 76 to 64 cm (~AD 1500–1575). Based on comparison of the core foraminiferal assemblages with the modern foraminiferal distribution in the SBIC, the bottom-water during deposition of the sediments from the lowermost 77–138 cm (~AD 850–1500) interval of the core was likely consistently anoxic to dysoxic (<1.0 mL/L) and relatively warm (~8–9 °C). Intervals of non-fossiliferous laminated sediments through portions of the basal section of FC04 provide additional evidence of intervals of sustained anoxic bottom water conditions. Similar occurrences of laminated sediments have been documented in similar fjord environments where there is little exchange with open oceanic waters, resulting in the development of dysoxic to fully anoxic bottom water conditions (e.g., Effingham Inlet, Vancouver Island, Chang and Patterson, 2005; Havstens and Koljö Fjord, Sweden, Gustafsson and Nordberg, 2002; Saanich Inlet, Vancouver Island, Nederbragt and Thurow, 2001; Patterson et al., 2004b; Frederick Sound, SBIC, Wigston, 2006).

There are two possible hypotheses that may explain the presence of anoxic/dysoxic conditions in the bottom waters of Belize Inlet during this interval. Under the first scenario, upwelling may have been suppressed in the area, in which case, the density of ocean waters would have been too similar to that of the water
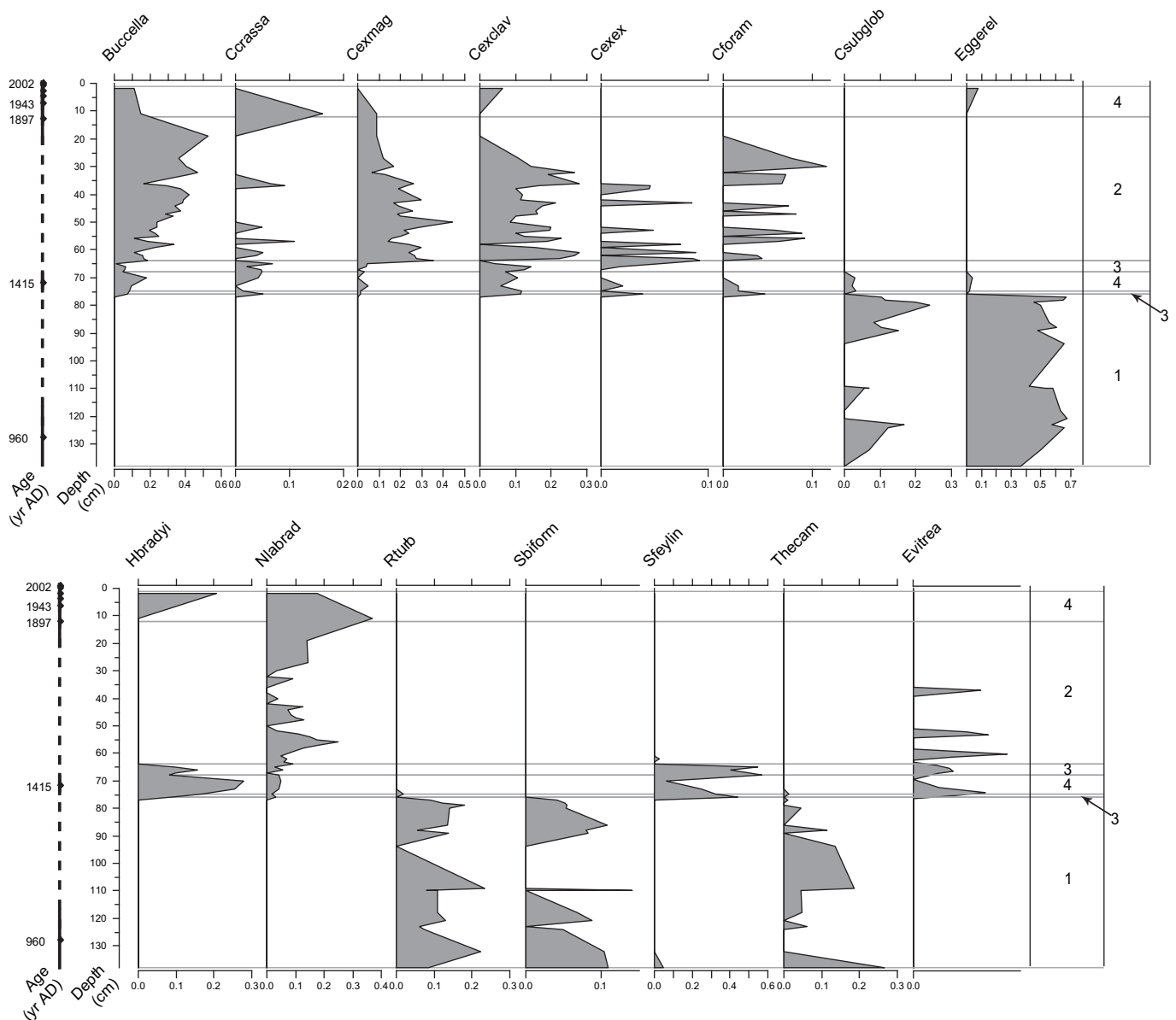
Fig. 7. Foraminiferal and thecamoebian stratigraphy of core FC04. Age down core corresponds to the age-depth model presented in Fig. 4, with some of the dated levels shown for clarity, with their error bars as filled lines. The numbers on the right-hand side correspond to the assemblages of the cluster analysis. The *X*-axis values for the species are given in fractional abundances. Buccella: *Buccella* species; Ccrassa: *C. crassa*; Cexmagna: *C. excavatum* forma *magna*; Cexclav: *C. excavatum* forma *clavata*; Cexex: *C. excavatum* forma *excavata*; Cforam: *C. foraminosum*; Csubglob: *C.* cf. *subglobosum*; Eggerel: *Eggerella* species; Evitrea: *E. vitrea*; Hbradyi: *H. bradyi*; Nlabrad: *N. labradorica*; Rturb: *R. turbinatus*; Sbiform: *S. biformis*; Sfeylin: *S. feylingi*; Thecam: thecamoebian species.

