Journal of Foraminiferal Research, v. 32, no. 2, p. 110–125, April 2002

POST-GLACIAL PALEOCEANOGRAPHIC HISTORY OF SAANICH INLET, BRITISH COLUMBIA, BASED ON FORAMINIFERAL PROXY DATA

R. TIMOTHY PATTERSON[1] AND ARUN KUMAR

Ottawa Carleton Geoscience Centre & Department of Earth Sciences, College of Natural Sciences, Carleton University, 2240 Herzberg Building, 1125 Colonel By Drive, Ottawa, Ontario, K1S 5B6, CANADA

ABSTRACT

Five benthic foraminiferal biofacies characterize the late Pleistocene to Recent succession at ODP Sites 1033B and 1034B (Leg 169S) in Saanich Inlet, southern Vancouver Island, British Columbia. These faunas document three distinct paleoceanographic phases in the evolution of this inlet. From the latest Pleistocene, ~14,000 years BP, to the earliest Holocene, the distribution of benthic foraminifera (*Cribroelphidium excavatum* [Biofacies 5]), *Islandiella norcrossi* [Biofacies 4], and *Nonionella stella* [Biofacies 3]) in Saanich Inlet was strongly controlled by the influence of cold, low-salinity waters associated with deglaciation. Early Holocene sediments are characterized by *Stainforthia feylingi* Biofacies 2. Despite a shallower sill depth at the entrance of Saanich than exists today sedimentological and foraminiferal evidence indicate that bottom waters were oxygenated. The foraminiferal fauna indicates that oxygen levels varied from a minimum low oxic (1.5–3 ml/l [67–133 μM]) level early on to suboxic (0.3–1.5 ml/l [13.3–67 μM]) conditions up section where sediments become progressively more laminated. During the early Holocene air temperatures in the region were up to 4°C warmer, and it was much drier than at present. The resultant reduced freshwater flow into the southern Strait of Georgia was conducive to the free exchange of Saanich Inlet bottom waters with those of well-oxygenated Haro Strait.

After 7000 years BP the climate in the region cooled and, as the influence of freshwater from Strait of Georgia increased, oxygenation of Saanich bottom waters became a rare occurrence. Finely-laminated sediments characterized mid-Holocene to Recent sediments in the inlet reflecting the development of full anoxic conditions at depth. The *Lobatula fletcheri–Buccella frigida* Biofacies 1 characterizing this interval is allochthonous and derived by down-slope transport from shallower, more oxygenated regions of Saanich Inlet.

INTRODUCTION

The Ocean Drilling Program (ODP) drilling ship JOIDES Resolution drilled at two sites in Saanich Inlet during Leg 169S to southern Vancouver Island in August, 1996 (Fig. 1). A 105 m core was obtained at Site 1033B while at Site 1034B, 118 m of core was recovered. These cores provide a continuous sedimentary record from the termination of the last glaciation (~15 k yr BP) to the present (Bornhold and others, 1998; Blais-Stevens and others, 2001). The sites were located along the axis of the inlet at 238 and 200 m water depth respectively, 4.8 km apart.

Inlets and fjords such as Saanich Inlet are useful in paleoceanographic research because in many cases only strong oceanographic events are recorded in the sedimentary record (Thomson, 1981). This characteristic makes paleoceanographic interpretation easier for researchers as the noise of background productivity is filtered out (Patterson and others, 2000). Saanich Inlet was selected for coring because the bottom of this inlet is dysoxic to anoxic, resulting in very few bioturbating benthic organisms. These undisturbed layers of sediments record climatic events as subtle as seasonal variations. Derived sedimentological and micropaleontological (e.g., pollen, diatom and foraminifera) data provide a good proxy record for a number of phenomena including paleoceanography, sea-level changes, climatic oscillations and catastrophic events like earthquakes, floods and tsunamis (Blais, 1995).

The Quaternary stratigraphic, environmental and climatic history of southern British Columbia has been addressed by several researchers (e.g. Blaise and others, 1990; Clague, 1994; Clague and Mathewes, 1989; Huntley and others, 2001). Studies on the distribution of late Quaternary benthic foraminifera in the area has played a key role in these research efforts (e.g. Culver and Buzas, 1985; Patterson and Cameron, 1991; Patterson, 1993; Patterson and others, 1995; Guilbault and others, 1997; Patterson and others, 2000). For example, abrupt climatic events like the Younger Dryas cold event are clearly recognizable on the British Columbia coast based on benthic foraminiferal and palynological evidence (Mathewes and others, 1993; Patterson and others, 1995). Other significant Quaternary events in this region recognizable with micropaleontological proxy data include fluctuations in sea-level in response to climatic changes and post glacial isostatic rebound (Friele and Hutchinson, 1993; Clague and Mathewes, 1996; Cowan and others, 1996; Hutchinson and others, 1997; Hutchinson and others, 1998; Luternauer and others, 1989; Reinhardt and others, 1996).

Within Saanich Inlet, Blais-Stevens and Patterson (1998) identified benthic foraminiferal assemblages from recent sediments representing distinct sub-environments. This information was utilized to assess the intensity, genesis, and periodicity of earthquake generated turbidity currents for the latest Holocene within the basin (Blais-Stevens and others, 1997, 2001; Blais-Stevens and Clague, 2001). The objective of this study is to examine the foraminiferal faunas within these ODP cores to characterize the paleoceanographic history of the inlet and surrounding water masses.

SAANICH INLET AND ITS SEDIMENTS

Saanich Inlet is a 26 km long and 0.4 to 7.6 km wide anoxic fjord on the southeast coast of Vancouver Island (Fig. 1). The inlet is a single basin separated from the oceanic

---

[1] E-mail: tpatters@ccs.carleton.ca

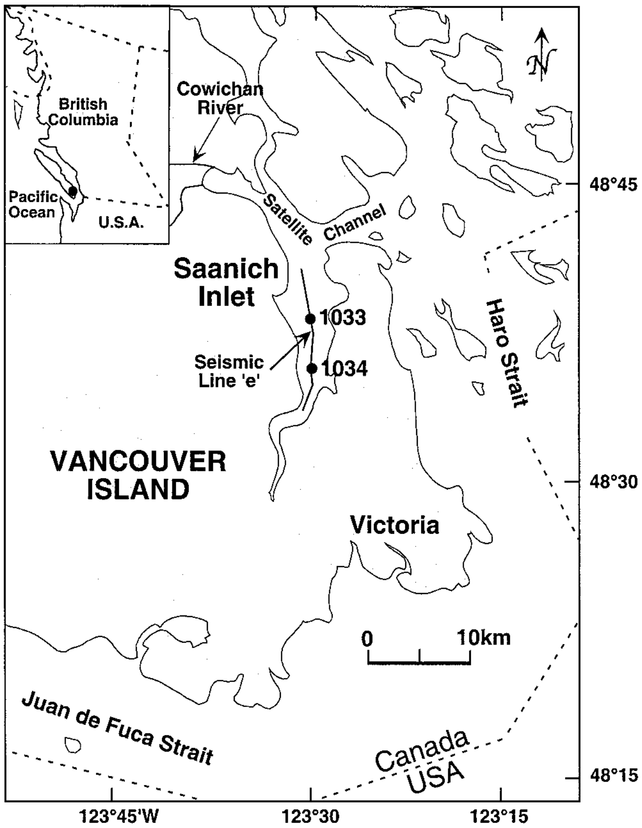

FIGURE 1. Map of Saanich Inlet showing location of ODP Sites 1033 and 1034. Line through sites 1033 and 1034 indicates location of seismic profile shown in Figure 2.

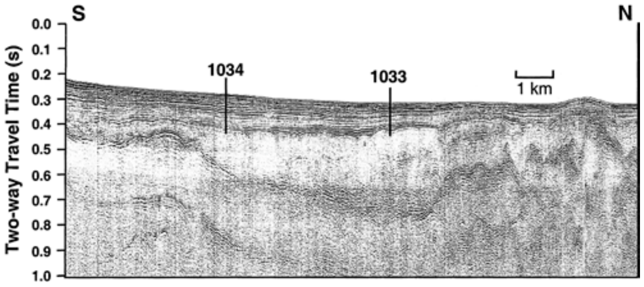

FIGURE 2. Single channel seismic Profile 'e' (151/0708-0852) through sites 1033 and 1034 (adapted after Bornhold and others, 1998). See Figure 1 for transect location.

waters of Haro Strait by a bedrock sill at the north end in Satellite Channel (Holland, 1980). The average depth of the inlet is 120 m and its maximum depth is 238 m. The sill at the mouth of the inlet rises to 70 m below the water surface, restricting deep-water circulation. The mean tidal range in Saanich Inlet and Haro Strait is 2.4 m with large tides ranging up to 3.9 m (R. E. Thomson, written communication, 2001).

The lower part of the water column, below 70 m is dysoxic (0.1–0.3 ml/l [4.4–13.3 μM]) to anoxic (0–0.1 ml/l [0–4.4 μM]; Blais-Stevens and others, 2001). High primary productivity in the inlet during spring and summer, sluggish estuarine circulation, and the presence of abundant fresh water from the Fraser River discharging from the mainland into Haro Strait contribute to the development of bottom water anoxia almost year round in the inlet. This anoxia leads to an almost complete absence of benthic fauna, thus preserving the seasonal depositional record of fine laminae that alternate between plankton fall and terrigenous sediments (Blais-Steven and others, 2001).

The distribution of the various modern sediment types and sedimentary environments in this basin along with their associated foraminiferal biofacies have been documented by Blais (1995) and Blais-Stevens and Patterson (1998). These data have been invaluable in identifying the source of various foraminiferal species found in the Saanich Inlet cores.

The sediments draping Saanich Inlet were deposited during the Wisconsinan glaciation and subsequent Holocene deglaciation (Blais-Stevens and others, 2001) and have been widely studied in land-exposed sections (Blyth and Rutter, 1993; Blyth and others, 1993; Clague, 1994; Huntley and others, 2001). However, the low-oxygen environment within Saanich Inlet archives a much higher quality record than was previously available (Fig. 2). Two distinct sedimentary units were identified at sites 1033B and 1034B (Fig. 3). Late Pleistocene sediments (>70 meters below sea floor (mbsf) at Site 1034 and >50 mbsf at Site 1033) are irregularly to non laminated glaciomarine mud, rich in terrestrial organic matter (>12 k yr BP) and were deposited under oxygenated conditions (Cowan, 2001). These units also contain poorly sorted sand lenses and dropstones, as well as graded and contorted sand and silt beds (Bornhold and others, 1998). The overlying earliest Holocene sediments are poorly laminated and contain a rich bivalve fauna suggesting a period of 2–3 thousand years of well oxygenated waters during the earliest Holocene (Blais-Stevens and others, 2001; Bornhold and others, 1998).

