Journal of Foraminiferal Research, v. 21, no. 3, p. 228-243, July 1991

FORAMINIFERAL BIOFACIES SUCCESSION IN THE LATE QUATERNARY FRASER RIVER DELTA, BRITISH COLUMBIA

R. TIMOTHY PATTERSON[1] AND BRUCE E. B. CAMERON[2]

ABSTRACT

Three foraminiferal biofacies indicating distinct depositional environments were identified in cores FD87A1 and FD88A1 from the Fraser River delta. The *Cassidulina-Islandiella* biofacies, in the basal portion of Core FD87A1 (347.5-367 m), was probably deposited in about 100-200 m of normal-salinity, cold water during the penultimate glaciation (Late Wisconsinan or older). The *Cribroelphidium bartletti* biofacies, identified in Core FD87A1 (197-256 m), may have been deposited in water depths of less than 150 m during the Everson Interstade. The *Cribroelphidium excavatum* biofacies, found in both Core FD87A1 (64-182.7 m) and Core FD88A1 (76.2-122.3 m) is associated with ancestral Strait of Georgia Holocene prodelta and delta slope sediments that accumulated in water depths of less than 200 m. The high frequency of *Cribroelphidium excavatum* in these sediments indicates depressed salinities during deposition (6 and 12 ka). Similar conditions are found today in the Strait of Georgia where the salinity range is 27-31‰.

INTRODUCTION

The highly urbanized Fraser Delta is located in one of the most seismically active zones of North America (Milne and others, 1978). This seismic setting, coupled with the incipiently unstable, thick late Quaternary deposits of the delta, provides considerable threat of a devastating earthquake to the inhabitants of metropolitan Vancouver (Luternauer, 1988; McKenna and Luternauer, 1987). Unfortunately, an exact determination of the seismic risk has been impossible because the depositional history of the delta is incompletely known. To increase this knowledge the Geological Survey of Canada has recently begun acquiring both subsurface seismic data and continuous cores from the Fraser Delta (Fig. 1).

Analysis of foraminiferal distribution patterns has proven indispensable in interpreting late Quaternary marine and glaciomarine deposits worldwide (e.g., Feyling-Hanssen, 1954, 1964, 1981; Feyling-Hanssen and others, 1971; Knudsen, 1976; Osterman, 1984; Rodriguez and Richard, 1986; Hald and Vorren, 1987; Patterson and others, 1990). The purpose of this study is to document the distribution of foraminifera in two cores obtained from the delta, as well as to recognize various foraminiferal biofacies within the cores. In conjunction with sedimentologic information from the cores, these paleontological data will be used to determine paleoenvironments during deposition of the delta.

PREVIOUS WORK

Few published studies on Recent shelf foraminifera (Cushman, 1925; Cushman and Todd, 1947; Cockbain, 1963; Phleger, 1967; Scott, 1974; McCulloch, 1977; Gallagher, 1979; Jones and Ross, 1979; Williams, 1989; Patterson, in press, 1990) and only three studies of Pleistocene foraminifera (Smith, 1970, 1978; Patterson, in press) have been carried out along the coast of British Columbia or from adjacent Washington state waters. Of most interest to the present research, Cockbain (1963) conducted a distributional study of foraminifera found at depths ranging from 112 to 293 meters in the Strait of Georgia. The most recent foraminiferal studies from the region have been detailed analyses of marsh foraminiferal biofacies from the Fraser Delta (Williams, 1989; Patterson, 1990).

DELTA PHYSIOGRAPHY

Formed by sediments discharging from the Fraser River into the Strait of Georgia, the Fraser Delta is triangular, with a surface area of more than 1,000 km^2 (Fig. 1). The delta is bounded on the west by the Strait of Georgia, on the north by the Coast Mountains, and on the south and southeast by the Cascade Mountains (Clague and others, 1983). The delta runs from a narrow gap in the Pleistocene uplands at New Westminster and meets the sea along a 40-km perimeter.

Sediment discharged on the Fraser Delta is predominantly used (Clague and others, 1983). This is particularly true during the river freshet, when the Fraser's plume extends across the Strait of Georgia. During the river freshet there is also an increase in the deposition of continentally derived material such as plant debris, megaspores, and so forth. River sedimentation during the remainder of the year, when discharge decreases, consists primarily of slit and clay (Milliman, 1980). The maximum tidal range on the delta is five m (mesotidal) at the mouth of the river, decreasing landward and seasonally in connection with increasing river flow (Ages and Woolard, 1976).

Active sedimentation, consisting primarily of fine to medium sand, currently occurs on Sturgeon and Robert's Banks. The delta progrades on the order of 5 m/yr along the active western margin and on the order of 8.6 m/yr near the river mouth (Hutchinson, 1990; Tassone, 1990). Between 1984 and 1988 accretion rates in the western marshes were measured at 18 mm/yr (Hutchinson, 1990). Due to a combination of northward-oriented longshore drift and the Coriolis effect, sedimentation rates tend to be higher on Sturgeon Bank than on Robert's Bank. The Fraser River has not en-

[1] Ottawa-Carleton Geoscience Center and Department of Earth Sciences, Carleton University, Ottawa, Ontario, K1S 5B6, Canada.
[2] Geological Survey of Canada, Pacific Geoscience Centre, 9860 West Saanich Road, Sidney, B.C., V8L 4B2, Canada.

tered the inactive Boundary Bay portion of the delta for 5,000 years, as evidenced by the lack of river sediments in the continuous late Holocene organic sequence in Burns Bog, between Boundary Bay and the Fraser River (Clague and others, 1983).

Coastal Hydrography

The inside waterways of British Columbia and Washington occupy a relatively young and narrow coastal trough known as the Georgia–Hecate Depression. The Strait of Georgia (Fig. 1), found within the depression, is of particular interest to this study because of its proximity to the Fraser River Delta. It is linked to the Pacific Ocean to the north via several narrow but relatively long channels, notably Discovery Passage and Johnstone Strait, and the broader Queen Charlotte Strait. To the south, the Strait of Georgia is linked to the ocean via Juan de Fuca Strait and a few wide channels between the San Juan and Gulf islands (Thompson, 1981).

The most important influences on currents in the Strait of Georgia are tidal streams; other factors include river flow, wind, the Coriolis effect, centrifugal forces, and channel bathymetry. Large rivers such as the Skeena, Nass, and Fraser, emptying into the Georgia-Hecate depression from glacier-carved valleys, have a profound effect on the structure and circulation of coastal waters. Freshwater input into the larger mainland inlets reaches its peak during the freshet, or snowmelt period, beginning each May. During this period the volume of water discharged by these rivers can exceed the corresponding discharge rate for the late fall to early spring period by a factor of 10, or more. The Fraser River, in particular, influences the currents throughout the entire Strait of Georgia from the entrance of Juan de Fuca Strait to the entrance of Queen Charlotte Sound. With a mean discharge of 3,400 m^3/sec, the Fraser River is the largest river reaching the west coast of Canada (Mathews and Shepard, 1962).

Water depths within the Georgia-Hecate Depression are generally shallower than 400 m. The average depth within the Strait of Georgia is 155 m (Thompson, 1981). Strong vertical mixing due to upwelling in southern tidal passes like Haro Strait and Active Pass keeps the surface temperature in the southern Strait of Georgia below 10°C year round. Surface (top 10–20 m) water temperatures over most of the strait are more variable, falling to as low as 5–6°C in February and March and warming to around 20°C by mid July. Bottom temperatures in the Strait of Georgia remain a relatively constant 8–10°C year round. In addition, surface temperatures in inlets with rivers at their heads generally remain cool throughout the summer as snow melt has little opportunity to warm during the journey seaward. Surface temperatures off the mouth of the Fraser River are cooler than in most other parts of the Strait of Georgia for this reason.

Salinity within the Strait of Georgia has a marked two-layer structure. In deeper waters of the strait salinity values range from 29.5‰ at 50 m to 31‰ at the bottom (>150 m) throughout the year. Salinity values within the top 50 m are less, ranging from 27–28‰ at the surface to 29.5‰ at 50 m. This two-layer salinity structure is due to the influence of freshwater river flow into the strait, particularly from the Fraser River. The Fraser River forms what is known as a "salt-wedge estuary," sending a plume of less dense low salinity water out over the surface of the strait. This phenomenon probably explains the paucity of planktonic foraminifera in the area. During summer freshet, freshwater discharge from the Fraser River forms a thin, one- to 10-m, relatively low salinity (17‰) layer over much of the strait. Due to the large volumes of fresh water produced by the Fraser River, the entire southwestern passage from the entrance of Juan de Fuca Strait to the entrance of Queen Charlotte Strait may be considered part of the Fraser River, as 60 percent of the dilution of these waters can be attributed to this one river.