masses found within the SBIC to favor circulation exchange. However, at present upwelling conditions prevail in the open water areas outside the SBIC and do not penetrate past the restricted entrance at the Nakwakto Rapids, where very strong seaward currents dominate (Thomson, 1981). As the bottom waters in the more open areas of the SBIC are currently well oxygenated, this hypothesis is negated. A second possible explanation hinges on the hypothesis that estuarine flow was severely reduced during deposition of the lower unit. This scenario would unfold if precipitation in the area became reduced, resulting in the low salinity layer that forms within the surface waters at present becoming poorly developed. This more homogenous water mass would have a reduced tendency to flow towards the open ocean, which in turn would result in a reduction of return flow at depth of denser and well oxygenated subsurface water over the sill at the Nakwakto Rapids. This diminished flow into the SBIC would have quickly

resulted in the development of stagnant bottom-water conditions and a concomitant decrease in oxygen levels, which would have given an ecological advantage to opportunistic foraminiferal species tolerant of low-oxygen concentrations (e.g., *E. advena*, *S. biformis* or *Cribrostomoides* sp.). Even if full anoxic conditions dominated bottom water for a significant part of the year, some foraminifera are known to be able to survive with only infrequent exposure to oxygenated water (Sen Gupta and Machain-Castillo, 1993; Alve, 2000; Bernhard and Sen Gupta, 2000). The abundance of fecal pellets is very high below 77 cm in the core, indicating conditions of high productivity in the surface waters, which may also have contributed to the development of reduced oxygen levels at depth. Weak estuarine circulation and high levels of productivity are consistent with a warm, low precipitation climatic regime. Immediately above the 77 cm (∼AD 1500) the sudden replacement of the agglutinated foraminiferal Assemblage 1 by calcareous taxa-

dominated Assemblages 3 and 4 indicates that there was an abrupt change in oceanographic conditions, which led to better-oxygenated waters penetrating to deeper parts of Belize Inlet coincident with a decline in bottom water temperature. Both Assemblages 3 and 4, are dominated by *S. feylingi*, frequently making up more than 50% of the fauna. *S. feylingi* has been correlated with low-oxygen environments, appearing even under fully anoxic conditions (Patterson et al., 2000; Patterson and Kumar, 2002b). Patterson et al. (2000) observed a *Stainforthia*-dominated assemblage under fully anoxic (with H₂S) conditions in Effingham Inlet. Based on this evidence they concluded that even the most isolated basins of that fjord were periodically oxygenated. This hypothesis was later corroborated when long-term monitoring of physical water property data was carried out in Effingham Inlet (Patterson et al., 2004a; Chang and Patterson, 2005). *Stainforthia fusiformis* (Williamson, 1858), a species closely related to *S. feylingi*, is a typical dweller in fjords of Norway, where it frequently appears as the first recolonizer in formerly anoxic areas (Sen Gupta and Machain-Castillo, 1993; Alve, 1995, 2000; Alves Martins and Ruivo Dragão Gomes, 2004). This species has also been found to thrive during periods of high primary productivity, which contribute to the organic content of the sediment (Alve, 2000). Most species found in Assemblage 3 in particular are dysoxic tolerant generalists, providing further evidence that oxygen concentrations were higher with respect to the unit below. For example, *H. bradyi* and *N. labradorica*, which have become adapted to dysoxic conditions due to their infaunal habitat (Sen Gupta and Machain-Castillo, 1993). Research has indicated that *Nonionella labradorica* has accomplished this adaptation through the sequestration of algal chloroplasts in its cytoplasm, though the exact mechanism is unknown (Guilbault et al., 2003). *Epistominella vitrea* is also common through this core interval and it too has previously been reported as living in dysoxic environments in Swedish fjords (Gustafsson and Nordberg, 2000), although it is also abundant in outer neritic zones along the Pacific and Atlantic coasts where high sedimentation rates prevail (Patterson, 1993; Alves Martins and Ruivo Dragão Gomes, 2004).