Most subsequent Holocene sediments are well-laminated hemipelagic sediments, deposited under conditions of moderately high marine primary productivity in the surface waters as indicated by abundant diatom remains and anoxic conditions at the ocean floor (Bornhold and others, 1998; Hobson and McQuoid, 2001; McQuoid and Hobson, 2001; McQuoid and others, 2001). Such rhythmically laminated varved sediments can archive ultra-high resolution information, providing valuable data on seasonal scale processes as well as intra- and inter-annual variability (Kemp, 1996; Blais-Stevens and others, 2001). Each laminated sequence consists of "triplets" of thin dark gray terrigenous mud, gray terrigenous mud, and light olive laminae of diatom ooze (Bornhold and others, 1998). The observed sequence can be correlated to varying depositional conditions during late fall and winter, early spring, and late spring and summer. The thicknesses of the annual packages vary considerably (5–9 mm) reflecting changes in the amount and seasonal distribution of runoff in nearby watersheds, and variation in primary productivity (Gross and others, 1963; Gucluer and Gross, 1964; Sancetta and Calvert, 1988; Bobrowsky and Clague, 1990; Blais-Stevens and others, 1997; Bornhold and others, 1998). Varves tend to be thicker (9 mm) in the northern part of the inlet than in the southern (5 mm) part confirming that a major source of sediments in the basin is the Cowichan River watershed at the north end of the inlet (Blais-Stevens and others, 2001). SEM sediment fabric studies have identified evidence of micro-benthic bio-

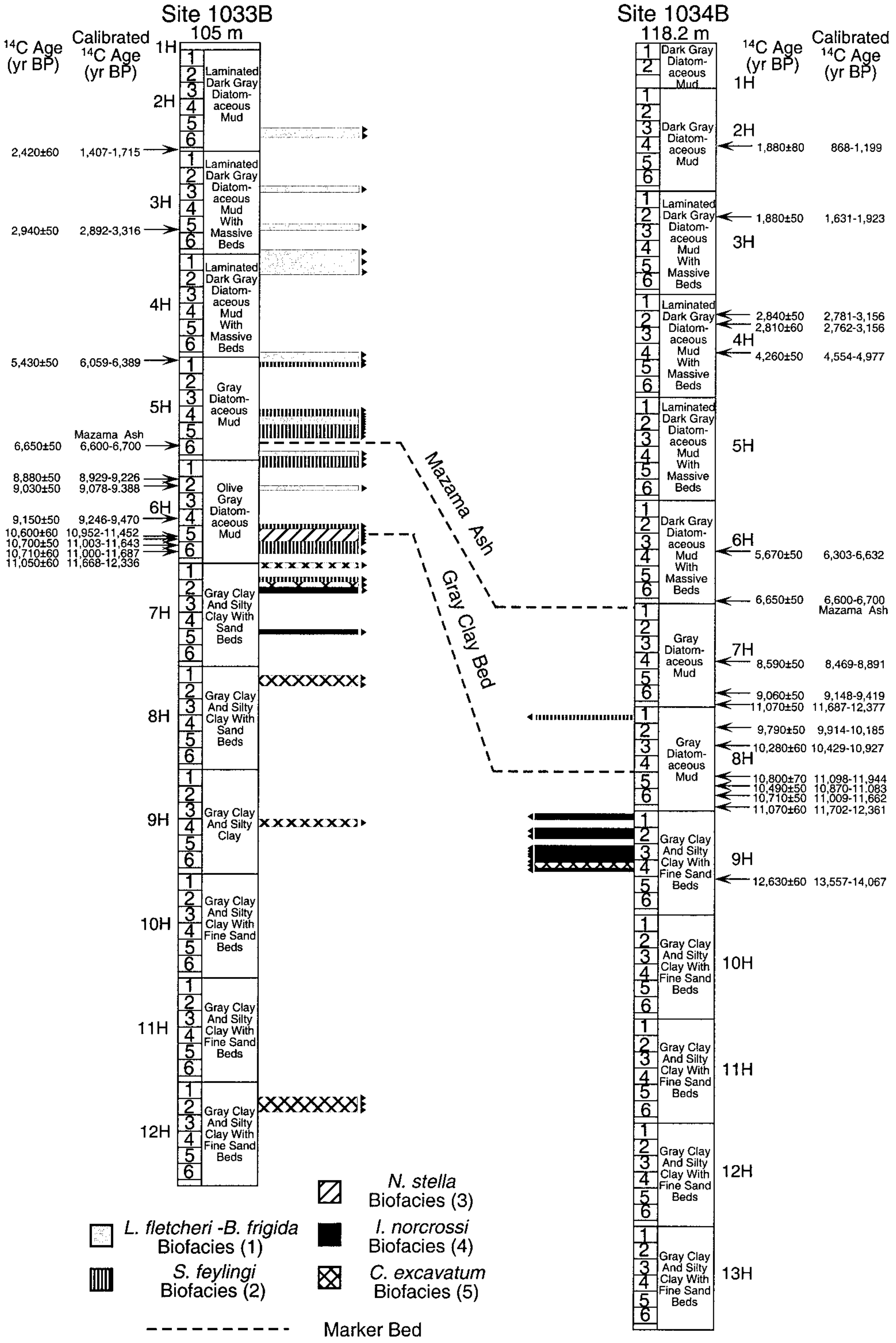

FIGURE 3. Late Quaternary lithology, chronology, and foraminiferal biofacies for cores recovered from ODP Sites 1033B and 1034B. Stratigraphy and chronology after Blais-Stevens and others (2001).

turbation, probably during episodes of bottom water renewal resulting from the flow of oxygenated, higher salinity, oceanic water over the sill (Dean and others, 2001).

Within the Holocene laminated mud interval of the cores there is a massive unit comprised of gray terrigenous clay with a sharp lower contact that grades upward into diatomaceous mud in Site 1034, core 6H-5, 67–123 cm. There is palynological and silicoflagellate evidence indicating considerable terrestrial input of nutrients and fresh water during its deposition (Melissa McQuoid, written communication, 1999). This interval has been interpreted as a massive flood event at 11 k yr BP (Bornhold and others, 1998).

Periodically interbedded with the varved sediments are less prominent massive layers that record evidence of major earthquakes in the region during the past over 7,000 years. The uppermost of these units has been correlated with an AD 1946 large crustal earthquake on central Vancouver Island (Blais-Stevens and others, 1997). A unit correlable with the AD 1700 great earthquake on Cascadia Subduction Zone is also recognized (Blais-Stevens and others, 1997). The 6,650±50 yrs BP eruption of Mount Mazama (Crater Lake), Oregon, USA, is recognizable as a 1.5–2.0 cm thick white volcanic ash layer at 37 mbsf at Site 1033B and 51 mbsf at Site 1034B (Blais-Stevens and others, 2001).

METHODS

SAMPLING AND CLUSTER ANALYSIS

Sub-sampling for this research was done at the Pacific Geoscience Centre (PGC), Sydney, British Columbia. A total of 423 sand fraction samples were analyzed; 254 from the twelve cores (1H–12H) of Site 1033B, and 169 from the thirteen cores (1H–13H) from Site 1034B. Details on core depths, lithology and ^{14}C dates are provided in Figure 3. Samples for foraminiferal analysis were washed over a 63 μm sieve to remove fines and dried at low temperature. The resultant sample residues were usually very small ranging from 0.001 g to 0.7 g out of 15 cc of core processed. Some processed samples did not have any measurable sand fraction while even fewer contained >1.0 g of sand fraction.

All foraminifera in each sample were picked and transferred to slides for subsequent identification. The number of foraminifera, total number of complete specimens, total number of broken/damaged specimens, and number of specimens of various foraminiferal species were recorded for all 423 samples (downloadable portable document format [pdf] appendices [Appendix PDF 1 and Appendix PDF 2] for cores 1033B and 1034B respectively are available in the data repository at www.carleton.ca/~tpatters). Selected specimens were digitally photographed at the Carleton University Research Facility for Scanning Electron Microscopy (CURFEM) and are illustrated in Plates 1 and 2. Identification of foraminifera followed Patterson and others (1998).

Patterson and Fishbein (1989) recommended a minimum count of at least 50 specimens for indicator species having a fractional abundance of 50% or greater and up to several hundred counts for samples with less dominant taxa. Out of 423 samples, only 58 samples fulfilled these criteria with the balance being either barren or containing too few specimens. The fractional abundance and standard error associated with each taxon in these 58 samples was calculated using the standard error equation (S_{xi}):

$$S_{x_i} = 1.96\sqrt{\frac{x_i(1 - x_i)}{N}}$$

where N → is the total number of specimens in a sample,
x → is the fractional abundance of a given species (Table 1; Patterson and Fishbein, 1989).

Q-mode cluster analysis was carried out on the 58 samples with significant populations using a technique that closely emulates results from the statistically significant ''error weighted maximum likelihood'' clustering method of Fishbein and Patterson (1993). This method requires that only species present in statistically significant populations be analyzed. Although a total of 41 species of benthic foraminifera were identified, only 22 species were common enough to be used for cluster analysis (Table 1). Q-mode cluster analysis was carried out on the 22 statistically significant species in these 58 samples using SPSS version 6.1 for Apple Macintosh. Euclidean distance correlation coefficients were used to measure similarity between pairs of species, and Ward's linkage method was utilized to arrange sample pairs and sample groups into a hierarchic dendrogram (Fig. 4).

R-mode cluster analysis was carried out on the 22 species present in statistically significant numbers as well as the collective category of planktic foraminifera using the same methodology as employed for the Q-mode analysis.

The population diversity for each of the 58 samples was calculated using the Shannon Diversity Index (Sageman and Bina, 1997):

$$S.I. = -\sum_{i=1}^{S}\left(\frac{X_i}{N_i}\right) \times \ln\left(\frac{X_i}{N_i}\right)$$

where X_i → is the abundance of each taxon in a sample,
N_i → is the total abundance of the sample, and
S → is equal to the species richness of the sample.

^{14}C DATING

^{14}C ages for samples from sites 1033B and 1034B were obtained at Lawrence Livermore Laboratory and are indicated in Table 2 and stratigraphically in Figure 3. The reservoir correction value applied is 801±23 years as determined by Robinson and Thomson (1981) using samples collected in Sooke, B.C. on the south-southwest coast of Vancouver Island.

Since Saanich Inlet is on the southeast coast of the island it may receive old carbon from sources different from those at Sooke though. To verify the relationship Bornhold and others (1998) tested wood/shell sample pairs from Saanich Inlet, obtaining a value of 798±50 years. As this value is very close to the published value of 801±23 (Robinson and Thomson, 1981) we use the literature value for the reservoir correction of all marine radiocarbon ages presented here. This practice was also followed by all other researchers examining these same ODP cores from Saanich Inlet (see contained papers in Marine Geology, 2001, v. 174; Blais-Stevens and Clague, 2001).

RESULTS

The observed foraminiferal taxa were predominantly calcareous, benthic forms. Planktic foraminifera were usually rare, although in a few varves and laminated samples from cores 3H-3, 4H-2, 5H-2, 5H-5 and 5H-7 at Site 1033B they occurred in significant numbers (10–50% of the sample assemblage; Table 1). Rare specimens of arcellaceans, freshwater foraminiferal analogues, were also observed, but only in massive layers.

TABLE 1. Total abundance (number per 15 cc of sediment), fractional abundance, standard error, biofacies assignment, and Shannon Diversity Index of taxonomic units and samples with statistically significant populations.