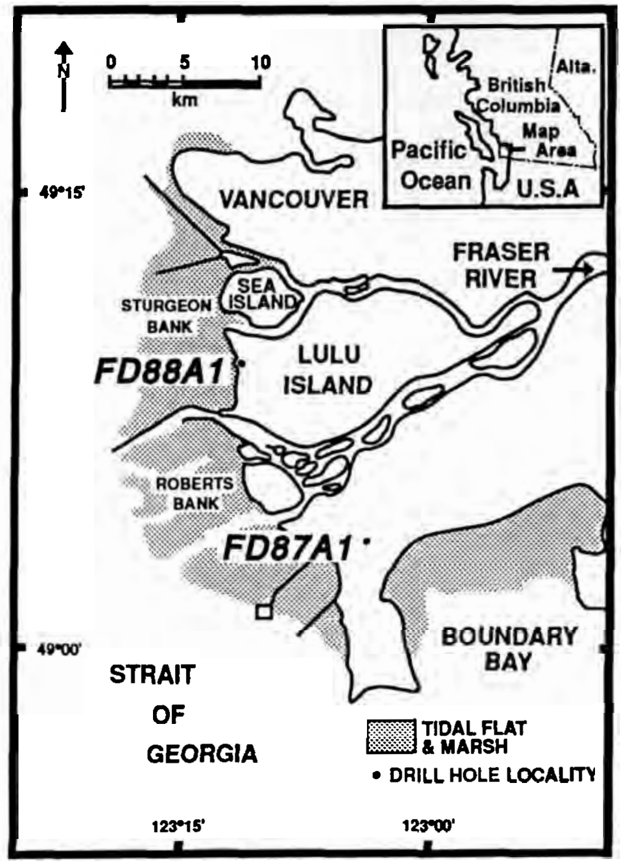


FIGURE 1. Locality map of the Fraser Delta area showing drill sites of Core FD87A1 and Core FD88A1.

Late Quaternary History of the Lower Fraser Delta

The late Quaternary in British Columbia is subdivided into three major units: the Olympia non-glacial interval (or Olympia Interglacial), the Fraser Glaciation, and post-glacial deposits. These late Quaternary sediments overlay older Semiahmoo Drift and Dashwood Drift; sediments deposited during the penultimate glacial event in British Columbia (Clague, 1981).

The age of the penultimate glacial deposits, which are typically glaciolacustrine and glaciofluvial, is not well defined. The overlying Olympia non-glacial interval deposits began accumulating more than 59 ka (Clague, 1981). This sequence from glacial to non-glacial sediments is apparently conformable. Cowichan Head Formation sediments deposited during the Olympia non-glacial interval are similar to those being deposited today. Rivers and streams flowed across the isostatically uplifted lowland and into the sea, and channel and overbank sediments were deposited on floodplains and along stream courses. Deltaic, lagoonal, and littoral sediments accumulated in coastal areas, while marine muds were deposited offshore (Clague, 1981).

About 29 ka, a climatic deterioration resulted in the buildup of "Fraser Glaciation" glacial ice in the Coast Mountains. This deterioration initially manifested itself by deposition of the "Quadra Sand" along the coast. These well-sorted sands were deposited as distal outwash aprons in front of or along the margins of glaciers moving from the Coast Mountains. Quadra Sand deposits are diachronous as deposition began more than 29 ka at the north end of the Strait of Georgia and no earlier than 15 ka at the south end of Puget Sound (Clague, 1981).

The Fraser Glaciation Cordilleran ice sheet reached its maximum extent in the Puget Lowland between 14.5 ± 0.2 ka and 15.0 ± 0.4 ka. The Everson Interstade in coastal northwestern Washington and southwestern British Columbia spans the interval between the Fraser Glaciation maximum and the Sumas glacial re-advance about 11.3 ka (Armstrong and others, 1965; Armstrong, 1981). Marine waters invaded the area during this interval. A variety of sediments including glacio-marine diamicton, marine silt and clay, subaqueous outwash, and deltaic sand and gravel was deposited on the isostatically depressed coastal lowland. Everson Interstade deposits exhibit complex facies changes due to differences in sediment supply and the rate and nature of glacial recession within the area. These deposits are known both as the Fort Langley Formation and Capilano sediments (Armstrong and Brown, 1953; Fyles, 1963; Armstrong, 1981).

The Everson Interstade ended in the eastern Fraser Lowlands with the readvance of glaciers. This readvance was triggered by a climatic episode known as the Sumas Stade. This glacial episode was very short as ^{14}C dates from the Fraser Canyon indicate that the Fraser Lowlands contained little or no ice after 11 ka (Clague, 1981). Deposits resulting from this glacial advance are in the form of outwash deposits.

The postglacial interval includes the period following the disappearance of Fraser Glaciation ice. These deposits formed in response to processes that remain active in the region today, although present erosion and sedimentation rates are much slower than during late glacial and early post-glacial time (Clague, 1981). Along the Vancouver Island and mainland coasts, relative sealevels were high during deglaciation due to glacio-isostatic depression of the crust. The maximum marine limit was reached in the Fraser Delta area around 12.9 ± 0.2 ka when sea level reached 200 m above present levels (Lowdon and others, 1977; Clague, 1981). Subsequent isostatic uplift resulted in a rapid fall in sea level relative to the land. Present day sea levels were reached in the Fraser Lowland between 10,000 and 11,000 years ago. There have not been any significant sea-level fluctuations in the last 5,500 years, although sea levels on the inner coast may have been a few meters below the present level during much of this interval (Hebda, 1977). Sea level is currently rising relative to the land on the mainland coast at a rate of 15–30 cm per century (de Jong and Siebenhuener, 1972; Mathews and others, 1970). This depression of the land is likely the result of tectonic movements (Riddihough, 1979) rather than from sediment loading on the Fraser Delta.

METHODS AND MATERIALS

One-hundred and two approximately 10-cc samples were taken from two Fraser delta cores (FD87A1 and FD88A1) that were obtained using a Tri-Core rotary drilling rig. Sixty-five samples are from a 367.3-m core (FD87A1) recovered from the northeast corner of the intersection of 28th Ave and 56th St., in the Municipality of Delta, (latitude 49°3.25′N; longitude 123° 3.95′W; Fig. 1). The remaining 37 samples are from a 122.4-m core (FD88A1) recovered on the dyke at the west end of Blundel Road in the Municipality of Richmond (Fig. 1; latitude 49°9.35′N; longitude 123° 11.70′W).

All samples examined by RTP were boiled with soda ash to cleanse the foraminiferal tests. Samples were then wet-sieved through mesh with 500-μm screen openings to retain coarse material and 63-μm screen openings to retain the foraminifera. Samples containing large amounts of sand were dried, and the foraminifera separated from the sand by flotation in sodium polytungstate (specific gravity 2.28). All residues were then examined under a stereo-microscope (generally at 40×) to identify and quantify the foraminifera.

All samples obtained by BEBC for this study were dried and then disintegrated in a mild "Quaternary O" surfactant. The resultant mixtures were then rinsed through 1-mm sieves for recovery of the coarser material and 75-μm sieves to recover the finer microfauna. The finer material was cleaned of any remaining clay material by ultrasonic vibration. The residues from both fractions were then examined and a representative portion of all microfauna and other organic and inorganic materials deemed to have relevance to the paleoenvironmental interpretation were extracted and identified. The relative frequencies observed by each author were then recorded (Tables 1, 2).

Only 29 of the 78 samples examined by RTP contained foraminifera, and of these only 11 contained statistically or marginally significant populations (i.e.,

TABLE 1. Foraminiferal occurrences in samples from Core FD87A1. Sample numbers preceded by a "P" were quantitatively analyzed by RTP and are recorded as percent occurrences. An "X" indicates that a particular taxa made up <1 percent of the fauna in a sample. Sample numbers preceded by a "C" were qualitatively analyzed by BEBC and are recorded as abundant (A = >20 specimens), common (C = 6–20 specimens), rare (R = 2–5 specimen), or as very rare (VR = 1 specimen). Biofacies designations followed by a "?" indicate a probable biofacies assignment, as the population of a sample was either not statistically significant or was qualitatively assessed and thus not always well known. The uncertainty (±) associated with percent occurrence of dominant indicator taxa is listed.

Sample	P106	P107	C3	P110	C4	P112	C5	P114	C6	C7	P115	C8
Biofacies	1?	1?	1?	1?	1?	1	1	1	1	1	1	1
No. of Species	3	3	3	1	1	5	5	14	17	8	19	25
Total Individ.	3	12	—	2	—	26	—	725	—	—	1283	—
Depth in Core (m)	64	82.3	82.9	112.8	113.4	137	140.1	143.6	147.7	153.8	155	161.8
Buccella frigida	33.3					3.9	A	2.3	C		5.4	A
Uncertainty±	54.4					7.6		1.1			1.3	
Cribroelphidium bartletti											X	
Uncertainty±											X	
Cribroelphidium excavatum	33.3		VR			61.5	A	66.1	A	A	83.4	A
Uncertainty±	54.4					3.5		3.5			2.1	
Elphidiella nitida	33.3	66.7	C	100.0	C	26.9	A	1.7	R	A	1.6	A
Uncertainty±	54.4	27.2		0.0		17.4		1			0.7	
Cassidulina reniforme											X	R
Uncertainty±											X	
Islandiella norcrossi												
Uncertainty±												
Nonionella stella		8.3	VR					23.2	A	A	7.9	A
Uncertainty±		15.9						3.1				
Angulogerina angulosa												
Angulogerina fluens												
Astrononion gallowayi						3.9		1.1			X	
Bolivina decussata												R
Bolivinellina pacifica											X	
Buccella tenerrima												
Buliminella elegantissima								X				
Cribroelphidium frigidum									R			R
Cribroelphidium groenlandicum												
Cribroelphidium microgranulosum												VR
Cribroelphidium tumidum								X			X	
Cornuspira involvens												
Dyocibicides biserialis												VR
Epistominella pacifica		25.0							R		X	
Epistominella vitrea								X	R		X	C
Favulina melo											X	
Fissurina sp. A												VR
Fissurina sp. B												R
Fissurina labiata								X				
Glandulina laevigata												
Globigerina bulloides												
Globigerina quinqueloba								X			X	VR
Globobulimina auriculata												VR
Globocassidulina crassa												VR
Homalohedra apiopleura											X	
Homalohedra borealis												
Laevidentalina sp.												VR
Lagena gracillima												
Lagena semilineata											X	
Lagena substriata									VR			VR
Lagena spicata											X	
Lagena striata												R
Lobatula fletcheri							R	1.1	R	R	X	C
Neogloboquadrina pachyderma									VR			
Nonion sp.									VR	VR		R
Nonionella turgida									VR			
Nonionellina labradoricum									VR			
Parafissurina sublata								X				
Procerolagena distoma											X	R
Pyrgo sp.												
Pullenia subcarinata												R
Quinqueloculina akneriana									R	C		C
Quinqueloculina seminulum							R	X		R		R
Siphonaperta stalkeri									C			R
Rosalina columbiensis								X				
Sestronophora arnoldi						3.9						
Scutuloris tegminis									R			
Stainforthia complanata											X	
Triloculina trigonula									VR			

TABLE 1. Continued.