The dramatic increase in the proportion of calcareous species, particularly *S. feylingi* through the 76–64 cm interval probably represents, as has been observed elsewhere (e.g., Alve, 1995), a pioneering stage colonization event when the previously stressed very low oxygen environment received a prolonged injection of more oxygenated waters and rapidly became habitable for a calcareous foraminiferal assemblage. The sudden abundance peak of *S. feylingi* may also at least in part be related to a climatological change, as atmospheric conditions shifted from a dryer to higher precipitation regime. During the transition, conditions may have been optimal for phytoplankton blooms in the surface waters that would have in turn increased the rain of organic material to the bottom of the inlet. In Norwegian fjords it has been observed that *S. fusiformis*, a species closely related to *S. feylingi* has been known to double its population in a short period of time following an increase in the input of organic matter. This rapid population growth is in part related to the ability of the species to reach full adult size and reproductive maturity in less than a month (Gustafsson and Nordberg, 2000).

The alternation of assemblage 3 and 4 faunas through the 76–64 cm interval suggests that bottom-water circulation patterns during the ~75 year span of this transitional phase were unstable with intervals of dysoxic and low oxic conditions prevailing. For example, the 75–70 cm interval is characterized by the transition from an Assemblage 3 to Assemblage 4 dominated fauna. Although high concentrations of *S. feylingi* are still present in Assemblage 4, *H. bradyi* is also important. Species of *Haplophragmoides* are common in muddy shelf environments on both Atlantic and Pacific Ocean coasts (Murray, 1991). The diversity of foraminiferal species increases through this zone and may indicate that the faunal

succession that was initiated with the first calcareous assemblages at 76 cm reached a climax phase within the ecological succession as bottom water conditions in the inlet changed. A transition back to a more *S. feylingi* dominated Assemblage 3 from 69 to 64 cm in the core indicates another shift in bottom-water circulation patterns.

By the 64 cm (~AD 1575) interval of the core the development of an Assemblage 2 foraminiferal fauna heralded the establishment of relatively stable oceanographic conditions that prevailed for the next ~450 years until the 11 cm horizon (~AD 1940). Comparison of the Assemblage 2 faunas found in the core with the modern distribution of foraminifera from the SBIC suggests that bottom water oxygen concentrations stabilized in the 4–5 mL/L range (relatively high) with water temperatures falling to around 8 °C (slightly depressed) (Fig. 7).

The introduction of well oxygenated water at depth was probably triggered by an increase in precipitation within the SBIC catchment area, which is the main variable that influences the extent of the brackish layer within a low run off inlet such as Belize Inlet (Pickard, 1961). Any increase in freshwater input results in development of a thicker brackish surface layer, which, on its way to the sea, entrains a higher amount of deeper saline water that gains velocity towards the mouth of the inlet (R. Thomson, written communication, 2006). The outflow of a large volume of low salinity surface water through the mouth of the SBIC at Nakwakto Rapids results in a return flow over the sill of cold, well oxygenated oceanic water from Queen Charlotte Sound in the subsurface layer. As long as precipitation levels remain high, estuarine flow is enhanced, which keeps oxygen levels in the bottom waters of Belize Inlet high, promoting the development of a diverse and primarily calcareous foraminiferal assemblage.

The most dominant species through the 64–11 cm interval are *B. frigida* and *C. excavatum*, species typical in normal open marine cool-water conditions. The range of *C. excavatum* strain 'clavata' is restricted to a high northern latitude belt in both the Pacific and Atlantic oceans (Sen Gupta, 1999). *Nonionella labradorica*, present in most samples of this assemblage, has been recorded in sediments from Drammensfjord (Norway) and is associated with normal saline deep water conditions (Alve, 1991; Gustafsson and Nordberg, 2002). As discussed above, this species is well adapted to dysoxic conditions because of its ability to use opportunistically the increased organic loads generally associated with dysoxia. However, the species is present in oxic environments as well, although its numbers are often reduced due to competition with other species (Sen Gupta and Machain-Castillo, 1993). Species of *Lobatula* are also found through this section. These epifaunal suspension feeders are most abundant in environments with good circulation, as the increased oxygen concentrations estimated for this interval suggest (Polyak et al., 2002).