Site	1033B	1033B	1033B	1033B	1033B	1033B	1033B	1033B	1033B	1033B	1033B	1033B	1033B	1033B	1033B
Section	2H5	2H5	2H6	3H3	3H5	3H7	4H1	4H1	4H2	4H7	5H1	5H1	5H4	5H4	5H4
Horizon (cm)	139–140	146–149	060–063	067–070	124–126	076–079	042–045	140–142	051–054	077–079	060–063	070–074	094–097	106–109	115–118
Total specimens	186	56	63	50	66	50	51	69	60	63	52	108	52	51	63
Shannon Diversity	1.684	1.770	1.881	1.987	2.073	2.002	1.787	0.909	1.599	1.950	1.479	0.840	1.678	0.994	1.595
Biofacies	2	1	1	1	1	1	1	1	1	1	1	2	2	2	1
C. excavatum	0.129	0.214	0.175	0.180	0.152	0.160	0.157	0.029	0.167	0.127	0.000	0.028	0.038	0.000	0.095
standard error ±	0.048	0.107	0.094	0.106	0.087	0.102	0.100	0.040	0.094	0.082	0.000	0.031	0.052	0.000	0.072
C. halladense	0.016	0.054	0.016	0.040	0.045	0.100	0.020	0.000	0.017	0.032	0.000	0.000	0.000	0.000	0.048
standard error ±	0.032	0.043	0.000	0.000	0.000	0.000	0.053	0.015	0.011	0.000	0.054	0.000	0.027	0.000	0.000
C. foraminosum	0.000	0.000	0.032	0.020	0.030	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
standard error ±	0.000	0.000	0.043	0.039	0.041	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
B. frigida	0.065	0.286	0.302	0.220	0.273	0.240	0.255	0.522	0.183	0.254	0.154	0.028	0.192	0.137	0.492
standard error ±	0.035	0.118	0.113	0.115	0.107	0.118	0.120	0.118	0.098	0.107	0.098	0.031	0.107	0.094	0.123
L. fletcheri	0.161	0.196	0.159	0.060	0.227	0.160	0.275	0.420	0.267	0.238	0.385	0.056	0.135	0.118	0.190
standard error ±	0.053	0.104	0.090	0.066	0.101	0.102	0.122	0.116	0.112	0.105	0.132	0.043	0.093	0.088	0.097
S. feylingi	0.452	0.071	0.175	0.040	0.045	0.180	0.000	0.000	0.017	0.190	0.077	0.787	0.500	0.667	0.063
standard error ±	0.072	0.067	0.094	0.054	0.050	0.106	0.000	0.000	0.032	0.097	0.072	0.077	0.136	0.129	0.060
B. eligantissima	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
standard error ±	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fissurina spp.	0.048	0.054	0.000	0.020	0.030	0.020	0.000	0.000	0.000	0.079	0.000	0.028	0.000	0.000	0.048
standard error ±	0.031	0.059	0.000	0.039	0.041	0.039	0.000	0.000	0.000	0.067	0.000	0.031	0.000	0.000	0.053
Trochammina spp.	0.081	0.125	0.079	0.000	0.076	0.060	0.098	0.000	0.017	0.000	0.000	0.000	0.135	0.000	0.000
standard error ±	0.039	0.087	0.067	0.000	0.064	0.066	0.082	0.000	0.032	0.000	0.000	0.000	0.093	0.000	0.000
N. stella	0.000	0.000	0.016	0.020	0.015	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.016
standard error ±	0.000	0.000	0.031	0.039	0.029	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.031
B. pacifica	0.016	0.000	0.016	0.020	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.077	0.000	0.000
standard error ±	0.018	0.000	0.031	0.039	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.072	0.000	0.000
S. agglutinata	0.000	0.000	0.000	0.020	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
standard error ±	0.000	0.000	0.000	0.039	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
M. fusca	0.000	0.000	0.000	0.000	0.015	0.020	0.000	0.000	0.000	0.000	0.000	0.000	0.019	0.078	0.016
standard error ±	0.000	0.000	0.000	0.000	0.029	0.039	0.000	0.000	0.000	0.000	0.000	0.000	0.037	0.074	0.031
I. helenae	0.016	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.032
standard error ±	0.018	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.043
I. norcrossi	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
standard error ±	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C. reniformae	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
standard error ±	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
N. labradorica	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
standard error ±	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S. tenuis	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
standard error ±	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C. microgranulosum	0.000	0.000	0.000	0.000	0.045	0.000	0.020	0.000	0.017	0.032	0.000	0.000	0.019	0.000	0.000
standard error ±	0.000	0.000	0.000	0.000	0.050	0.000	0.038	0.000	0.032	0.043	0.000	0.000	0.037	0.000	0.000
Buliminella sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
standard error ±	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
N. digitata	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
standard error ±	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Rosalina spp.	0.000	0.000	0.000	0.020	0.015	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
standard error ±	0.000	0.000	0.000	0.039	0.029	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Planktics	0.016	0.000	0.032	0.340	0.000	0.020	0.137	0.029	0.317	0.127	0.154	0.000	0.000	0.000	0.000
standard error ±	0.018	0.000	0.043	0.131	0.000	0.039	0.094	0.040	0.118	0.082	0.098	0.000	0.000	0.000	0.000

Q-mode cluster analysis resulted in the recognition of five biofacies (Figs. 3, 4). While only 58 of the 423 samples examined contained statistically significant populations these biofacies were concentrated together in specific parts of the cores and therefore provided valuable paleoceanographic proxy data. In addition, the faunal makeup of adjacent samples with non-statistically significant populations tended to be similar, permitting qualitative comparison. Although most samples contained at least a few specimens, many samples, especially in the late Pleistocene sections, were barren of specimens (≤5). The number of barren samples in cores 7H through 12H at Site 1033B and in cores 7H through 13H at Site 1034B was 89 and 86 respectively (see downloadable pdf appendices PDF1 and PDF2 at www.carleton.ca/~tpatters).

BIOFACIES AS BASED ON Q-MODE ANALYSIS RESULTS

The biofacies described below are named for the most abundant species in each cluster and further defined on the basis of additional species present. The more abundant species usually occur in all samples comprising a cluster, although there are some exceptions. Ages given are calibrated ^{14}C AMS dates.

Lobatula fletcheri–Buccella frigida *Biofacies (Biofacies 1; Figs. 3, 4)*

This biofacies (16 samples) is dominated by *Buccella frigida* (Cushman), 1922, (18–52%) and *Lobatula fletcheri* (Galloway and Wissler), 1927, (6–38%). Other commonly occurring species are *Cribroelphidium excavatum* (Ter-

TABLE 1. Extended.

1033B 5H5 002–005 560 1.641 1	1033B 5H5 008–011 1088 1.762 1	1033B 5H5 014–017 736 1.759 1	1033B 5H5 058–062 50 1.434 2	1033B 5H5 064–068 132 0.650 2	1033B 5H5 068–072 102 1.468 2	1033B 5H5 074–078 114 1.244 2	1033B 5H5 113–116 104 1.352 2	1033B 5H7 052–055 104 1.157 1	1033B 5H7 057–060 120 0.977 2	1033B 5H7 067–070 64 0.900 2	1033B 6H1 057–060 152 1.485 2	1033B 6H2 145–148 184 1.366 1
0.241	0.191	0.239	0.220	0.045	0.196	0.000	0.000	0.077	0.000	0.000	0.263	0.109
0.035	0.023	0.031	0.115	0.036	0.077	0.000	0.000	0.051	0.000	0.000	0.070	0.045
0.036	0.037	0.000	0.040	0.000	0.020	0.000	0.000	0.000	0.000	0.000	0.039	0.000
0.000	0.000	0.000	0.031	0.000	0.000	0.048	0.031	0.000	0.015	0.000	0.000	0.000
0.009	0.007	0.000	0.000	0.000	0.020	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.008	0.005	0.000	0.000	0.000	0.027	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.357	0.360	0.217	0.240	0.182	0.059	0.263	0.231	0.231	0.267	0.125	0.211	0.500
0.040	0.029	0.030	0.118	0.066	0.046	0.081	0.081	0.081	0.079	0.081	0.065	0.072
0.241	0.191	0.304	0.000	0.000	0.000	0.105	0.000	0.000	0.000	0.000	0.000	0.261
0.035	0.023	0.033	0.000	0.000	0.000	0.056	0.000	0.000	0.000	0.000	0.000	0.063
0.063	0.132	0.087	0.360	0.773	0.471	0.421	0.308	0.154	0.467	0.625	0.368	0.065
0.020	0.020	0.020	0.133	0.071	0.097	0.091	0.089	0.069	0.089	0.119	0.077	0.036
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.067	0.000	0.000	0.022
0.000	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.045	0.000	0.000	0.021
0.000	0.007	0.000	0.000	0.000	0.000	0.053	0.000	0.000	0.000	0.000	0.000	0.022
0.000	0.005	0.000	0.000	0.000	0.000	0.041	0.000	0.000	0.000	0.000	0.000	0.021
0.009	0.015	0.022	0.000	0.000	0.000	0.000	0.308	0.000	0.067	0.000	0.053	0.000
0.008	0.007	0.011	0.000	0.000	0.000	0.000	0.089	0.000	0.045	0.000	0.035	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.053	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.035	0.000
0.009	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.008	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.009	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.008	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.009	0.029	0.022	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.022
0.008	0.010	0.011	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.021
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.015	0.065	0.120	0.000	0.176	0.158	0.154	0.538	0.133	0.250	0.000	0.000
0.000	0.007	0.018	0.090	0.000	0.074	0.067	0.069	0.096	0.061	0.106	0.000	0.000

quem), 1876, *Buliminella elegantissima* (d'Orbigny), 1839, *Nonionella stella* (Cushman and Moyer), 1930, *Stainforthia feylingi* (Knudsen and Seidenkrantz), 1994, *Cribroelphidium halladense* (Brotzen), 1945, *Cribroelphidium foraminosum* (Cushman), 1939 and various *Fissurina* spp. This biofacies is also characterized by the common occurrence of planktic foraminifera (up to 34% in some samples). The average Shannon Diversity Index value for samples from this biofacies is 1.670. To put this value and those obtained for the other biofacies in perspective, Shannon Diversity index values obtained for more stable environments under optimal conditions are usually in the 2.5–3.5 range, whereas low values of 0.1–1.5 are obtained where there is environmental stress (Sageman and Bina, 1997). All biofacies discussed here had relatively low Shannon Diversity Index values indicating deposition under sub-optimal conditions.

The *Lobatula fletcheri–Buccella frigida* Biofacies biofacies was found exclusively in Core 1033B in sediments laid down little more than 1000 Years BP in laminated dark gray diatomaceous mud, to progressively more massive diatomaceous muds deposited 9,400 years BP. Foraminifera were not as abundant in these samples as in other biofacies but one sample did have a population of over 1,000 specimens.

Stainforthia feylingi *Biofacies (Biofacies 2; Figs. 3, 4)*

This biofacies (18 samples) is dominated by *S. feylingi* accounting for 26 to 97% of the assemblage and *B. frigida*

TABLE 1. Extended.

1033B 6H5 007–010 120 1.640 2	1033B 6H5 016–019 69 1.573 2	1033B 6H5 024–027 176 1.427 3	1033B 6H5 057–061 180 0.811 3	1033B 6H5 070–073 528 1.379 3	1033B 6H5 126–129 88 0.474 3	1033B 6H6 029–032 104 0.790 2	1033B 6H6 127–130 224 0.257 2	1033B 7H1 029–032 1760 1.110 5	1033B 7H2 008–011 219 0.145 2	1033B 7H2 059–062 262 1.259 5	1033B 7H2 110–113 134 2.436 4	1033B 7H5 029–031 237 1.270 4	1033B 8H1 127–130 57 1.034 5	1033B 8H2 029–032 137 1.360 5
0.133	0.087	0.182	0.033	0.167	0.182	0.000	0.000	0.668	0.014	0.534	0.194	0.165	0.070	0.197
0.061	0.066	0.057	0.026	0.032	0.081	0.000	0.000	0.022	0.015	0.060	0.067	0.047	0.066	0.067
0.000	0.043	0.045	0.000	0.030	0.000	0.000	0.000	0.036	0.000	0.061	0.030	0.051	0.018	0.058
0.009	0.000	0.029	0.029	0.028	0.034	0.039	0.000	0.048	0.095	0.000	0.000	0.000	0.000	0.032
0.000	0.000	0.000	0.000	0.015	0.000	0.000	0.000	0.023	0.000	0.015	0.000	0.013	0.018	0.000
0.000	0.000	0.000	0.000	0.010	0.000	0.000	0.000	0.007	0.000	0.015	0.000	0.014	0.034	0.000
0.200	0.130	0.000	0.000	0.023	0.000	0.231	0.071	0.073	0.000	0.015	0.075	0.051	0.000	0.000
0.072	0.079	0.000	0.000	0.013	0.000	0.081	0.034	0.012	0.000	0.015	0.044	0.028	0.000	0.000
0.000	0.130	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.000	0.000	0.030	0.000	0.000	0.000
0.000	0.079	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.029	0.000	0.000	0.000
0.333	0.391	0.227	0.433	0.000	0.000	0.692	0.929	0.164	0.973	0.008	0.119	0.000	0.000	0.000
0.084	0.115	0.062	0.072	0.000	0.000	0.089	0.034	0.017	0.022	0.011	0.055	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.043	0.000	0.000	0.008	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.048	0.000	0.000	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.067	0.000	0.045	0.000	0.000	0.000	0.000	0.000	0.005	0.000	0.000	0.000	0.139	0.000	0.000
0.045	0.000	0.031	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.044	0.000	0.000
0.200	0.000	0.455	0.533	0.568	0.818	0.077	0.000	0.000	0.000	0.000	0.030	0.000	0.000	0.022
0.072	0.000	0.074	0.073	0.042	0.081	0.051	0.000	0.000	0.000	0.000	0.029	0.000	0.000	0.025
0.000	0.000	0.000	0.000	0.068	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.013	0.000	0.000
0.000	0.000	0.000	0.000	0.022	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.000	0.000
0.067	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.004	0.090	0.000	0.684	0.547
0.045	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.015	0.007	0.048	0.000	0.121	0.083
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.221	0.269	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.075	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.164	0.152	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.063	0.046	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.045	0.000	0.008	0.000	0.000	0.000	0.027	0.000	0.076	0.000	0.000	0.000	0.000
0.000	0.000	0.031	0.000	0.007	0.000	0.000	0.000	0.008	0.000	0.032	0.000	0.000	0.000	0.000
0.000	0.130	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.008	0.000	0.000	0.000	0.000
0.000	0.079	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.114	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.158	0.058
0.000	0.000	0.000	0.000	0.027	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.095	0.039
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.063	0.053	0.102
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.031	0.058	0.051
0.000	0.043	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.048	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

which accounts for 7 to 71% of the assemblage. Other common species include *L. fletcheri, N. stella, Bolivinellina pacifica* (Cushman and McCulloch), 1942, *Fissurina* spp, *Trochammina* spp. and *Cribroelphidium* spp. The mean Shannon Diversity Index of samples in this biofacies is 1.167.