Sample	P116	P117	C9	C10	P118	P119	C11	P121	C12	P123	P126	C15
Biofacies	1	1?	1	1	1	1	1	2?	?	2?	2?	?
No. of Species	7	4	19	14	14	4	6	3	1	2	1	1
Total Individ.	103	18	—	—	1,969	26	—	5	—	3	1	—
Depth in Core (m)	163	171	171.3	177.2	178.2	181.4	182.7	192.9	199.3	199.6	219.2	251.3
Buccella frigida	13.6	22.2	A	A	11.1	30.8	C					
Uncertainty±	6.8	19.6			1.4	18.1						
Cribroelphidium bartletti					X			60.0		66.7	100.0	
Uncertainty±					X			43.8		54.4	0.0	
Cribroelphidium excavatum	77.7	38.9	A	A	64.9	30.8	C		VR			VR
Uncertainty±	8.2	23.0			2.2	18.1						
Elphidiella nitida	4.9	33.3	A	A	18.4	30.8	A	20.0		33.3		
Uncertainty±	4.3	22.2			1.8	18.1		35.8		54.4		
Cassidulina reniforme			R	VR	X							
Uncertainty±					X							
Islandiella norcrossi					X		R					
Uncertainty±					X							
Nonionella stella	4.9		A	C	X		VR					
Uncertainty±	4.3											
Angulogerina angulosa												
Angulogerina fluens												
Astrononion gallowayi					X							
Bolivina decussata												
Bolivinellina pacifica												
Buccella tenerrima					X	7.7						
Buliminella elegantissima	X		VR	R	1.5							
Cribroelphidium frigidum												
Cribroelphidium groenlandicum			VR									
Cribroelphidium microgranulosum			R									
Cribroelphidium tumidum					1.1			20.0				
Cornuspira involvens												
Dyocibicides biserialis			VR									
Epistominella pacifica			R		X							
Epistominella vitrea			R									
Favulina melo				VR								
Fissurina sp. A												
Fissurina sp. B												
Fissurina labiata												
Glandulina laevigata												
Globigerina bulloides												
Globigerina quinqueloba												
Globobulimina auriculata			R	VR								
Globocassidulina crassa												
Homalohedra apiopleura												
Homalohedra borealis			VR									
Laevidentalina sp.												
Lagena gracillima			R	R								
Lagena semilineata												
Lagena substriata				VR								
Lagena spicata												
Lagena striata												
Lobatula fletcheri	X		C	VR	X							
Neogloboquadrina pachyderma				VR								
Nonion sp.												
Nonionella turgida												
Nonionellina labradoricum			R									
Parafissurina sublata												
Procerolagena distoma				VR								
Pyrgo sp.												
Pullenia subcarinata												
Quinqueloculina akneriana			C				VR					
Quinqueloculina seminulum	2.9	5.6	VR		X							
Siphonaperta stalkeri			VR	R								
Rosalina columbiensis												
Sestronophora arnoldi												
Scutuloris tegminis												
Stainforthia complanata												
Triloculina trigonula												

TABLE 1. Continued.

Sample	P128	P130	C16	C20	P137	P139	C22	P141	P142	C23	C24	P143
Biofacies	2	2?	?	3?	3?	3	3	3?	3?	3)	3	3
No. of Species	2	1	1	2	1	4	5	1	2	2	12	7
Total Individ.	35	1	—	—	1	22	—	1	7	—	—	71
Depth in Core (m)	254 8	256	266 6	347	347 5	350.8	355.4	359.1	361.8	363.6	366.7	367
Buccella frigida												
Uncertainty±												
Cribroelphidium bartletti	94.3	100.0										
Uncertainty±	7.8											
Cribroelphidium excavatum	5.7		R				VR					
Uncertainty±	7.8											
Elphidiella nitida				VR		4.5						
Uncertainty±						8.8						
Cassidulina reniforme					100.0	68.2	A		71.4	R	A	76.1
Uncertainty±					0.0	19.9			34.2			10.1
Islandiella norcrossi				R		22.7	R		28.6		A	14.1
Uncertainty±						17.9			34.2			8.3
Nonionella stella												
Uncertainty±												
Angulogerina angulosa											A	
Angulogerina fluens						4.5						1.4
Astrononion gallowayi												
Bolivina decussata												
Bolivinellina pacifica												
Buccella tenerrima												
Buliminella elegantissima												
Cribroelphidium frigidum												
Cribroelphidium groenlandicum												
Cribroelphidium microgranulosum												
Cribroelphidium tumidum												
Cornuspira involvens											VR	
Dyocibicides biserialis												
Epistominella pacifica							R					
Epistominella vitrea												
Favulina melo												
Fissurina sp. A												
Fissurina sp. B												
Fissurina labiata												
Glandulina laevigata												2.8
Globigerina bulloides											R	1.4
Globigerina quinqueloba												
Globobulimina auriculata												
Globocassidulina crassa												
Homalohedra apiopleura												
Homalohedra borealis												
Laevidentalina sp.												
Lagena gracillima							VR					
Lagena semilineata												
Lagena substriata												
Lagena spicata												
Lagena striata												
Lobatula fletcheri											C	2.8
Neogloboquadrina pachyderma								100.0			R	
Nonion sp.												
Nonionella turgida												
Nonionellina labradoricum												
Parafissurina sublata												
Procerolagena distoma												
Pyrgo sp.											VR	
Pullenia subcarinata												
Quinqueloculina akneriana										R	C	
Quinqueloculina seminulum												1.4
Siphonaperta stalkeri											VR	
Rosalina columbiensis												
Sestronophora arnoldi												
Scutuloris tegminis											VR	
Stainforthia complanata												
Triloculina trigonula												

TABLE 2. Foraminiferal occurrences in samples from Core FD88A1. Sample numbers preceded by a "P" were quantitatively analyzed by RTP and are recorded as percent occurrences. Biofacies designations followed by a "?" indicate a probable biofacies assignment, as the population of the sample was not statistically significant. The uncertainty (±) associated with percent occurrence of dominant indicator taxa is listed.

Sample	P321	P324	P327	P328	P330	P331	P332	P333	P334
Biofacies	1?	1?	1?	1?	1?	1?	1	1	1?
No. of Species	4	1	2	2	2	2	5	6	4
Total Individ.	4	17	16	13	2	6	34	78	14
Depth in Core (m)	76.2	91.4	91.68	91.73	106.8	121.9	122	122.1	122.3
Astrononion gallowayi	25.0								
Uncertainty±	43.3								
Buccella frigida	25.0		5.2				5.9	6.4	7.1
Uncertainty±	43.3		11.1				8.1	5.5	13.7
Buliminella elegantissima							2.9	1.3	
Uncertainty±							5.8	2.6	
Cribroelphidium excavatum	25.0	100.0	94.8	92.3	50.0	83.3	85.3	79.5	71.4
Uncertainty±	43.3	0.0	11.1	14.8	70.7	30.5	12.1	9.1	24.2
Cribroelphidium tumidum								1.3	
Uncertainty±								2.6	
Elphidiella nitida				7.7			2.9	2.6	7.1
Uncertainty±				14.8			5.8	3.6	13.7
Nonionella stella					50.0	16.7	2.9	9.0	14.3
Uncertainty±					70.7	30.5	5.8	6.5	18.7
Cibicides sp.	25.0								
Uncertainty±	43.3								

samples P112, P119, P128, P139, and P332; Patterson and Fishbein, 1989). The standard error associated with the percent abundances of dominant species found in each quantitatively tallied sample is listed in Tables 1 and 2. In addition, only 16 of the 24 samples semi-quantitatively examined by BEBC contained foraminifera. Because of the generally meager foraminiferal recovery from these samples and the different tallying methods employed by the authors, biofacies were determined on the basis of dominant taxa rather than by multivariate analysis. Biofacies configurations were defined on the basis of the dominant species present in samples containing statistically significant or marginally significant populations of foraminifera. Using these samples as a baseline, biofacies were extrapolated to samples with similar yet statistically indeterminate (the semi-quantitatively tallied data of BEBC) or statistically insignificant populations (Tables 1, 2).