Many foraminiferal specimens recovered from samples through this section were highly etched, to the point of being unrecognizable in many instances, suggesting that dissolution may be a taphonomic biasing factor through this interval of the core. Dissolution of calcareous tests is a process enhanced by macrofaunal reworking of the sediments, which prevents CaCO₃ saturation of the pore waters (Green et al., 1993). The etched foraminiferal specimens therefore provide further corroborative evidence that a healthy benthos had developed at this site following the increase in levels of oxygenation of the bottom water.

There is an increase in the proportion of agglutinated foraminifera in FC04 in sediments deposited in the late 19th century and particularly in those deposited above 11 cm (~AD 1940) in the core, as indicated by the reappearance of an Assemblage 4 fauna. This faunal shift suggests a gradual breakdown in estuarine circulation and possibly a return to conditions as existed in the inlet in the 16th century. However, modern-day estuarine circulation has not become as weak, at least as of yet, to conditions that existed

during deposition of the interval of the core below 76 cm (prior to ~AD 1500; Fig. 7). The record is short but this assemblage shift could indicate that dysoxic conditions may again be slowly redeveloping in the open areas of Belize Inlet.

A trend similar to that observed in FC04 has been documented in cores from the Skagerrak Basin, NE North Sea (Alve, 1991, 1996). In that basin there are periodic shifts between agglutinated and calcareous foraminiferal faunas that have been interpreted to reflect varying bottom water oxygenation conditions brought on by infrequent deep-water renewal and increased organic matter in the basin.

7.3. Thecamoebian distribution in FC04

The relatively high abundance of freshwater thecamoebian tests, which are only found in the basal 138–77 cm interval of FC04 deposited prior to ~AD 1500 is difficult to explain. Since thecamoebians are freshwater organisms that cannot survive in salinities higher than 5‰ (Scott et al., 2001), the whole fauna was transported to the basin from soil and freshwater habitats on the margins of the fjord by runoff. The intuitive assumption would be that intervals characterized by higher numbers of thecamoebians would correspond with periods of higher precipitation, conditions that did not exist during deposition of the basal unit of the core. More thecamoebians probably do get washed into the inlet during intervals when precipitation is higher (e.g., the post-77 cm interval of FC04). However, due to the high velocity of the low salinity surface waters above the pycnocline during these intervals, they are most likely flushed out of the basin before they have time to settle to the bottom. This hypothesis is based on the observation that the distance that a particle will be carried in a surface water mass will depend on the time that the particle remains in suspension; the faster the velocity of the surface layer, the longer the particles will remain in suspension (Syvitski, 1989). This process has previously been documented in Sandsfjord, Norway, during an analysis of the impact of freshwater runoff on physical oceanography and plankton distribution. Kaartvedt and Svendsen (1990) found that when freshwater runoff increased, due to controlled discharge from a hydroelectric plant at the head of the fjord, the phytoplankton of the upper layers was flushed seawards. Therefore, the absence of freshwater thecamoebians on the SBIC during periods of high estuarine circulation and high precipitation is explained here as the result of them being flushed out of the basin by the high velocity of the surface layer.

7.4. Paleoclimatic interpretation

Changes over time in the position of the respective centers of action (COA; Patterson et al., 2004b) of the AL and NPH strongly influence atmosphere/ocean circulation patterns in the North Pacific region, which in turn affect the amount of rainfall and ultimately streamflow occurring in coastal BC (Cayan and Peterson, 1989; Trenberth and Hurrel, 1995). Changes in the COA and strength of the AL and NPH may therefore provide a good explanation for the climatic variability observed in the SBIC through the last ~1100 years. During an interval when the AL was weakened, or when the NPH was stronger, there would have been a diminished estuarine circulation, resulting in a reduced exchange with more open ocean waters, as occurred in the SBIC during the ~AD 850–1500 interval. In contrast, periods of a stronger or more persistent AL, accompanied by an increase in precipitation over coastal BC, would have enhanced estuarine circulation within the SBIC, as occurred after ~AD 1500.