This biofacies was found in gray diatomaceous mud deposited 6,000–12,500 years before present (BP) in Core 1033B and in a single sample deposited prior to 9,150 years BP in Core 1034B.

Nonionella stella *Biofacies (Biofacies 3; Figs. 3, 4)*

This biofacies (4 samples) is dominated by *N. stella* (45–81%) and *S. feylingi* (0–43%). *Cribroelphidium excavatum, C. halladense* and *B. frigida* occur commonly while *B. pacifica, Nonionella digitata* (Nørvang), 1945, *Fissurina* spp., *Trochammina* spp. and *B. elegantissima* are rare. The average Shannon Diversity Index value for the biofacies is 1.023.

This biofacies is found exclusively in Core 1033B in olive gray diatomaceous mud deposited between about 9,500 and 11,000 years BP.

Islandiella norcrossi *Biofacies (Biofacies 4; Figs. 3, 4)*

This biofacies (12 samples) is dominated by *Islandiella norcrossi* (Cushman), 1933, (6–46%); *Islandiella helenae* (Feyling-Hansen and Buzas), 1976, (21–42%), and *Spirosigmoilina tenuis* (Czjzek), 1848, (8–43%). Other common species include *C. excavatum, C. foraminosum,* and *C. ren-*

TABLE 1. Extended.

1033B 12H2 025–028 100 4 5	1033B 12H2 079–082 290 1.447 5	1033B 12H2 128–131 90 1.495 5	1034B 8H1 140–143 604 1.897 2	1034B 9H1 046–049 64 1.297 4	1034B 9H2 015–018 58 1.529 4	1034B 9H2 045–048 60 1.783 4	1034B 9H3 062–065 249 1.832 4	1034B 9H3 097–100 94 1.585 4	1034B 9H3 102–105 56 0.959 4	1034B 9H3 108–110 188 1.655 4	1034B 9H3 125–128 132 1.380 4	1034B 9H4 028–031 63 1.543 4	1034B 9H4 038–041 80 1.030 5	1034B 9H4 048–051 50 0.637 4
0.560	0.414	0.333	0.000	0.094	0.172	0.150	0.193	0.043	0.000	0.085	0.167	0.143	0.500	0.360
0.097	0.057	0.097	0.000	0.071	0.097	0.090	0.049	0.041	0.000	0.040	0.064	0.086	0.110	0.133
0.000	0.224	0.300	0.000	0.000	0.000	0.000	0.072	0.000	0.000	0.043	0.000	0.000	0.000	0.000
0.000	0.000	0.029	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.120	0.034	0.133	0.000	0.000	0.000	0.000	0.205	0.000	0.000	0.064	0.000	0.000	0.000	0.000
0.064	0.021	0.070	0.000	0.000	0.000	0.000	0.050	0.000	0.000	0.035	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.119	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.026	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.258	0.000	0.000	0.100	0.000	0.000	0.000	0.000	0.000	0.000	0.200	0.000
0.000	0.000	0.000	0.035	0.000	0.000	0.076	0.000	0.000	0.000	0.000	0.000	0.000	0.088	0.000
0.000	0.000	0.000	0.245	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.034	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.053	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.018	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.106	0.000	0.000	0.000	0.000	0.064	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.025	0.000	0.000	0.000	0.000	0.049	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.073	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.021	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.200	0.207	0.133	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.078	0.047	0.070	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.344	0.241	0.200	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.116	0.110	0.101	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.040	0.103	0.100	0.000	0.000	0.000	0.000	0.217	0.362	0.429	0.255	0.288	0.238	0.300	0.000
0.038	0.035	0.062	0.000	0.000	0.000	0.000	0.051	0.097	0.130	0.062	0.077	0.105	0.100	0.000
0.000	0.000	0.000	0.119	0.063	0.276	0.200	0.181	0.234	0.464	0.362	0.409	0.238	0.000	0.640
0.000	0.000	0.000	0.026	0.059	0.115	0.101	0.048	0.086	0.131	0.069	0.084	0.105	0.000	0.133
0.000	0.017	0.000	0.020	0.063	0.069	0.150	0.060	0.149	0.107	0.085	0.000	0.000	0.000	0.000
0.000	0.015	0.000	0.011	0.059	0.065	0.090	0.030	0.072	0.081	0.040	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.095	0.000	0.000
0.000	0.000	0.000	0.006	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.029	0.072	0.000	0.000
0.000	0.000	0.000	0.000	0.438	0.241	0.233	0.072	0.149	0.000	0.085	0.121	0.286	0.000	0.000
0.000	0.000	0.000	0.000	0.122	0.110	0.107	0.032	0.072	0.000	0.040	0.056	0.112	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

iforme. The average Shannon Diversity Index value for this biofacies is 1.492.

This biofacies is found in gray clay and silty clay in both cores 1033B and 1034B. Deposition of this biofacies in Core 1033B is prior to about 12,000 years BP while in Core 1034B deposition is bracketed by ^{14}C dates indicating deposition between 12,000 and 14,000 years BP.

Cribroelphidium excavatum *Biofacies (Biofacies 5; Figs. 3, 4)*

This biofacies (8 samples) is generally dominated by *C. excavatum* (7–66%) and *Siphonaperta stalkeri* (Loeblich and Tappan), 1953, (0–68%). Other common species are *N. digitata, I. helenae, I. norcrossi* and *Rosalina* spp. Other rare species include *C. halladense, C. foraminosum, Cribroelphidium microgranulosum* (Galloway and Wissler) in Thalmann, 1951, *C. reniforme* and *N. stella*. The average Shannon Diversity Index value for the biofacies is 1.213.

This biofacies was deposited in silty clay and very fine sands in both cores 1033B and 1034B. Deposition was prior to 12,000 years BP in core 1033B. The single representative of the biofacies in Core 1034B and was deposited around 12,000 years BP as well.

SPECIES ASSOCIATIONS BASED ON R-MODE ANALYSIS RESULTS

R-mode cluster analysis revealed five major groupings of species and individual taxa with the relationships shown

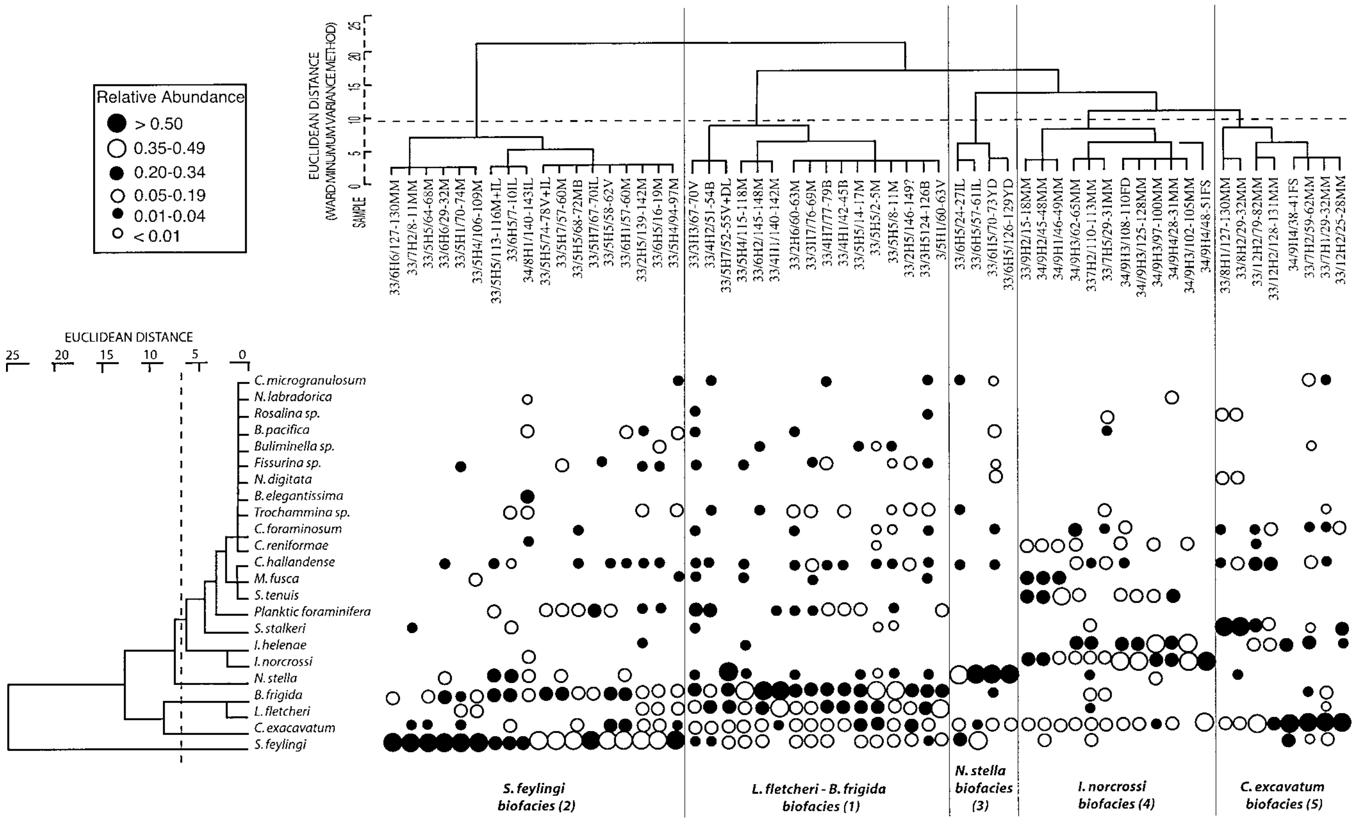

FIGURE 4. Integrated Q- and R-Mode cluster dendrograms utilizing 58 samples with statistically significant number of specimens and the 23 taxonomic units with statistically significant populations. For both the Q- and R-Mode clusters correlation coefficients greater than a selected level (dashed vertical line) are considered to indicate recognizable relationships.

closely matching those observed in the Q-Mode cluster analysis results (Fig. 4). *Stainforthia feylingi* groups separately from all others reflecting the overwhelming dominance of this species in the *Stainforthia feylingi* Biofacies (2), in which it has a mean abundance of 41.6%. There is a strong grouping of *B. frigida, L. fletcheri* and *C. excavatum* as appears in the *Lobatula fletcheri–Buccella frigida* Biofacies (1), in which these species average 30.3%, 22.3% and 14.5% respectively. The separation of *C. excavatum* from these other two species within the R-mode cluster analysis results reflect the high dominance of this species ($\bar{x}$ = 41.6%) in the *Cribroelphidium excavatum* Biofacies (5), in which *B. frigida* and *L. fletcheri* are absent. Although *N. stella* is found in all biofacies except Biofacies 5 it clusters separately from the balance of the species reflecting its dominance ($\bar{x}$ = 59.4%) in the *Nonionella stella* Biofacies (3). The rest of the taxa group together, in part a reflection of the more equitable distribution of species in the *Islandiella norcrossi* Biofacies (4). The absence of some taxa in this group, such as *B. elegantissima* and assorted fissurinids, from this biofacies is indicative of the relatively low abundance of all these taxa. The fact that they are present in generally low numbers causes them to artificially group together.