AGE

Fourteen ^{14}C radiocarbon dates were obtained from wood and shells recovered from core FD87A1 by the Isotrace Laboratory at the University of Toronto (Table 3; Fig. 2). The results were the average of two machine-ready targets measured on different occasions. The wood samples were corrected for natural, preparation, and sputtering fractionation to a base of $\delta^{13}C = -25‰$. The shell samples were first pre-leached to remove the outer 20–40% of the shell. Shell samples were corrected to a base of $\delta^{13}C = 0‰$, equivalent to a reservoir correction of 410 years. The ages are quoted in uncalibrated radiocarbon years using the Libby ^{14}C mean life of 8,033 years. The errors represent 68.3% confidence limits.

Radiocarbon dates above 185 m (5.82 ± 0.06 to 11.92 ± 0.09 ka) are considered to accurately represent the age of the respective sampling intervals. However, dates below 185 m depth (0.02 ± 0.46 to 46.43 ± 0.80 ka) are in a jumbled chronological order and thus apparently do not accurately reflect the age of the enclosing sediments.

RESULTS

Fifty-six species of benthic and planktonic foraminifera were identified from 45 samples. The 11 quantitatively examined samples containing statistically significant or marginally significant numbers of foraminifera were used to define biofacies (Tables 1, 2), based on the proportions of the dominant species found in individual samples.

Biofacies 3 occurs between 347.5 m and 367 m in core FD87A1 but was not found in core FD88A1 (Fig. 2; Table 1). This biofacies is characterized by a high proportion of *Cassidulina reniforme* Nørvang (68.2–76.1%), and *Islandiella norcrossi* (Cushman) (14.1–

TABLE 3. Radiocarbon dates obtained from shell and wood material from Core FD87A1.

Depth (m)	Lab no.	Material	Age
39.94	TO-777	wood	5,820 ± 60
66.14	TO-778	shell	6,420 ± 60
99.5	TO-779	wood	6,250 ± 80
143.89	TO-780	wood	7,470 ± 60
158.34	TO-781	shell	8,310 ± 70
170.36	TO-782	shell	9,150 ± 70
171.64	TO-783	shell	9,410 ± 70
178.77	TO-784	shell	9,950 ± 80
184.66	TO-1094	shell	11,920 ± 90
202.38	TO-785	wood	37,460 ± 660
219.73	TO-1095	shell	46,430 ± 880
221.63	TO-786	shell	26,880 ± 200
247.34	TO-787	wood	33,490 ± 270
267.44	TO-788	wood	24,460 ± 160

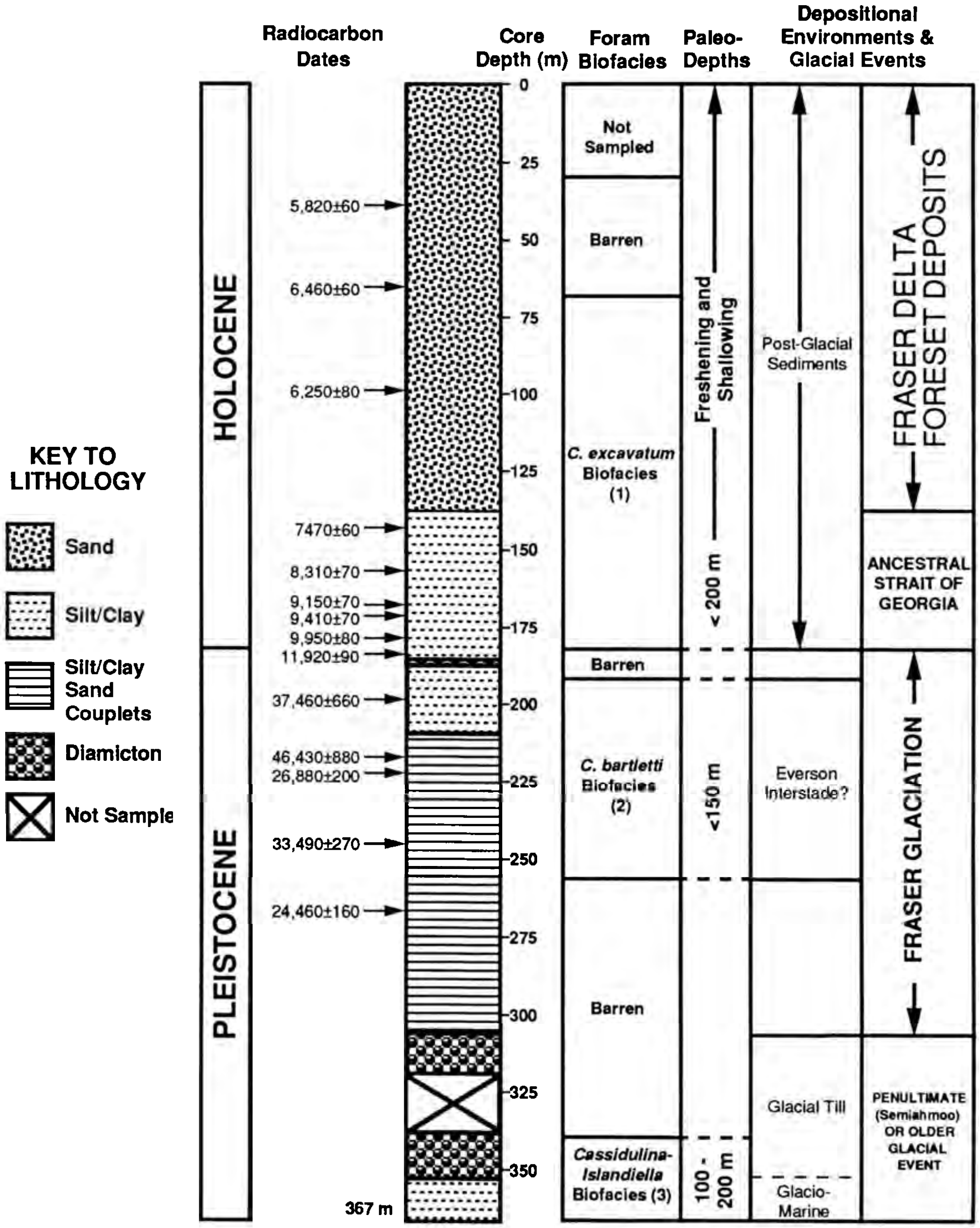


FIGURE 2. Stratigraphic section of Core FD87A1 showing lithology, ^{14}C radiocarbon dates, foraminiferal biofacies, depositional environments, and climatic events.

22.7%). It spans two lithologic units, a diamicton from 347 to 358.6 m, and a silty clay from 358.6 m to the base of the hole at 367 m. Species diversity in samples containing this biofacies is low, with the 12 species found in sample C24 being the most diverse fauna. Sample P143, with 71 specimens, has the largest number of foraminifera.

Biofacies 2 occurs between 192.9 m and 256 m in core FD87A1 but was not observed in Core FD88A1 (Fig. 2; Table 1). It is dominated by *Cribroelphidium bartletti* (Cushman): 94.3% in sample P128, the only Biofacies 2 sample with a statistically significant population, and 60–100% in other samples (Table 1). This biofacies spans two lithologic units: one comprising silt and clay (192.9–197 m), and another consisting of silt, clay, and sand couplets and triplets (197–256 m). Diversity in samples containing this biofacies is low with a maximum of three species in sample P121. Total

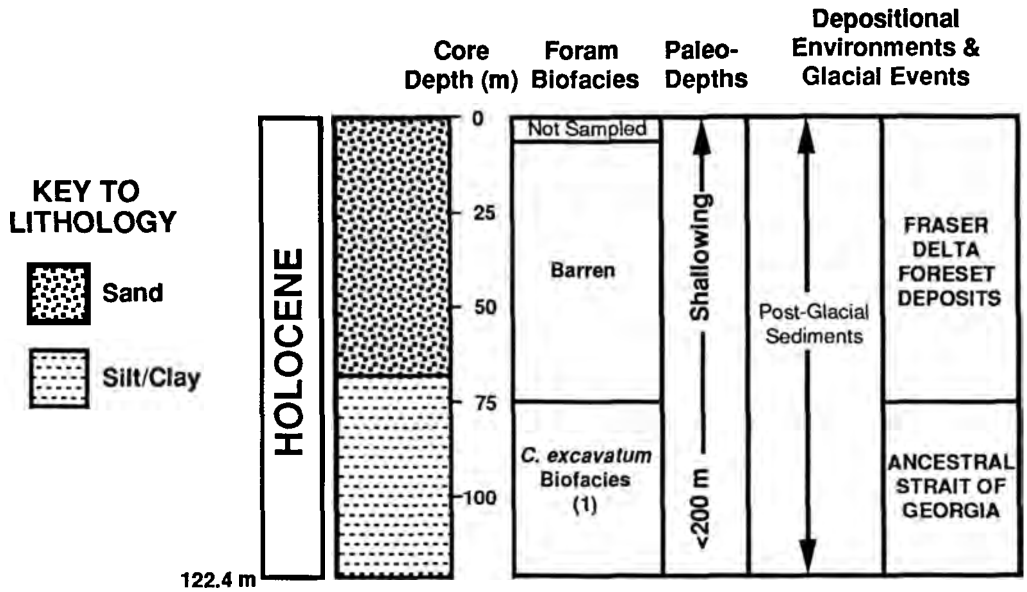


FIGURE 3. Stratigraphic section of Core FD88A1 showing lithology, foraminiferal biofacies, depositional environments, and climatic events.

abundances are also low with the 35 specimens from sample P128 being the largest fauna.