This period of strengthened AL influence that impacted the SBIC between ~AD 1500 and the gradual faunal shift that was initiated here in the late 19th century and which was complete by ~ AD 1940, correlates well with the Little Ice Age (LIA), which has been

described as occurring between approximately AD 1500 and 1850 in western Canada (Bradley and Jones, 1995). Though the determination of the initiation of the LIA is controversial, and seems to vary locally, there is a general agreement that the period between the 15th and late 19th century was cooler and/or wetter than at present in most areas of BC. Clague et al. (2004) observed that glaciers from the region were at their greatest extent of the last 3000 years, and perhaps the last 10,000 years, during the LIA, and recognized evidence of a gradual climatic amelioration commencing in the 20th century. A second study that utilized varve thickness as a proxy for precipitation in Saanich Inlet, Vancouver Island, also correlates with a period of increased precipitation after AD 1450 with the LIA, which ties in with the SBIC record (Nederbragt and Thurow, 2001). Recently, Loso et al. (2006) described a cool period between AD 1500 and AD 1850, also correlatable with the LIA, in their varve record from south-central Alaska.

Analysis of an oxygen isotope record from lacustrine carbonates at Jelly Bean Lake in Yukon Territory also records similar climatic transitions, although the events there began a little later (*ca.* AD 1700) and terminated slightly earlier (*ca.* AD 1900) than observed in the SBIC and other areas to the south (Anderson et al., 2005). The authors correlated the observed sharp transition at *ca.* AD 1700 in the Jelly Bean Lake record with an initial eastward shift of the COA of the AL, which caused precipitation in the area to increase. When the COA of the AL eventually gradually shifted westward again at *ca.* AD 1900, the amount of precipitation began to decrease in the area, marking the "end of the LIA".

At the hemispheric scale, there are many similar paleoclimatic proxy records of increased/decreased precipitation through the last millennium that were also influenced by changes in atmosphere-ocean circulation. For example, in the eastern Barents Sea region, there was an extended period of glacial retreat that has been linked to the comparatively mild climate that characterized the MWE in the Northern Hemisphere prior to AD 1400 (Polyak et al., 2004). The subsequent expansion of these glaciers during the LIA was the result of increased precipitation, which in turn originated with an intensification of the Icelandic Low (Polyak et al., 2004). In another study, Lassen et al. (2004) carried out a high-resolution stratigraphic analysis of foraminifera deposited during the last millennium in Igaliku Fjord, South Greenland, which revealed several distinct climatic episodes. Although the present record is too short to indicate climatic fluctuations on a centennial scale, it is possible that the period between ~AD 1500 and AD 1940 may correspond to a well documented ~500 years solar cycle (Hu et al., 2003). This cycle characterizing the interval between lower and higher solar irradiance levels has been correlated with wetter/drier conditions and an intensified/weakened AL (Patterson et al., 2004b). The cycle is prevalent in the Northern Hemisphere (Hu et al., 2003), and has been observed in the North Atlantic region to broadly match the LIA and MWE (Bond et al., 2001).

8. Conclusions

High-resolution analysis of Recent and fossil foraminifera from the SBIC has provided evidence of alternating warmer and dryer and wetter and cooler intervals through the past ~1100 years. These climate regimes seem to have been controlled in large part by the relative strength, and long-term migration of the COA's of both the NPH and AL. Reduced precipitation in the SBIC catchment during the ~AD 900–AD 1500 interval resulted in weakened estuarine circulation and the development of dysoxic and anoxic conditions in the bottom waters, as indicated by the low diversity agglutinated foraminiferal fauna characterizing this interval. There was a major increase in precipitation in the SBIC area after ~AD 1500 as the COA of the AL migrated eastward. This gradual change

in atmospheric – ocean circulation is marked in the core by a transitional interval that terminates by ~AD 1575. Conditions during this ~75 year transitional interval varied though as there were not only episodes when cold, well oxygenated water entered the fjord but episodes when anoxia prevailed as well. Strong estuarine circulation permanently prevailed in the SBIC after ~AD 1575 as reflected by the diverse calcareous foraminiferal fauna found in the interval of the core deposited after this time. Estuarine circulation eventually began to weaken in the late 19th century and by AD 1940 conditions began to develop that closely resembled those that prevailed in the SBIC prior to ~AD 1500, although precipitation levels and bottom water oxygen levels are still not as low as they were during the 10th–16th centuries.

This study shows the potential of high-resolution foraminiferal research in the development of accurate climate chronologies in fjord environments. Cluster analysis proves to be a resourceful qualitative exploratory aid in the description of assemblages, and ordination methods are useful complementary tools for the determination of the environmental factors that define those assemblages.

Acknowledgements

Appendix A. Supplementary information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.quascirev.2009.07.015.

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