DISCUSSION

Sediments from cores 1033B and 1034B deposited prior to 13,000 years BP are nearly devoid of foraminifera. However, sedimentological analysis of these same core horizons, and from similarly aged land-exposed sites in the vicinity of Saanich Inlet, provide evidence that during that time much of the region was still covered with ice (Huntley and others, 2001). These researchers define this interval as the early to middle deglacial phase (15,000 to 13,000 years BP). During this time ice began to clear from the peaks and high ridges of Vancouver Island and was increasingly confined to valleys and coastal lowlands.

Isostatically depressed lowland areas surrounding Saanich Inlet were also inundated by the sea, and sea level in the region was higher relative to land than it is today with a late glacial marine limit of about 90 m amsl being reached in the Saanich Inlet area (Huntley and others, 2001). Increased oceanic influence to the inlet was largely offset by a massive influx of freshwater from retreating ice sheets. The large number of barren samples in the lower part of both cores is most likely related to the inhospitable foraminiferal habitat provided by the resultant very low salinity levels, as well as the relatively high sedimentation rates (Blais-Stevens and others, 2001).

Sediments deposited prior to ~12,000 years BP at Site 1033B and as old as ~14,000 years BP in core 1034B are variably comprised of massive gray silts interspersed with sandier units. The presence of dropstones and contorted silt and sand laminae in the interval provides evidence that this is a glaciomarine marine unit (Blais-Stevens and others, 2001). The *Cribroelphidium excavatum* Biofacies (5) that

TABLE 2. ^{14}C dates obtained at Lawrence Livermore Laboratory for samples from ODP Sites 1033B and 1034B presented in both radiocarbon years and corrected calendar years (see text for explanation). Reservoir correction value applied is 801 ± 23 years (after Robinson and Thomson, 1981).

Core section interval (cm)	Sample	Taxon	^{14}C age (yr BP)	Calibrated ^{14}C age (yr BP)
169S-1033B-				
2H-7, 28	Shell	Bivalvia *Compsomyax subdiaphana*	2,420 ± 60	1,407–1,715
3H-5, 144	Charcoal		2,940 ± 50	2,892–3,316
5H-1, 8	Charcoal		5,430 ± 50	6,059–6,389
6H2, 15	Shell	Bivalvia *Macoma calcarea*	8,880 ± 50	8,929–9,226
6H2, 60	Shell	Bivalvia *Axinopsida serricata*	9,030 ± 50	9,078–9,388
6H2, 90	Shell	Bivalvia *Axinopsida serricata*	9,150 ± 50	9,246–9,474
6H4, 110	Shell	Bivalvia *Axinopsida serricata*	10,190 ± 70	10,304–10,879
6H5, 135	Shell	Bivalvia *Macoma calcarea*	10,600 ± 60	10,952–11,452
6H5, 141	Shell	Bivalvia *Macoma calcarea*	10,700 ± 50	11,003–11,643
6H6, 13	Shell	Bivalvia *Macoma calcarea*	10,710 ± 60	11,000–11,687
6H6, 88	Shell	Bivalvia *Macoma calcarea*	11,050 ± 60	11,668–12,336
169S-1034B-				
2H-4, 118	Shell	Bivalvia *Mytilus edulis*	1,880 ± 80	868–1,199
3H-2, 113	Wood		1,880 ± 50	1,631–1,923
4H-2, 52	Wood		2,840 ± 50	2,781–3,156
4H-2, 108	Wood		2,810 ± 60	2,762–3,156
4H-4, 56	Wood		4,260 ± 50	4,554–4,977
6H-4, 3	Wood		5,670 ± 50	6,303–6,632
6H-CC, 0	Shell	Bivalvia *Macoma calcarea*	7,320 ± 50	7,271–7,471
7H-4, 107	Shell	Bivalvia *Macoma calcarea*	8,590 ± 50	8,469–8,891
7H-6, 129	Shell	Bivalvia *Macoma calcarea*	9,060 ± 50	9,148–9,419
7H-CC, 0	Shell	Bivalvia *Macoma calcarea*	11,070 ± 70	11,677–12,377
8H-2, 57	Shell	Bivalvia *Macoma calcarea*	9,790 ± 50	9,914–10,185
8H-3, 53	Shell		10,280 ± 60	10,429–10,927
8H-5, 16	Shell	Bivalvia *Macoma calcarea*	10,800 ± 70	11,098–11,944
8H-5, 134	Shell		10,490 ± 50	10,870–11,083
8H-6, 66	Shell		10,710 ± 50	11,009–11,662
8H-7, 10	Shell		11,070 ± 60	11,702–12,361
9H-5, 21	Shell	Bivalvia *Nuculana fossa*	12,630 ± 60	13,557–14,067

dominates this interval provides corroborative evidence of a glaciomarince origin for these sediments as indicated by the presence of key indicator species, *S. stalkeri, C. excavatum, C. reniforme* and *I. helenae.*

Siphonaperta stalkeri has previously been reported from courser substrates on the British Columbia shelf and in Holocene sediments from the Fraser River delta, thus explaining its presence in these silty and sandy samples (Patterson and Cameron, 1991; Patterson and others, 1995). *Cribroelphidium excavatum* is presently widely distributed at shallow depths in both temperate and polar seas (Phleger, 1952; Loeblich and Tappan, 1953; Hald and others, 1994; Patterson and others, 1995; Hald and Korsun, 1997; Korsun and Hald, 2000). It is also very common in late Pleistocene, and modern, glaciomarine deposits in higher latitude areas, at times comprising as much as 80% of the foraminiferal fauna (Hutchinson and others, 1998). The presence of this species has also been previously used to provide evidence that salinity during deposition was depressed (<35‰; Patterson and others, 1995). Thus the presence of high numbers of *C. excavatum* alone in these sediments is indicative of either cold, normal-salinity marine waters (the warm ice-margin fauna of Scott and others, 1989) or low salinity conditions. Definitive evidence of the glaciomarine origin of these sediments is the additional presence of *I. helenae* and *C. reniforme,* as both prefer Arctic-like conditions (Patterson and others, 1995; Korsun and Hald, 2000). The presence of these species provides evidence that oceanic conditions were very cool. *Cassidulina reniforme* may have been even more abundant in these samples if it was not so susceptible to dissolution (Patterson and others, 1995). *Islandiella helenae* was also very common in lower salinity regimes such as existed in the Champlain Sea and in modern glacial seas (Guilbault, 1989, 1993). Thus evidence provided by these species indicate that both water temperature and salinity was depressed during deposition, confirming the sedimentological evidence that sediments deposited prior to 12,000 years BP in Saanich Inlet were glaciomarine in origin.

The *Islandiella norcrossi* Biofacies (4) is concentrated within a single unit in both cores 1033B and 1034B and like the *Cribroelphidium excavatum* Biofacies (5) was deposited during the middle to late deglaciation phase between ~12,000 and 14,000 years BP. The flux of melt water and sediment into Saanich Inlet was maximal between 13,500 and 12,500 years BP as evidenced by the presence in the area of substantial glacial prodeltas of this age (Huntley and others, 2001). Even lower salinity conditions than found in the *Cribroelphidium excavatum* Biofacies (5) characterized these horizons, as clearly indicated by the dominance of *I. helenae* in these samples. The co-dominance of species such as *I. norcrossi, S. tenuis, I. helenae,* and *C. reniforme* that also occur in icy cold temperate waters and glacial marine sediments provide additional evidence of a low salinity subglacial environment (Vilks, 1980; Patterson and others, 1995; Guilbault and others, 1997).

The *Nonionella stella* Biofacies (3) (Fig. 4) was depos-

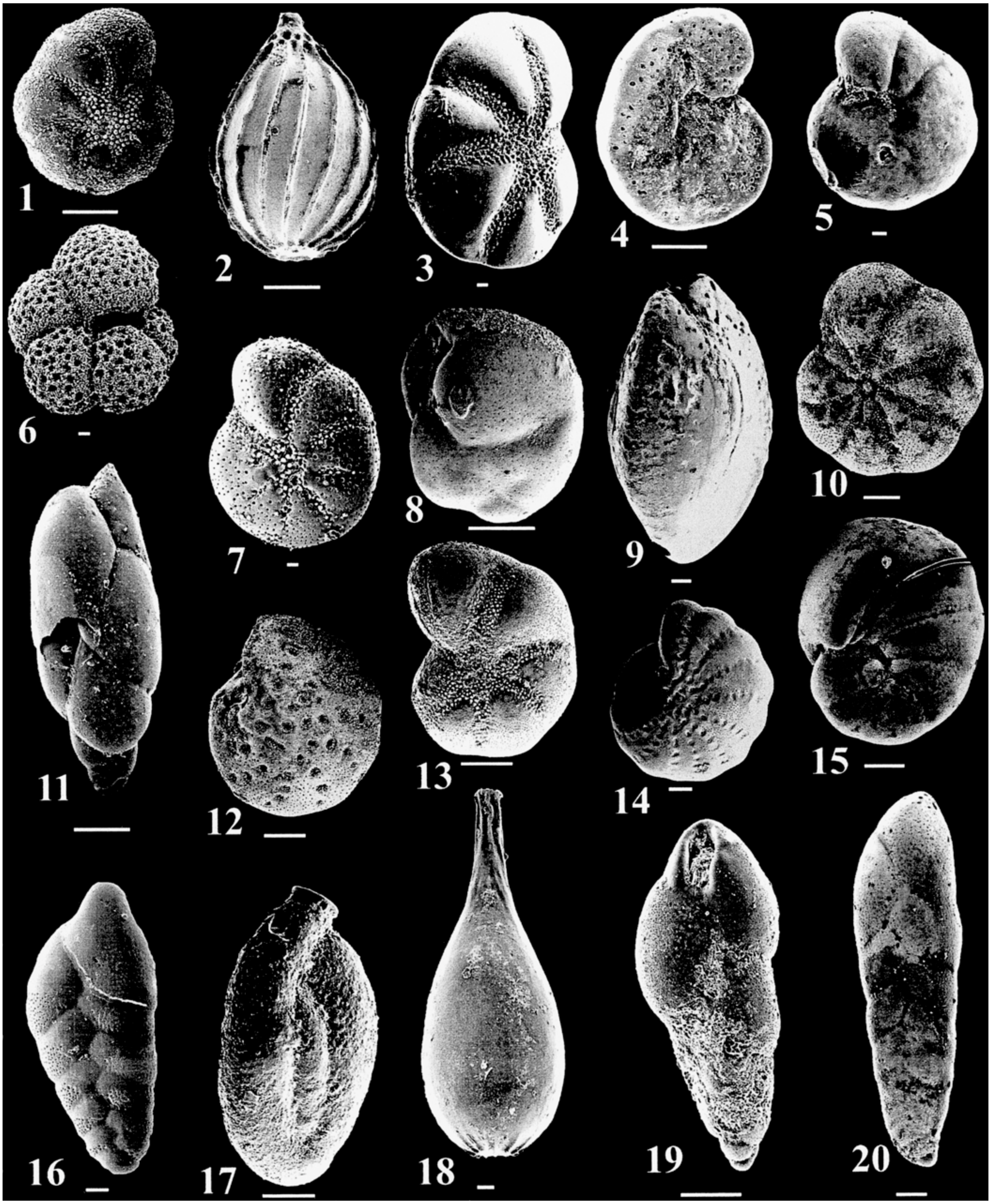

PLATE 1

Bar size: <0.5 cm = 10 μm; >0.5 cm = 100 μm. **1.** *Cribroelphidium excavatum* (Terquem); side view showing gently curved, incised sutures and pustules along sutures; × 300. **2.** *Homalohedra guntheri* (Earland); side view showing longitudinal costae and apertural neck; × 300. **3.** *Buccella frigida* (Cushman); ventral view showing pustule concentration along depressed sutures; × 400. **4.** *Lobatula fletcheri* (Galloway and Wissier); coarsely perforate spiral view; × 300. **5.** *Lobatula fletcheri* (Galloway and Wissier); dorsal view with only a few perforations; × 500. **6.** *Globigerina quinqueloba* Natland; typical of cool-water planktic foraminifera found in these samples; × 450. **7.** *Cribroelphidium excavatum* ited during the Late Pleistocene–early post-glacial phase (12,000 to 10,000 yr BP) of Huntley, and others (2001). By this time Cowichan Valley and adjacent parts of southeastern Vancouver Island had become free of ice (Alley and Chatwin, 1979; Huntley and others, 2001). As a result of the disappearance of ice the flux of meltwater and sediment markedly decreased. Relict wave-cut platforms and raised beaches, ranging in elevation from 5 to 20 m amsl, indicate that glacio-isostatic rebound continued well after deglaciation. By the time that the *Nonionella stella* Biofacies (3) came into being relative sea-level had fallen several tens of meters lower than today (Huntley and others, 2001). As a result water depth over the sill at north end of the Saanich Inlet was about 15 m lower than the 70 m present today resulting in circulation patterns much different than now (Huntley and others, 2001; Blais-Stevens and others, 2001).