Biofacies 1 occurs in both FD87A1 (64–181.4 m) and core FD88A1 (76.2–122.3 m) (Figs. 2, 3; Tables 1, 2). In core FD87A1, *Cribroelphidium excavatum* (Terquem) is the most abundant species in Biofacies 1, ranging in frequency from 30.8–83.4% of the fauna. Other species are also characteristic of this biofacies, although their frequencies vary considerably: *Elphidiella nitida* Cushman (1.6–30.8%); *Buccella frigida* (Cushman) (2.3–30.8%); *Nonionella stella* Cushman and Moyer (0.0–23.2%). Biofacies 1 spans two lithologies in Core FD87A1, a sandy unit from 64.0–132.8 m, and a silt/clay unit from 132.8–181.4 m. Total numbers of foraminifera generally decrease upward and are lowest in the sandy unit. Samples of this biofacies in core FD87A1 have both the highest diversity (19 species in sample P115) and the highest abundances (1,969 specimens in sample P118) of any samples from these cores.

Similarly, samples of Biofacies 1 in core FD88A1 are dominated by *Cribroelphidium excavatum* (79.5–85.3%). The major accessory species are generally less abundant than in Core FD87A1: *Elphidiella nitida* (2.6–2.9%); *Nonionella stella* (2.9–9.0%); *Buccella frigida* (5.9–6.4%). The entire Biofacies 1 interval in Core FD88A1 is lithologically uniform, consisting primarily of silts and clays. Foraminiferal diversity and abundance are low in this core. The most diverse and abundant fauna was found in sample P333, with six species and a total of 78 specimens.

There are several units barren of foraminifera in both drill holes. In core FD87A1 these include the sand interval from 13.0 to 64 m, a silt/clay unit containing a thin diamicton layer between 181.4 and 192.9 m, a lengthy interval of silt/clay/sand couplets between 266.6 and 347 m, and the underlying diamicton unit (347–358.5 m). In core FD88A1 sand between 7.6 and 76.2 m lacked foraminifera.

DISCUSSION

It is difficult to compare the Biofacies 3 (Fig. 2; Table 1) with modern cold-water shelf assemblages. This is because there has been a tremendous decline in the proportion of *Cassidulina reniforme* present in high latitude environments from as much as 40–50% of the fauna in the late Pleistocene to as little as 0.5–4% in late Holocene sediments (Patterson, in press). The only modern fauna known to be dominated by *Cassidulina reniforme* (identified as *Cassidulina crassa*) was found adjacent to a subpolar grounded glacier in the inner basin of Kongsfjorden, Spitsbergen Island (Elverhøi and others, 1980).

However, similar Pleistocene and early Holocene cassidulinid faunas have been reported from other high latitude localities. Based on modern and fossil analogues, Rodriguez and Richard (1986) determined that the presence of a *Cassidulina–Islandiella* dominated biofacies in samples from the late Quaternary Champlain Sea of eastern Canada indicated salinities of 30–34‰. Similarly, Guilbault (1980, 1989) concluded that faunas dominated by *Cassidulina reniforme* and *Islandiella norcrossi* probably inhabited the deeper portions of the Champlain Sea where salinities were relatively high (27–33‰). Osterman (1984) suggested that the presence of a cassidulinid dominated fauna in a late Quaternary core from Frobisher Bay, Northwest Territories may be indicative of a proximal glaciomarine environment. Bahnson and others (1974) also concluded that a depauperate fauna dominated by cassidulinids is indicative of a position near a glacier front. Sejrup and Guilbault (1980) determined that abundant occurrences of *Cassidulina reniforme* are almost exclusively restricted to biofacies strongly influenced by glacial conditions. Scott and others (1989) also reported this fauna from glacial sections of cores obtained all along the eastern coast of Canada. Although finding no evidence of local glaciation, Patterson

(1990b) has identified *Cassidulina reniforme* dominated faunas from core intervals dated at 10 to 12 ka in Queen Charlotte Sound and southern Hecate Strait. This fauna inhabited waters as deep as 200 m and seems to indicate the influx of very cold water onto the shelf, perhaps related to the Younger Dryas Event of eastern North America and Europe.

The present-day and paleo-distribution of the major foraminiferal species in the *Cassidulina–Islandiella* biofacies, as well as evidence provided by raised marine terraces in the Fraser lowlands (Clague, 1981), indicates deposition in marine waters of normal salinity at depths of approximately 100–200 m. However, this fauna has been reported from much shallower waters on the east coast of Canada (Scott and Medioli, 1980). No ^{14}C dates are available for the silt/clay and diamicton facies in the core interval spanned by the *Cassidulina–Islandiella* biofacies. However, on the basis of stratigraphic position (the unit is overlain by a glacial till, J. Clague, written communication, 1990) and from evidence provided by the foraminifera, it is likely that the silt/clay unit and lower diamicton in core FD87A1 are the equivalent of the Semiahmoo Drift which was deposited in southwestern British Columbia during the penultimate glaciation, or an even older Wisconsinan glacial episode. The trace amount of pollen from this interval (R. Mathewes, written communication, 1990) provides additional evidence of glacial conditions.

The overlying diamicton between 310 and 350 m in Core FD87A1 was barren of foraminifera as would be expected if the unit were deposited as a glacial till (Fig. 2). The presence of the *Cassidulina–Islandiella* biofacies in the basal-most part of this unit may be due to reworking of the older silts and clays.

Several ^{14}C dates have been obtained on wood and shell collected from the silt/clay/sand couplet interval and the silt/clay unit between 185 and 310 m in core FD87A1. These range from 24.46 ± 0.16 to 46.43 ± 0.88 ka (Fig. 2). In view of the lack of stratigraphic order in these ages, the dated material probably has been largely reworked from older units. Alternatively, as many of the dates are near the practical resolvable limit for ^{14}C dating, a shortage of radiogenic daughter atoms (the half-life of carbon is only 5,730 years) may be partially responsible for the jumbled results (Faure, 1986). Sediments below 256 m are barren, making a paleoenvironmental interpretation based on foraminifera impossible.

The part of core FD87A1 spanned by biofacies 2 (192.9 and 256 m) consists of silt/clay/sand couplets and triplets (197–256 m) and silt and clay (192.9–197 m). The former are lithologically continuous with the barren sediments found below (Fig. 2; Table 1). Jumbled ^{14}C dates indicate that reworking of microfossils is a major concern when interpreting the environment of this interval. However, *Cribroelphidium bartletti* dominates the fauna of the Biofacies 2 and is found nowhere else in the core. Therefore, a paleoenvironmental interpretation based on the presence of this species is considered reliable. In addition to the problematic radiocarbon dates, this interval is difficult to interpret because the ecology of the dominant species, *Cribroelphidium bartletti*, is not well known. *Cribroelphidium bartletti* has been recorded from generally shallow, high-latitude localities: for example Frobisher Bay (24 to 55 m depth); off western Greenland (25–82 m depth); off northern Greenland (13–31 m depth); and in the Gulf of Alaska at depths shallower than 150 m (Loeblich and Tappan, 1953; Todd and Low, 1967; Bergen and O'Neil, 1979; Smith, 1970).

R. Mathewes (written communication, 1990) has developed two alternative depositional hypotheses for this interval based on the distribution of pollen. Two pollen zones, FD-2 (the Alnus–Filicales Zone, 210–250 m) and FD-3 (the Picea–Abies–Sphagnum Zone, 180–210 m) span the interval where the *Cribroelphidium bartletti* biofacies was recovered. In option 1 Mathewes interprets the interval spanned by the FD-2 Zone as being deposited during the Fort Langley time interval (Everson Interstade; 13–11.4 ka). The interval spanned by the overlaying FD-3 Zone, which includes a non-foraminifera bearing diamicton at 185 m, is interpreted to be a Late Glacial deposit, possibly Sumas Till (11.4–10 ka; possibly correlative to the Younger Dryas event of eastern North America and Europe). In option 2 Mathewes suggests that the interval delineated by the FD-2 Zone is correlative to Coquitlam Drift (Evans Creek Stade and late Quadra Sand; 23–18 ka). The overlaying FD-3 Zone is interpreted in option 2 as indicative of Vashon Stade and Late Glacial Deposits (Vashon Till; 18–10 ka). The presence of *Cribroelphidium bartletti* in a Weichselian age fauna from Skaerumhed in Vendsyssel, Denmark, has been taken as evidence of interglacial conditions (Bahnson and others, 1974) so Mathewes' option 1 may be more consistent with the foraminiferal data. However, it is impossible to determine whether the limited glacial recession represented by the Everson Interstade would have warmed the marine environment sufficiently for this fauna to develop. Further analysis of *Cribroelphidium bartletti* distribution is required to determine whether this species fills the same paleoecological niche in Pleistocene localities from the west coast of North America. Based on the limited west coast distributional data available for *Cribroelphidium bartletti*, water depths are tentatively interpreted as being less than 150 m during deposition of the *Cribroelphidium bartletti* biofacies.