This change was the result of Late Quaternary sea-level variations in the region that were governed by a combination of eustatic lowering, as well as isostatic loading and rebound, and persisted for several thousand years (Clague and others, 1982). It would seem that this lowering of sea level would have restricted circulation, and thus depressed oxygen levels, further in the basin. Although *N. stella*, the dominant species in this assemblage, is widely distributed on the continental shelf of western North America (Uchio, 1960; Stott and others, 1996; Patterson and others, 2000), Bernhard and others (1997) found that the species thrives in most oxygen-depleted sediments of the Santa Barbara Basin of the California Borderland. The presence of other species in the assemblage, less tolerant of reduced oxygen conditions, suggests that other factors must have been impacted circulation in the inlet as well.

At present the oceanography of the southern Strait of Georgia region, including Saanich Inlet, is controlled by a combination of surface discharge from the Fraser River, intrusion of partially mixed high salinity water from the Pacific through the Strait of Juan de Fuca and Haro Strait, and by the seasonally variable direction and strength of prevailing winds in the area (Thomson, 1981). Currents above the sill located at the entrance to the inlet are controlled by tidal and estuarine circulation. Exchange of bottom waters in the inlet with bottom waters in Haro Strait are severely limited because of this barrier. Thus, renewal of bottom waters in Saanich Inlet can only occur when surface salinities in Haro Strait exceed those of the bottom waters, a phenomenon that only occurs when freshwater input to the southern Strait of Georgia is at a minimum; usually at the end of the summer (Thomson, 1981). Palynological evidence suggests that terrestrial conditions were characterized by severe summer droughts, a reflection of greater-than-present summer solar radiation and less-than-present winter solar radiation (Mathewes, 1985; Hebda and Whitlock, 1997). Proxy palynological results suggest that temperatures in the area were up to 4°C warmer, and much drier, than at present during the peak warming between ~9000 and 7500 years BP. The resultant lower freshwater flow into the southern Strait of Georgia from the Fraser River would have created conditions conducive to increased injection of oxygenated water to bottom water areas of Saanich Inlet.

Changes in oceanic circulation through this interval are also indicated by the occurrence of planktic foraminifera in these cores for the first time through the horizons dominated by both the *Stainforthia felylingi* and *Lobatula fletcheria–Buccella frigida* biofacies (Fig. 4).

Species characteristic of the *Nonionella stella* biofacies are more temperate in character as indicated by the common occurrence of species such as *N. stella* and *C. halladense* (Patterson and others, 1995; Guilbault and others, 1997).

The deposition of the gray clay bed in the core 6H-5, 67–123 cm at Site 1033B, found within the interval containing the *Nonionella stella* Biofacies has been interpreted as a massive flood event at 11,000 yr BP caused by breakage of an ice dam (Bornhold and others, 1998). Bornhold and others (1998) concluded that because of similar periodic massive floodings the salinity of Saanich Inlet remained depressed. The foraminiferal fauna of this biofacies can easily tolerate such lowered salinities (Guilbault and others, 1997), and the low diversity of this fauna may provide some indication of the local oceanic instability that prevailed at the time.

Foraminiferal evidence of the Younger Dryas Cold episode (11,000–10,000 years BP) that occurred isochronous with deposition of the *Nonionella stella* Biofacies is scant here despite being well developed elsewhere on the British Columbia shelf (Mathewes and others, 1993; Patterson and others, 1995). The explanation for the lack of foraminiferal evidence is that key indicator species such as *C. reniforme, I. helenae* and *I. norcrossi*, useful YD event indicators elsewhere on the British Columbia shelf, do not occur in the *Nonionella stella* Biofacies due to the inhospitable conditions.

Sediments deposited between ~12,000 and 6,000 years BP became more distinctly laminated up core reflecting progressively declining oxygen levels. The predominant fauna found through this interval is the *Stainforthia feylingi* Biofacies (2). This fauna is almost identical to the *Lobatula fletcheri–Stainforthia feylingi* Subbiofacies of Blais-Stevens and Patterson (1998). This fauna is comprised of a mixture

---

←

(Terquem); side view showing gently curved, incised sutures and pustules along sutures; × 400. **8.** *Islandiella helenae* (Feyling-Hansen and Buzas); side view showing smooth surface and slitted aperture along periphery; × 350. **9.** *Siphonaperta stalkeri* (Loeblich and Tappan); side view showing terminal aperture; × 80. **10.** *Buccella depressa* (Anderson); umblical view showing straight sutures and perforated test; × 200. **11.** *Protoglobobulimina elongata* (d'Orbigny); side view showing distinct elongate test; × 300. **12.** *Cribroelphidium foraminosum* (Cushman); side view showing perforate surface and fossettes along suture; × 200. **13.** *Cribroelphidium hallandense* (Brotzen); side view showing pustules concentrated along sutures; × 300. **14.** *Cribroelphidium foraminosum* (Cushman); side view showing perforate surface and elongate fossettes along sutures; × 95. **15.** *Nonionella stella* (Cushman and Moyer); dorsal view showing straight to slightly curved sutures; × 200. **16.** *Bolivinellina pacifica* (Cushman and McCulloch); side view showing elongate test; × 250. **17.** *Spirosigmoilina tenuis* (Czjzek); side view showing lipped aperture atop elongated neck; × 270. **18.** *Lagena striatocollis* (d'Orbigny); side view showing poorly developed longitudinal costae restricted to neck and basal region; × 400. **19.** *Stainforthia feylingi* (Knudsen and Seidenkrantz); side view of elongate specimen showing distinct aperture and perforate surface; × 300. **20.** *Bolivinellina pacifica* (Cushman and McCulloch); side view showing elongate test; × 150.

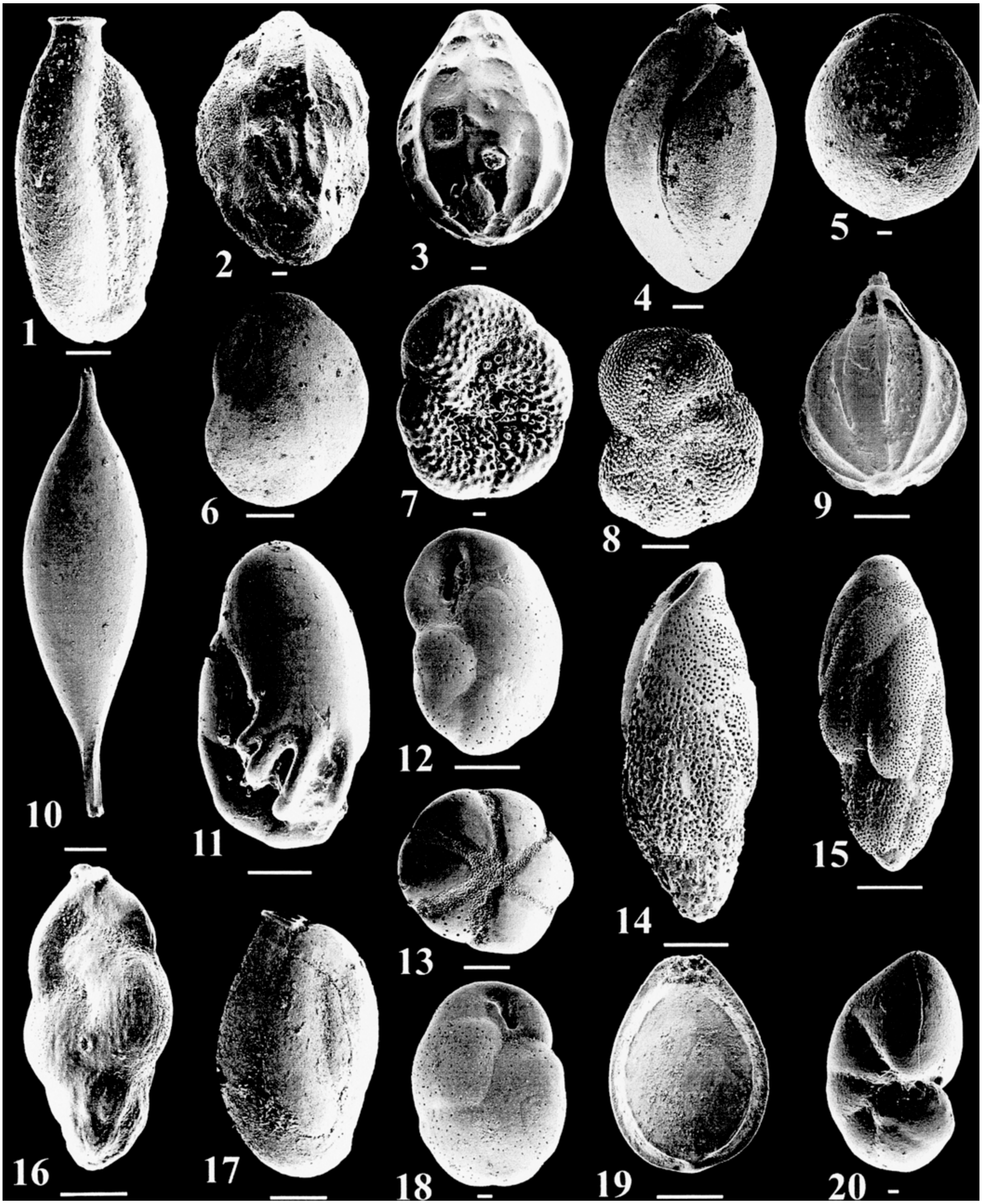

PLATE 2

Bar size: <0.5 cm = 10 μm; >0.5 cm = 100 μm. **1.** *Spirosigmoilina tenuis* (Czjzek); side view showing lipped aperture atop elongated neck; × 230. **2.** *Angulogerina angulosa* (Williamson); side view showing discontinuous longitudinal costae; × 600. **3.** *Favulina melo* (d'Orbigny); side view showing curved cross-hatched surface sculpture; × 500. **4.** *Siphonaperta stalkeri* (Loeblich and Tappan); side view showing terminal aperture with tooth; × 140. **5.** *Fissurina eburnea* (Buchner); side view showing almost circular profile; × 800. **6.** *Islandiella norcrossi* (Cushman); side of allochthonous (e.g. *L. fletcheri* and *B. frigida*) and autochthonous (primarily *S. feylingi*) components. The allochthonous taxa were supplied regularly via down slope transport where they mixed with the low diversity in-situ fauna (e.g., Alve, 1995). At the 90 m maximum depth where this modern fauna is found oxygen levels are typically in the suboxic (0.3–1.5 ml/l [13.3–67 μM]; see Kaiho, 1994) with mean values of around 0.5 ml/l (Herlinveaux, 1962). The dominant species in this fauna, *S. feylingi*, can persist under dysoxic (0.1–0.3 ml/l [4.4–13.3 μM] conditions (Patterson and others, 2000). However, the presence of possibly autochthonous, less low oxygen tolerant species such as *B. elegantissima* suggest that oxygen levels may have been higher than the minimum concentration required for *S. feylingi* to survive at the time of deposition. In a transect to progressively less well oxygenated levels in Effingham Inlet Patterson and others (2000) found that *B. elegantissima* became progressively less abundant and disappeared beneath 60 m where oxygen levels fell beneath the low oxic thresh hold of 1.5 ml/l (67 μM). Regardless of the absolute levels present during deposition, oxygen concentrations were depressed as further evidenced by the low Shannon Diversity Index value for this biofacies ($\bar{x}$ = 1.167%).