Biofacies 1, dominated by *Cribroelphidium excavatum*, occurs in core FD87A1 between 64.0 and 185 m and in core FD88A1 between 76.2 and 122.3 m (Figs. 2, 3; Tables 1, 2). This species is presently widely distributed in shallow, temperate and polar seas (Phleger, 1952; Loeblich and Tappan, 1953; Miller and others, 1982) and is also common in Pleistocene marine sections where it is often associated with near glacial conditions (Osterman, 1984). Hald and Vorren (1987) reported that occurrences of *Cribroelphidium excavatum* in warmer waters, such as nearshore North Sea and coastal North America, are indicative of salinities lower than 35‰.

Although several ecophenotypic variants of *Cribroelphidium excavatum* exist, only the "clavatum" phenotype of this species was found in these samples. This particular variant is indicative of either cold, normal marine waters (sometimes described as a "warm ice margin fauna"; Scott and others, 1989), or of waters characterized by slightly reduced salinities (Miller and others, 1982).

Although *Cribroelphidium excavatum* is an important component of modern foraminiferal faunas in the oceans surrounding North America, commonly comprising more than 30% of the fauna (Cockbain, 1963; Vilks and others, 1979; Miller and others, 1982), its representation is generally reduced from late Pleistocene-early Holocene occurrences where it often constitutes 50–80% of the foraminiferal fauna (Feyling-Hanssen, 1976; Knudsen, 1976; Osterman, 1984; Hald and Vorren, 1987; Rodriguez and Richard, 1986; Patterson, 1990b). Similarly, the frequency of *Cribroelphidium excavatum* (Biofacies 1) in early Holocene samples from cores FD87A1 and FD88A ranges up to 85.3%. Osterman (1984) suggests that the dramatic reduction in the percent frequency of *Cribroelphidium excavatum* in modern oceans is related to the retreat of glaciers and an associated reduction in suitable environments for this species. During the Holocene the ecospace utilized by this species has become reduced. Patterson (1990b) observed a similar reduction in the proportions of this species in late Pleistocene to modern samples in cores from Queen Charlotte Sound and southern Hecate Strait.

In the Strait of Georgia *Cribroelphidium excavatum* presently comprises no more than 24% of the fauna, primarily in Cockbain's (1963) "*Elphidium-Elphidiella*" biofacies and occurs in water depths averaging between 50 and 200 m. *Buccella frigida, Elphidiella nitida,* and *Nonionella stella,* common in the *Cribroelphidium excavatum* biofacies, are found in shallow waters and all along the west coast of North America including the Strait of Georgia (Culver and Buzas, 1985). Williams (1989) reports an apparently similar fauna (there are some taxonomic inconsistencies) to a maximum of 152 m on the present Fraser delta foreslope, although as Cockbain reported, elements of the fauna are present at greater depths elsewhere in the Strait of Georgia. Taking the Holocene decline of *Cribroelphidium excavatum* into account, the foraminiferal fauna of the *Cribroelphidium excavatum* biofacies in cores FD87A1 and FD88A1 is most similar to that presently found in the Strait of Georgia (Cockbain, 1963). Therefore, the silt/clay unit bearing the *Cribroelphidium excavatum* biofacies in both cores is interpreted to be ancestral Strait of Georgia prodelta deposits.

Based on an analysis of paleo-marsh deposits, Williams and Roberts (1989) estimate that there has been a relative sea-level rise of about 13 m in the region during the last 9,000 years. Considering only sediment thickness, without taking subsidence into account, water depths at the core FD87A1 locality were on the order of 150 m, 9,000 years ago during ancestral Strait of Georgia deposition (silt/clay interval). This paleodepth estimate is well within the range presently occupied by this biofacies in the modern Strait of Georgia. Therefore, based on sedimentological data and the present distribution of the *Cribroelphidium excavatum* biofacies in the Strait of Georgia, the depth of deposition for the silt/clay interval was probably between 150 and 200 m. Several radiocarbon dates from core FD87A1 indicate that the silt/clay interval was deposited between about 12 and 6 ka. Because of freshwater dilution by the Fraser River, salinities were probably similar to the relatively low values of 27–31‰ presently found in the strait. The presence of the "clavatum" phenotype of *Cribroelphidium excavatum* in this case is probably indicative of depressed salinities rather than particularly cold temperatures.

The facies change from silt and clay to sand at 132.8 m in core FD87A1 and at 76.2 m in core FD88A1 is interpreted as resulting from progradation of Fraser Delta foreset deposits over the floor of the Strait of Georgia. However, a much reduced *Cribroelphidium excavatum* biofacies foraminiferal fauna persists well into the sand interval in core FD87A1. The continued shallowing and freshening of the water due to progradation of delta sediments resulted in the eventual disappearance of the foraminifera from this locality around 6 ka (Fig. 2).

Examination of the foraminiferal faunas from these cores has resulted in the identification and characterization of depositional environments not readily recognizable by sedimentologic methods alone. Further analysis of foraminiferal faunas from the Fraser delta will be invaluable not only in providing information on past depositional environments but also in facilitating the interpretation and correlation of lithologically enigmatic cores.

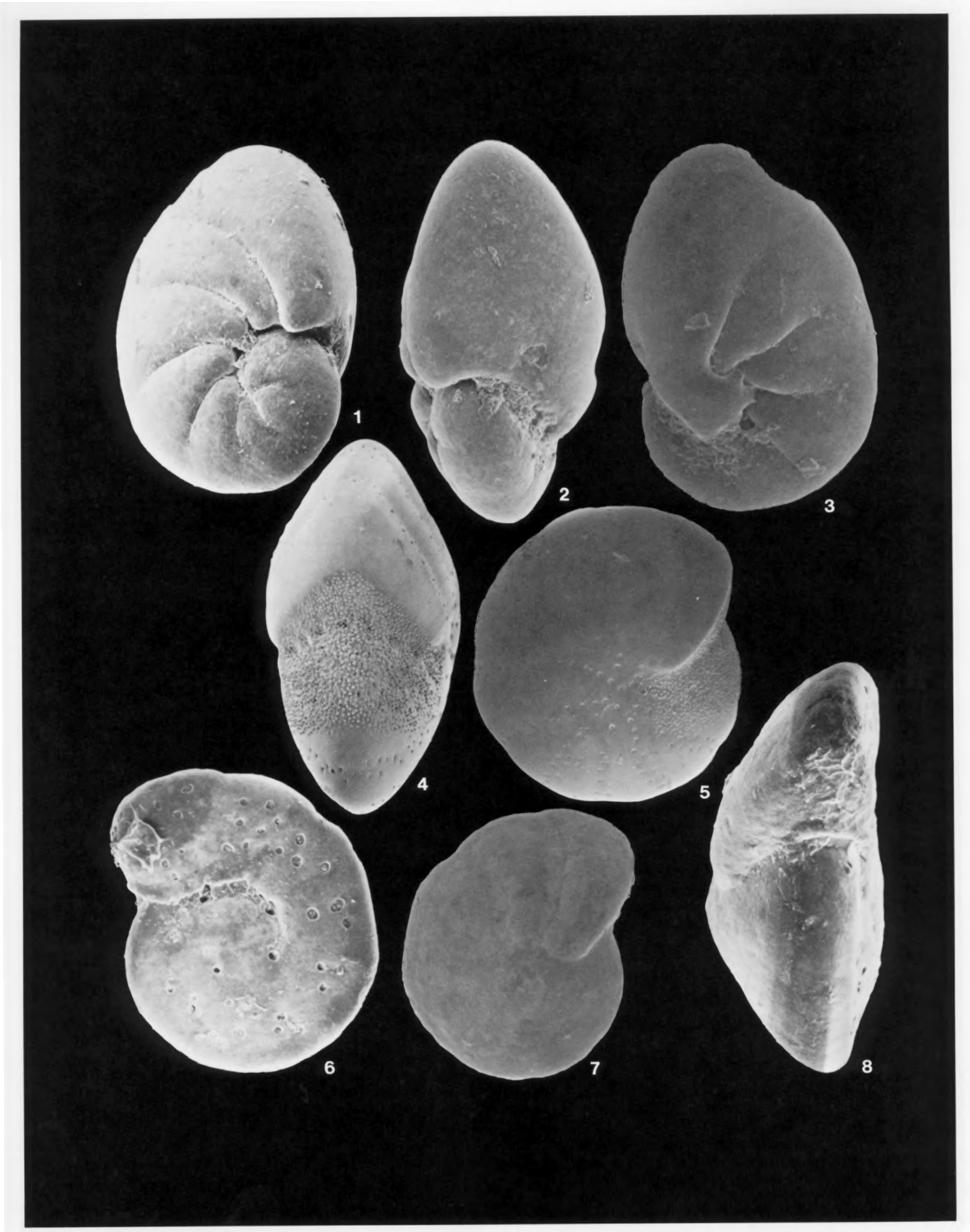
FAUNAL REFERENCE LIST

On the abbreviated list of species given below, bracketed names indicate the original generic designations.