The uppermost 40–50 m of sediment in both cores 1033B and 1034B were deposited under primarily anoxic conditions as indicated by the varved sediments and low benthic foraminiferal fauna counts. The *Lobatula fletcheri–Buccella frigida* Biofacies (1) characterizing this interval is primarily allochthonous, being redeposited from shallower more oxygenated portions of the inlet. Although *S. feylingi* can live under very low oxygen conditions because this biofacies was found primarily in massive and brecciated layers, the fauna seems to have been mostly transported. For comparative purposes the fauna described here bears close similarity to the modern *Lobatula fletcheri–Buccella frigida* Subbiofacies of Blais-Stevens and Patterson (1998) described from modern bays around Saanich Inlet at 10–30 m water depths. However, the presence of significant numbers of *S. feylingi* ($\bar{x}$ = 8.5% and up to 19%) also suggests some similarity to the *Lobatula fletcheri–Stainforthia feylingi* Subbiofacies of Blais-Stevens and Patterson (1998) found in water depths of up to 90 m. As *S. feylingi* does not dominate the fauna in the biofacies discussed here the origin of the allochthonous fauna is probably derived from a range of shallower environments in the inlet.

SUMMARY

During the Late Pleistocene and earliest Holocene the distribution of benthic foraminiferal biofacies (*Cribroelphidium excavatum* (5), *Islandiella norcrossi* (4), and *Nonionella stella* (3)) in Saanich Inlet was strongly controlled by the influence of cold low salinity waters associated with deglaciation.

Early Holocene sediments are characterized by the *Stainforthia feylingi* Biofacies (2). Despite sea level being 15 m lower than at present, resulting in a sill depth at the entrance of Saanich Inlet of only 55 m, sedimentological evidence and the presence of this fauna indicate a minimum suboxic level of oxygenation. At present oxygen renewal in bottom waters can only occur in the inlet when surface water salinity exceeds those of bottom waters, a rare occurrence due to the strong influence of the Fraser River. During the early Holocene temperatures were up to 4°C warmer and much drier than at present resulting in reduced freshwater flow into the southern Strait of Georgia. This resulted in conditions conducive to the free exchange of Saanich Inlet bottom waters with those of well-oxygenated Haro Strait.

As the Holocene progressed the climate cooled in the area and by 7000 years BP, as the influence of freshwater from Strait of Georgia increased, the injection of oxygen into Saanich Inlet bottom waters became a progressively rare occurrence. The development of generally anoxic conditions at depth in Saanich Inlet was conducive to the development of finely laminated sediments. Once these restrictive modern oceanographic circulation conditions developed it became generally impossible for benthic foraminifera to inhabit the deeper anoxic portions of Saanich Inlet except during brief intervals following infrequent exchanges of bottom water with Haro Strait. The *Lobatula fletcheri–Buccella frigida* Biofacies (1) found in these sediments is allochthonous and derived by down slope transport from shallower more oxygenated regions of Saanich Inlet.

ACKNOWLEDGMENTS

This research was supported by a NSERC research grant and NSERC collaborative special grant to RTP. The authors thank Elizabeth Alve and Bob Thunell for their constructive criticism of the manuscript.

REFERENCES

ALLEY, N. F., and CHATWIN, S. C., 1979, Late Pleistocene history and geomorphology, southwestern Vancouver Island, British Columbia: Canadian Journal of Earth Sciences, v. 16, p. 1645–1657.

ALVE, E., 1995, Benthic foraminiferal distribution and recolonization of formerly anoxic environments in Drammensfjord, southern Norway: Marine Micropaleontology, v. 25, p. 169–186.

BERNHARD, J. M., SEN GUPTA, B. K., and BORNE, P. F., 1997, Benthic

---

←

view showing smooth surface and planispiral position of aperture; × 270. **7.** *Cribroelphidium microgranulosum* (Galloway and Wissler); side view showing granular surface and incised sutures; × 500. **8.** *Cribroelphidium microgranulosum* (Galloway and Wissler); side view showing granular surface and fossettes along sutures; × 250. **9.** *Homalohedra borealis* (Buchner); side view showing thick longitudinal costae extending from an apical ring to aperture; × 300. **10.** *Hyalinonetrion clavatum* (d'Orbigny); side view of smooth surfaced, elongate form; × 190. **11.** *Nonionella digitata* (Norvang); umbilical view showing distinctive fingerlike projections covering umbilical region; × 350. **12.** *Cassidulina reniforme* (Nørvang); edge view showing perforate surface and characteristic flap projecting into apertural opening; × 500. **13.** *Buccella frigida* (Cushman); ventral view showing pustule concentration along depressed sutures; × 250. **14.** *Buliminella elegantissima* (d'Orbigny); side view of elongate test with broad apertural opening and perforations all over the surface; × 350. **15.** *Buliminella elegantissima* (d'Orbigny); test surface showing perforations; × 350. **16.** *Euuvigerina juncea* (Cushman and Todd); × 350. **17.** *Siphonaperta stalkeri* (Loeblich and Tappan); side view showing terminal aperture with tooth; × 300. **18.** *Cassidulina reniformae* (Nørvang); edge view showing perforate surface and characteristic flap; × 500. **19.** *Palliolatella frangens* (Buchner); side view showing development of secondary carina along the margin of each test face; × 350. **20.** *Nonionella labradorica* (Dawson); apertural view showing characteristic broad flattened apertural face; × 450.

foraminiferal proxy to estimate dysoxic bottom-water oxygen concentrations: Santa Barbara Basin, U.S. Pacific continental margin: Journal of Foraminiferal Research, v. 27, p. 301–310.

Blais, A., 1995, Foraminiferal biofacies and Holocene sediments from Saanich Inlet, British Columbia: Implications for environmental and neotectonic research: unpublished Ph.D. dissertation, Carleton University, Ottawa, Ontario, Canada, 280 p.

Blais-Stevens, A., and Clague, J. J., 2001, Paleoseismic signature in late Holocene sediment cores from Saanich Inlet, British Columbia: Marine Geology, 175: 131–148.

Blais-Stevens, A., Bornhold, B. D., Kemp, A. E. S., Dean, J. M., and Vaan, A. A., 2001, Overview of Late Quaternary stratigraphy in Saanich Inlet, British Columbia: results of Ocean Drilling Program Leg 169S: Marine Geology, v. 174, p. 3–20.

Blais-Stevens, A., Clague, J. J., Bobrowsky, P. T., and Patterson, R. T., 1997, Late Holocene sedimentation in Saanich Inlet, British Columbia, and its paleoseismic implications: Canadian Journal of Earth Sciences, v. 34, p. 1345–1357.

Blais-Stevens, A., and Patterson, R. T., 1998, Environmental indicator potential of foraminifera from Saanich Inlet, Vancouver Island, British Columbia, Canada: Journal of Foraminiferal Research, v. 28, p. 201–219.

Blaise, B., Clague, J. J., and Mathewes, R. W., 1990, Time of maximum Late Wisconsin glaciation, west coast of Canada: Quaternary Research, v. 34: 282–295.

Blyth, H. E., and Rutter, N. W., 1993, Surficial geology of the Sydney area: Ministry of Energy, Mines and Petroleum Resources, BC., Open file map 1993-24, NTS 92B/11.

Blyth, H. E., Rutter, N. W., and Sankeralli, L. M., 1993, Surficial geology of the Shawnigan Lake area: Ministry of Energy, Mines and Petroleum Resources, BC. Open file map 1993-26, NTS 92B/12.

Bobrowsky, P. T., and Clague, J. J., 1990, Holocene sediments from Saanich Inlet, British Columbia, and their neotectonic implications: In Current Research, part E. Geological Survey of Canada Paper 90-1E, p. 251–256.

Bornhold, B. D., Firth, J. V., Adamson, L. M., Baldauf, J. G., Blais, A., Elver, M., Fox, P. J., Hebda, R., Kemp, A. E. S., Moran, K., Morford, J. H., Mosher, D. C., Prairie, Y. T., Russell, A. D., Schulteiss, P., and Whiticar, M. J., 1998, Proceedings of the Ocean Drilling Program. Sites 1033 and 1034 Initial reports, Saanich Inlet, Victoria, British Columbia, Canada, v. 169S, 138 p.

Clague, J. J., 1994, Quaternary stratigraphy and history of south-coastal British Columbia. In Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, in J. W. H. Monger (ed.), Geological Survey of Canada, Bulletin 481, p. 181–192.

Clague, J. J., and Mathewes, R. W., 1989, Early Holocene thermal maximum in western North America: New evidence from Castle Peak, British Columbia: Geology, v. 17: p. 277–280.

Clague, J. J., and Mathewes, R. W., 1996, Neoglaciation, Glacier-dammed lakes, and Vegetation change in Northwestern British Columbia, Canada: Arctic and Alpine Research, v. 28, p. 10–24.

Clague, J. J., Harper, J. R., Hebda, R. J., and Howes, D. E. 1982, Late Quaternary sea-level and crustal movements, coastal British Columbia: Canadian Journal of Earth Sciences, v. 19, p. 597–618.

Cowan, E. A., 2001, Late Pleistocene glacimarine record in Saanich Inlet, British Columbia, Canada: Marine Geology, v. 174, p. 43–57.

Cowan, E. A., Carlson, P. R., and Powell, R. D., 1996, The marine record of the Russel Fiord outburst flood, Alaska, U.S.A: Annals of Glaciology, v. 22, p. 194–199.

Culver, S. J., and Buzas, M. A., 1985, Distribution of Recent benthic foraminifera off the North American Pacific Coast from Oregon to Alaska: Smithsonian Contribution to Marine Sciences, no. 26, 234 p.

Dean, J. M., Kemp, A. E. S., and Pearce, R. B., 2001, Palaeo-flux records from electron microscope studies of Holocene laminated sediments, Saanich Inlet, British Columbia: Marine Geology, v. 174, p. 139–158.

Fishbein, E., and Patterson, R. T., 1993, Error-weighted maximum likelihood (EWML): a new statistically based method to cluster quantitative micropaleontological data: Journal of Paleontology, 67, p. 475–486.

Friele, P. A., and Hutchinson, I., 1993, Holocene sea-level change on the central-west coast of Vancouver Island, British Columbia: Canadian Journal of Earth Sciences, v. 30, p. 832–840.

Gross, M. G., Gucluer, S. M., Creager, J. S., and Dawson, W. A., 1963, Varved marine sediments in a stagnant fjord. Science, v. 141, p. 918–919.

Gucluer, S. M., and Gross, M. G., 1963, Recent marine sediments in Saanich Inlet, a stagnant marine basin: Limnology and Oceanography, v. 9, p. 359–376.

Guilbault, J.-P., 1989, Foraminiferal distribution in the central and western parts of the Late Pleistocene Champlain Sea basin, Eastern Canada: Géographie Physique et Quaternaire, v. 43, p. 3–26.

Guilbault, J.-P., 1993, Quaternary foraminiferal stratigraphy in sediments of the eastern Champlain Sea basin, Québec: Géographie Physique et Quaternaire, v. 47, p. 43–68.

Guilbault J-P., Patterson, R. T., Thomson, R. E., Barrie, J. V., and Conway, K. W., 1997, Late Quaternary paleoceanographic changes in Dixon Entrance, Northwest British Columbia, Canada: Evidence from the foraminiferal faunal succession. Journal of Foraminiferal Research, v. 27, p. 151–174.

Hald, M., and Korsun, S., 1997, Distribution of modern benthic foraminifera from fjords of Svalbard, European Arctic: Jorunal of Foraminiferal Research, v. 27, p. 101–122.

Hald, M., Steinsund, P. I., Dokken, T., Korsun, S., Polyak, L., and Aspelli, R., 1994, Recent and Late Quaternary distribution of Elphidium excavatum f. clavatum in Arctic Seas, Cushman Foundation for Foraminiferal Research Special Publication no 32, p. 141–153.

Hebda, R. J., and Whitlock, C., 1997, Environmental History: in Schoonmaker, P. K., von Hagen, P., and Wolf, E. C. (eds.), The Rainforest of Home: Profile of a North America Bioregion. Island Press (Covelo), p. 227–254.

Herlinveaux, R. H., 1962, Oceanography of Saanich Inlet in Vancouver Island, British Columbia: Journal of the Fisheries Research Board of Canada, v. 19, p. 1–37.

Hobson, L. A., and McQuoid, M. R., 2001, Pelagic diatom assemblages are good indicators of mixed water intrusions into Saanich Inlet, a stratified fjord in Vancouver Island: Marine geology, v. 174, p. 125–138.

Holland, S. S., 1980, Landforms of British Columbia, a physiographic outline. British Columbia Ministry of Energy, Mines and Petroleum Resources, Bulletin, v. 48, 138 p.

Huntley, D. H., Bobrowsky, P. T., and Clague, J. J., 2001, Ocean Drilling program Leg 169S: Surficial Geology, Stratigraphy and geomorphology of the Saanich Inlet area, southeastern Vancouver Island, British Columbia: Marine Geology v. 174, p. 27–41.

Hutchinson, I., Clague, J. J., and Mathews, R. W., 1997, Reconstructing the tsunami record on an emerging coast: a case study of Kanim Lake, Vancouver Island, British Columbia, Canada: Journal of Coastal Research, v. 13, p. 545–553.

Hutchinson, I., Patterson, R. T., and Mathewes, R. W., 1998, Plant macrofossil, pollen, diatom, and foraminiferal biofacies of the Fraser delta. in Clague, J. J., Luternauer, J. L., and Mosher, D. C. (eds.), Geology and Natural Hazards of the Fraser River Delta, British Columbia: Geological Survey of Canada Bulletin 525, p. 161–175.

Kaiho, K., 1994, Benthic foraminiferal dissolved-oxygen index and dissolved-oxygen levels in the modern ocean: Geology, v. 22, p. 719–722.

Kemp, A. E. S., 1996, Palaeoclimatology and palaeoceanography from laminated sediments. Geological Society Special. Publication No. 116. The Geological Society, London., 258 p.

Korsun, S., and Hald, M., 2000, Seasonal dynamics of benthic foraminifera in a glacially fed fjord of Svalbard, European Arctic: Journal of Foraminiferal Research v. 30, p. 251–271.

Loeblich, A. R., Jr., and Tappan, H., 1953, Studies of Arctic foraminifera: Smithsonian Miscellaneous Collections, v. 121, p. 1–150.

Luternauer, J. L., Clague, J. J., Conway, K. W., Barrie, J. V., Blaise, B., and Mathewes, R. W., 1989, Late Pleistocene terrestrial deposits on the continental shelf of western Canada: Evidence for rapid sea-level change at the end of the last glaciation: Geology, v. 17, p. 357–360.

MATHEWES, R. W., 1985, Paleobotanical evidence for climate change in southern British Columbia during late glacial and Holocene time: In Harrington, C. R. (ed.) Climate Change in Canada 5: Critical Periods in the Quaternary Climatic History of Northwestern North America: Syllogeus, v. 55, p. 397–422.

MATHEWES, R. W., HEUSSER, L. E., and PATTERSON, R. T., 1993, Evidence for a Younger Dryas-like cooling event on the British Columbia coast: Geology, v. 21, p. 101–104.

MCQUOID, M. R., and HOBSON, L. A., 2001, A Holocene record of diatom and silicoflagellate microfossils in sediments of Saanich Inlet, ODP Leg 169S: Marine geology, v. 174, p. 111–123.

MCQUOID, M. R., WHITICAR, M. J., CALVERT, S. E., and PEDERSEN, T. F., 2001, A post-glacial isotope record of primary production and accumulation in the organic sediments of Saanich Inlet, ODP Leg 169S: Marine Geology, v. 174, p. 273–286.

PATTERSON, R. T., 1993, Late Quaternary benthic foraminiferal assemblages and paleoceanography of Queen Charlotte Sound and southern Hecate Strait, British Columbia: Journal of Foraminiferal Research, v. 23, p. 1–18.

PATTERSON, R. T., and CAMERON, B. E. B., 1991, Foraminiferal biofacies succession in the late Quaternary Fraser River Delta, British Columbia: Journal of Foraminiferal Research, v. 21, p. 228–243.

PATTERSON, R. T., GUILBAULT, J.-P., THOMSON, R. E., and LUTERNAUER, J. L., 1995, Foraminiferal evidence of Younger Dryas isochronous cooling on the British Columbia Shelf, west coast of Canada: Géographie Physique et Quaternaire, v. 49, p. 409–428.

PATTERSON, R. T., BURBIDGE, S. M., and LUTERNAUER, J. L., 1998, Atlas of common benthic foraminiferal species for Quaternary shelf environments of western Canada: Geological Survey of Canada Bulletin 503, 91 p.

PATTERSON, R. T., and FISHBEIN, E., 1989, Re-examination of the statistical methods used to determine number of point counts needed for micropaleontological quantitative research: Journal of Paleontology, v. 63, p. 245–248.

PATTERSON, R. T., GUILBAULT, J. P., and THOMSON, R. E., 2000, Oxygen level control on foraminiferal assemblage distribution in Effingham Inlet, Vancouver Island, British Columbia: Journal of Foraminiferal Research, v. 30, p. 321–335.

PHLEGER, F. B., JR., 1952, Foraminifiera distribution in some sediment samples from the Canadian and Greenland Arctic. Contributions From the Cushman Foundation for Foraminiferal Research, v. 3, p. 80–89.

REINHARDT, E. G., EASTON, N. A., and PATTERSON, R. T., 1996, Foraminiferal evidence of Late Holocene sea-level change and Amerindian site distribution at Montague Harbour, British Columbia: Géographie Physique et Quaternaire, v. 50, p. 35–46.

ROBINSON, S. W., and THOMSON, G., 1981, Radiocarbon corrections for marine shell dates with application to southern Pacific Northwest Coast prehistory: Syesis, v. 14, p. 45–57.

SAGEMAN, B. B., and BINA, C., 1997, Diversity and species abundance patterns in Late Cenomanian black shale biofacies: Western Interior, U.S.: Palaios, v. 12, p. 449–466.

SANCETTA, C., and CALVERT, S. E., 1988, The annual cycle of sedimentation in Saanich Inlet, British Columbia: implications for the interpretation of diatom fossil assemblages: Deep-Sea Research, v. 35, p. 71–90.

SCOTT, D. B., BAKI, V., and YOUNGER, C. D., 1989, Late Pleistocene-Holocene paleoceanographic changes on the eastern Canadian margin: stable isotopic evidence: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 74, p. 279–295.

STOTT, L., HAYDEN, T. P., and GRIFFITH, J., 1996, Benthic foraminifera at the Los Angeles County Whites Point revisited: Journal of Foraminiferal Research, v. 26, p. 357–368.

THOMSON, R. E., 1981, Oceanography of the British Columbia coast: Canadian Special Publication of Fisheries and Aquatic Sciences, no. 56, 291 p.

UCHIO, T., 1960, Ecology of living benthonic foraminifera from the San Diego, California area: Cushman Foundation for Foraminiferal Research Special Publication no. 5, 72 p.

VILKS, G., 1980, Postglacial basin sedimentation on Labrador Shelf: Geological Survey of Canada, Paper 78-28, 28 p.

Received 27 November 2000
Accepted 15 July 2001

APPENDIX

FAUNAL LIST

Foraminiferal species observed in this study. Identification and naming of the taxa are based on Patterson and others (1998). Italicized names enclosed with in brackets indicate the original generic designations. Plate and figure numbers refer to taxa illustrated here.

Angulogerina angulosa (Williamson), 1858, (*Uvigerina*), (Pl. 2, Fig. 2)
Angulogerina fluens Todd, 1948
Astrononion gallowayi Loeblich and Tappan, 1953
Bolivinellina pacifica (Cushman and McCulloch), 1942, (*Bolivina acerosa* Cushman var.) (Pl. 1, Fig. 16, 20)
Buccella depressa (Anderson), 1952, (Pl. 1, Fig. 10)
Buccella frigida (Cushman), 1922, (*Pulvinulina*), (Pl. 1, Fig. 3 and Pl. 2, Fig. 13)
Buliminella elegantissima (d'Orbigny), 1839, (*Bulimina*), (Pl. 2, Fig. 14, 15)
Buliminella sp.
Cassidulina reniforme (Nørvang), 1945, (*Cassidulina crassa* d'Orbigny var.), (Pl. 2, Fig. 12, 18)
Cribroelphidium excavatum (Terquem), 1876, (*Polystomella*), (Pl. 1, Fig. 1, 7)
Cribroelphidium foraminosum (Cushman), 1939, (*Elphidium hughesi* Cushman and Grant var.), (Pl. 1, Fig. 12, 14)
Cribroelphidium halladense (Brotzen), 1943, (*Elphidium*), (Pl. 1, Fig. 13)
Cribroelphidium microgranulosum (Galloway and Wissler) in Thalmann, 1951 (*Elphidium*) (Pl. 2, Fig. 7, 8)
Chilostomella oolina Schwager, 1878
Euuvigerina juncea (Cushman and Todd), 1941, (*Uvigerina*), (Pl. 2, Fig. 16)
Euuvigerina sp.
Favulina melo (d'Orbigny), 1839, (*Oolina*), (Pl. 2, Fig. 3)
Fissurina eburnea (Buchner), 1940, (*Lagena*), (Pl. 2, Fig. 5)
Fissurina sp.
Homalohedra borealis (Buchner), 1954, (*Oolina*), (Pl. 2, Fig. 9)
Homalohedra guntheri (Earland), 1934, (*Lagena*), (Pl. 1, Fig. 2)
Homalohedra sp.
Hyalinonetrion clavatum (d'Orbigny), 1846, (*Oolina*), (Pl. 2, Fig. 10)
Islandiella helenae (Feyling-Hansen and Buzas), 1976 (Pl. 1, Fig. 8)
Islandiella norcrossi (Cushman), 1933, (*Cassidulina*), (Pl. 2, Fig. 6)
Lagena striatocollis (d'Orbigny), 1839, (*Oolina*), (Pl. 1, Fig. 18)
Lobatula fletcheri (Galloway and Wissler), 1927, (*Cibicides*), (Pl. 1, Fig. 4, 5)
Miliammina fusca (Brady), 1870, (*Quinqueloculina fusca*)
Nonionella digitata (Nørvang), 1945, (*Nonionella turgida* (Williamson) var.), (Pl. 2, Fig. 11)
Nonionella labradorica (Dawson), 1860, (*Nonionina scapha* var. *labradorica*), (Pl. 2, Fig. 20)
Nonionella stella (Cushman and Moyer), 1930, (*Nonionella miocenica* Cushman var.), (Pl. 1, Fig. 15)
Palliolatella frangens (Buchner), 1940 (*Lagena*), (Pl. 2, Fig. 19)
Protoglobobulimina elongata (d'Orbigny), 1826, (*Bulimina*), (Pl. 1, Fig. 11)
Quinqueloculina sp.
Rosalina columbiensis (Cushman), 1925, (*Discorbis*)
Rosalina sp.
Siphonaperta stalkeri (Loeblich and Tappan), 1953, (*Quinqueloculina*), (Pl. 1, Fig. 9 and Pl. 2, Fig. 4, 17)
Spirosigmoilina tenuis (Czjzek), 1848, (*Quinqueloculina*), (Pl. 1, Fig. 17 and Pl. 2, Fig. 1)
Stainforthia feylingi (Knudsen and Seidenkrantz), 1993, (Pl. 1, Fig. 19)
Trochammina charlottensis Cushman, 1925
Trochammina nana (Brady), 1881, (*Haplophragmium*)