PLATE 1

1 *Cribroelphidium excavatum* (Terquem). Side view of "clavata" phenotype hypotype (GSC 100754), sample 114, core FD87A1, ×297. **2, 3** *Cribroelphidium bartletti* (Cushman). **2** Apertural view of hypotype (GSC 100755) showing concentration of pustules on apertural face, sample 128, core FD87A1, ×235. **3** Side view of same hypotype showing concentration of pustules in umbilical region, ×230. **4–6** *Buccella frigida* Cushman. **4** Spiral view of hypotype (GSC 100756) showing slightly lobulate periphery, sample 114, core FD87A1, ×289. **5** Umbilical view of same hypotype showing typical concentration of pustules along sutures, ×281. **6** Edge view of same hypotype showing slightly inflated chambers, ×339. **7** *Cassidulina reniforme* Nørvang. Side view of hypotype (GSC 100757) showing typical broad lip almost filling aperture and finely perforate test, sample 143, core FD87A1, ×215. **8** *Islandiella norcrossi* (Cushman). Side view of hypotype (GCS 100758) showing toothplate protruding from aperture, sample 139, core FD87A1, ×151.


1
2
3
4
5
6
7
8


1
2
3
4
5
6
7
8

Original references are cited in the Catalogue of Foraminifera (Ellis and Messina, 1940 and supplements). Plate and figure numbers refer to taxa illustrated here.

Order Foraminiferida

Angulogerina angulosa (Williamson), 1858. [*Uvigerina*].
Angulogerina fluens TODD (in Cushman and McCulloch), 1948.
Astrononion gallowayi LOEBLICH and TAPPAN, 1953.
Bolivina decussata BRADY, 1881.
Brizalina pacifica (Cushman and McCulloch), 1942, [*Bolivina acerosa* Cushman var.].
Buccella frigida (Cushman), 1922, [*Pulvinulina*], (Pl. 1, Figs. 4–6).
Buccella tenerrima (Bandy), 1950, [*Rotalia*].
Buliminella elegantissima (d'Orbigny), 1839 (a), [*Bulimina*].
Cassidulina reniforme NØRVANG, 1945, [*Cassidulina crassa* d'Orbigny var.], (Pl. 1, Fig. 7).
Cibicides sp.
Cornuspira involvens (Reuss), 1850, [*Operculina*].
Cribroelphidium bartletti (Cushman), 1933, [*Elphidium*], (Pl. 1, Figs. 2, 3).
Cibroelphidium excavatum (Terquem), 1876, [*Polystomella*], (Pl. 1, Fig. 1).
Cibroelphidium frigidum (Cushman), 1933, [*Elphidium*].
Cibroelphidium groenlandica (Cushman), 1933, [*Elphidium*].
Cribroelphidium microgranulosum (Galloway and Wissler), 1927b, [*Themeon*].
Cribroelphidium tumidum (Natland), 1938, [*Elphidium*].
Dyocibicides biserialis CUSHMAN and VALENTINE, 1930.
Elphidiella nitida CUSHMAN, 1941, (Pl. 2, Figs. 4, 5).
Epistominella pacifica (Cushman), 1927, [*Pulvinulina*].
Epistominella vitrea PARKER (in Parker, Phleger, and Peirson), 1953.
Favulina melo (d'Orbigny), 1839 (a), [*Oolina*].
Fissurina sp. A.
Fissurina sp. B.
Fissurina labiata (Buchner), 1940, [*Lagena laevigata* var.].
Glandulina laevigata (d'Orbigny), 1826, [*Nodosaria* (*Glanduline*)].
Globigerina bulloides D'ORBIGNY, (1826).
Globigerina quinqueloba NATLAND, 1938.
Globocassidulina crassa (d'Orbigny), 1839, [*Cassidulina*].
Globobulimina auriculata (Bailey), 1851, [*Bulminia*].
Homalohedra apiopleura (Loeblich and Tappan), 1953, [*Lagena*].
Homalohedra borealis (Loeblich and Tappan), 1954, [*Oolina*].
Islandiella norcrossi (Cushman), 1933, [*Cassidulina*], (Pl. 1, Fig. 8).
Laevidentalina sp.
Lagena gracillima (Seguenza), 1862, [*Amphorina*].
Lagena semilineata WRIGHT, 1886.
Lagena spicata CUSHMAN and McCULLOCH, 1950, [*Lagena sulcata* (Walker and Jacob) var.].
Lagena striata (d'Orbigny), 1839 (a), [*Oolina*].
Lagena substriata WILLIAMSON, 1848.
Lobatula fletcheri (Galloway and Wissler), 1927a, [*Cibicides*], (Pl. 2, Figs. 6–8).
Neogloboquadrina pachyderma (Ehrenberg), 1861, [*Aristerospira*].
Nonionella stella CUSHMAN and MOYER, 1930, [*Nonionella miocenica* Cushman var.], (Pl. 2, Figs. 1–3).
Nonionella turgida WILLIAMSON, 1858.
Nonionellina labradoricum (Dawson), 1870, [*Nonionina scapha* var.].
Parafissurina sublata PARR, 1950.
Procerolagena distoma (Parker and Jones in Brady), 1864, [*Lagena*].
Pullenia subcarinata (d'Orbigny), 1839a, [*Nonionina*].
Pyrgo sp.
Quinqueloculina akneriana D'ORBIGNY, 1846.
Quinqueloculina seminulum (Linné), 1758, [*Serpula*].
Siphonaperta stalkeri (Loeblich and Tappan), 1953, [*Quinqueloculina*].
Rosalina columbiensis (Cushman), 1925, [*Discorbis*].
Scutuloris tegminis LOEBLICH and TAPPAN, 1953.
Sestronophora arnoldi LOEBLICH and TAPPAN, 1957.
Stainforthia complanata (Egger), 1895, [*Virgulina schreibersiana* Czjzek var.].
Triloculina trigonula (Terquem), 1876, [*Quinqueloculina*].

REFERENCES

AGES, A., and WOOLARD, A., 1976, The tides in the Fraser Estuary; Canada Department of Environment, Institute of Ocean Sciences: Pacific Marine Science Report 76-5, 100 pp.

ARMSTRONG, J. E., 1981, Post-Vashon Wisconsin glaciation, Fraser Lowland, British Columbia: Geological Survey of Canada, Bulletin 322, 34 p.

———, and BROWN, W. L., 1953, Ground-water resources of Surrey Municipality, British Columbia: Geological Survey of Canada, Water Supply Paper 322, 48 p.

———, CRANDELL, D. R., EASTERBROOK, D. J., and NOBLE, J. B., 1965, Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington: Geological Society of America Bulletin, v. 76, p. 321–330.

BAHNSON, H., PETERSON, K. S., KONRADI, P. B., and KNUDSEN, K. L., 1974, Stratigraphy of Quaternary deposits in the Skaerumhede II boring: Lithology, molluscs and foraminifera: Danmarks Geologiske Undersøgelse, Årbog 1973, p. 27–62.

BERGEN, F. W., and O'NEIL, P., 1979, Distribution of Holocene foraminifera in the Gulf of Alaska: Journal of Paleontology, v. 53, p. 1267–1292.

CLAGUE, J. J., 1981, Late Quaternary geology and geochronology of British Columbia: Geological Survey of Canada Paper 80-35, 41 p.

———, LUTERNAUER, J. L., and HERBA, R. J., 1983, Sedimentary environments and postglacial history of the Fraser Delta and lower Fraser Valley, British Columbia: Canadian Journal of Earth Sciences, v. 20, p. 1314–1326.

COCKBAIN, A. E., 1963, Distribution of foraminifera in Juan de Fuca and Georgia Straits, British Columbia, Canada: Contributions From the Cushman Foundation for Foraminiferal Research, v. 14, p. 37–57.

CULVER, S. J., and BUZAS, M. A., 1985, Distribution of Recent benthic foraminifera off the North American Pacific coast from Oregon to Alaska: Smithsonian Contributions to the Marine Sciences, Number 26, 234 p.

CUSHMAN, J. A., 1925, Recent foraminifera from British Columbia: Contributions from the Cushman Laboratory for Foraminiferal Research, v. 1, p. 38–47.

———, and TODD, R., 1947, Foraminifera from the coast of Washington: Cushman Laboratory for Foraminiferal Research Special Publication 21, 23 p.

←

PLATE 2

1–3 *Nonionella stella* Cushman and Moyer. **1** Spiral view of hypotype (GSC 100759) showing low trochospiral coil, sample 107, core FD87A1, ×211. **2** Apertural view of same hypotype showing rounded periphery, ×225. **3** Umbilical view of same hypotype showing characteristic flaplike projection overhanging the umbilicus, ×217. **4, 5** *Elphidiella nitida* Cushman. **4** Apertural view of hypotype (GSC 100762) showing concentration of pustules around aperture, sample 107, core FD87A1, ×116. **5** Side view of same hypotype showing characteristic double rows of pores along sutures and fourteen chambers in final whorl, ×94. **6–8** *Lobatula fletcheri* (Galloway and Wissler). **6** View of perforate, flattened spiral side of hypotype (GSC 100761), sample 107, core FD87A1, ×114. **7** Umbilical view of same hypotype showing curved sutures and slightly inflated chambers, ×306. **8** Edge view of same hypotype showing gently convex spiral side and rounded periphery, ×406.

ELLIS, B. F., and MESSINA, A., 1940, Catalogue of Foraminifera; New York, American Museum of Natural History, with supplements.

ELVERHØI, A., LIESTØL, O., and NAGY, J., 1980, Glacial erosion, sedimentation and microfauna in the inner part of Kongsfjorden, Spitsbergen: Norsk Polarinstitutt, v. 172, p. 33–62.

FAURE, G., 1986, Principles of Isotope Geology: Second Edition, John Wiley & Sons, New York, 589 p.

FEYLING-HANSSEN, R.W., 1954, Late Pleistocene foraminifera from the Oslofjord area, southeast Norway: Norsk Geologisk Tidsskrift, v. 33, p. 109–152.

———, 1964, Foraminifera in late Quaternary deposits from the Oslofjord area: Norges Geologiske Undersökelse, v. 225, p. 1–385.

———, 1976, A mid-Wisconsinian interstadial on Broughton Island, Arctic Canada, and its foraminifera: Arctic and Alpine Research, v. 8, p. 161–182.

———, 1981, Foraminiferal indication of Eemian interglacial in the northern Sea: Bulletin of the Geological Society of Denmark, v. 31, p. 175–189.

———, JØRGENSEN, J. A., KNUDSEN, K. L., and ANDERSEN, A. L. L., 1971, Late Quaternary foraminifera from Vendsyssel, Denmark and Sandnes, Norway. Bulletin of the Geological Society of Denmark, v. 21, p. 61–317.

FYLES, J. G., 1963, Surficial geology of Horne Lake and Parksville map-areas, Vancouver Island, British Columbia: Geological Survey of Canada, Memoir 318, 142 p.

GALLAGHER, M. T., 1979, Substrate controlled biofacies: Recent foraminifera from the continental shelf and slope of Vancouver Island, British Columbia: Unpublished Ph.D. Thesis, University of Calgary, 232 p.

GUILBAULT, J.-P., 1980, A stratigraphic approach to the study of the Late-Glacial Champlain Sea deposits with the use of foraminifera: Unpublished Licentiat Thesis, Aarhus University, Denmark, 294 p., University microfilms no. 82-27, 762.

———, 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.

HALD, M., and VORREN, T. O., 1987, Foraminifera stratigraphy and environment of late Weichselian deposits on the continental shelf off Troms, northern Norway: Marine Micropaleontology, v. 12, p. 129–160.

HEBDA, R. J., 1977, The paleoecology of a raised bog and associated deltaic sediments of the Fraser River delta: Unpublished Ph.D. Thesis, University of British Columbia, Vancouver, 202 p.

HUTCHINSON, I., 1990, Intertidal marshes of the Fraser River Delta: The geological theatre and the ecological play: Geological Association of Canada/Mineralogical Association of Canada Annual Meeting, May 16–18, 1990, Programs with Abstracts, v. 15, p. A62.

JONES, G. D., and ROSS, C. A., 1979, Seasonal distribution of foraminifera in Samish Bay, Washington: Journal of Paleontology, v. 53, p. 245–257.

JONG, S. H., DE, and SIEBENHUENER, H. F. W., 1972, Seasonal and secular variations of sea level on the Pacific coast of Canada: Canadian Surveyor, v. 26, p. 4–19.

KNUDSEN, K. L., 1976, Foraminifera faunas in Weichselian stadial and interstadial deposits of the Skaerumhede boring, Jutland Denmark, *in* Schafer, C., and Pelletier, B. R. (eds.), First International Symposium on Benthonic Foraminifera of Continental Margins, Halifax, 1975, Part B; Paleoecology and Biostratigraphy. Maritime Sediments Special Publication 1, p. 131–151.

LOEBLICH, A. R., JR., and TAPPAN, H., 1953, Studies of Arctic Foraminifera: Smithsonian Miscellaneous Collections, v. 121, 150 p.

LOWDON, J. A., ROBERTSON, I. M., and BLAKE, W., JR., 1977, Geological Survey of Canada radiocarbon dates XVII: Geological Survey of Canada Paper 77-7, 25 p.

LUTERNAUER, J. L., 1988, Geoarchitecture, evolution, and seismic risk assessment of the southern Fraser River delta, B.C. Current Research, Part E, Geological Survey of Canada, Paper 88-1E, p. 105–109.

MATHEWS, W. H., and SHEPARD, F. P., 1962, Sedimentation of Fraser River delta, British Columbia: American Association of Petroleum Geologists Bulletin 46, p. 1416–1443.

———, FYLES, J. G., and NASMITH, H. W., 1970, Postglacial crustal movements in southwestern British Columbia and adjacent Washington State: Canadian Journal of Earth Sciences, v. 7, p. 690–702.

McCULLOCH, I. A., 1977, Qualitative observations on Recent foraminiferal tests with emphasis on the eastern Pacific: University of Southern California, Los Angeles, 1078 pp. (3 pts.).

McKENNA, G. T., and LUTERNAUER, J. L., 1987, First documented large failure at the Fraser River delta front, British Columbia: Current Research, Part A, Geological Survey of Canada, Paper 87-1A, p. 919–924.

MILLER, A. A. L., SCOTT, D. B., and MEDIOLI, F. S., 1982, *Elphidium excavatum* (Terquem); ecophenotypic versus subspecific variation: Journal of Foraminiferal Research, v. 12, p. 116–144.

MILLIMAN, J. D., 1980, Sedimentation in the Fraser River and its estuary, southwestern British Columbia (Canada): Estuarine and Coastal Marine Science, v. 10, p. 609–633.

MILNE, W. G., ROGERS, G. C., RIDDIHOUGH, R. P., McMECHAN, G. A., and HYNDMAN, R. D., 1978, Seismicity of western Canada: Canadian Journal of Earth Sciences, v. 15, p. 1170–1193.

OSTERMAN, L., 1984, Benthic foraminifera zonation of a glacial/interglacial transition from Grobisher Bay, Baffin Island, North West Territories, Canada, *in* Orleti, H. J. (ed.), Benthos '83, Second International Symposium on Benthic Foraminifera (Pau, 1983). Elf Aquitane, Esso REP, TOTAL, CFP, Bordeaux, France, p. 471–476.

PATTERSON, R. T., 1990, Intertidal benthic foraminiferal biofacies on the Fraser River Delta, British Columbia: Modern distribution and paleoecological importance: Micropaleontology, v. 36, p. 229–244.

———, Benthic foraminiferal biofacies in Queen Charlotte Sound and southern Hecate Strait, British Columbia: Late Quaternary distribution and paleoecological importance: Geological Survey of Canada Paper. (In press).

———, BRUNNER, C. A., CAPO, R., and DAHL, J., 1990, A paleoenvironmental study of Pleistocene foraminifera of the Santa Barbara Formation, at Santa Barbara, California: Journal of Paleontology, v. 64, p. 1–25.

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

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

———, 1967, Marsh foraminiferal patterns, Pacific coast of North America: Universidad Nacional Autónoma de México Instituto de Biologia Anales 38, Ser. Ciencia del Mar y Limnologia, v. 1, p. 11–38.

RIDDIHOUGH, R. P., 1979, Gravity and structure of an active margin—British Columbia and Washington: Canadian Journal of Earth Sciences, v. 16, p. 350–363.

RODRIGUEZ, C. G., and RICHARD, S. H., 1986, An ecostratigraphic study of late Pleistocene sediments of the western Champlain Sea Basin, Ontario and Quebec: Geological Survey of Canada Paper 85–22, 33 p.

SCOTT, D. B., 1974, Recent benthonic foraminifera from Samish and Padilla Bays, Washington: Northwest Science, v. 48, p. 211–218.

———, and MEDIOLI, F. S., 1980, Post-glacial emergence curves in the maritimes determined from marine sediments in raised basins: Canadian Coastal Conference Proceedings, April 22–24, 1980, Burlington, Ontario, p. 428–446.

———, 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.

SEJRUP, H.-P., and GUILBAULT, J.-P., 1980, *Cassidulina reniforme* and *C. obtusa* (Foraminifera), taxonomy, distribution, and ecology: Sarsia, v. 65, p. 79–85.

SMITH, R. K., 1970, Late glacial foraminifera from southeast Alaska and British Columbia and a world-wide high northern latitude shallow-water faunal province: Archives des Sciences, v. 23, p. 675–702.

———, 1978, Systematics of the North American high latitude very shallow cold water foraminiferal fauna. Archives des Sciences, v. 31, p. 133–262.

TASSONE, B. L., 1990, Recent growth patterns of the Fraser River delta: Geological Association of Canada/Mineralogical Association of Canada Annual Meeting, May 16–18, 1990, Programs with Abstracts, v. 15, p. A129.

THOMPSON, R. E., 1981, Oceanography of the British Columbia coast: Canadian Special Publication of Fisheries and Aquatic Sciences, v. 56, p. 291.

TODD, R., and LOW, D., 1967. Recent foraminifera from the Gulf of Alaska and southeastern Alaska: U.S. Geological Survey Professional Paper 573-A, 58 p.

VILKS, G., WAGNER, F. J. E., and PELLTIER, B. R., 1979, The Holocene marine environment of the Beaufort Shelf: Geological Survey of Canada Bulletin 303, 43 p.

WILLIAMS, H. F. L., 1989, Foraminiferal zonations on the Fraser River Delta and their application to paleoenvironmental interpretations. Paleogeography, Paleoclimatology, Paleoecology, v. 73, p. 39–50.

———, and ROBERTS, M. C., 1989, Holocene sea-level change and delta growth: Fraser River delta, British Columbia: Canadian Journal of Earth Sciences, v. 26, p. 1657–1666.

Received 23 February 1990
Accepted 1 June 1990