Intertidal benthic foraminiferal biofacies on the Fraser River Delta, British Columbia: Modern distribution and paleoecological importance

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ABSTRACT: Six foraminiferal biofacies from the marshes and tidal flats of the Fraser Delta, British Columbia vary in faunal makeup according to differences in elevation, salinity and organic content of surficial sediments. Based on the distribution of these biofacies, the marsh may be divided into two major faunal zones: a High Marsh Zone [≈>0.8m above mean sea level (a.m.s.l.)], and a Low Marsh Zone (≈0.0 to 0.8m a.m.s.l.). The fauna from the High Marsh Zone includes the *Jadammina macrescens* Biofacies, indicative of low salinity, and the *Jadammina macrescens/Trochammina inflata* Biofacies, indicative of higher salinity. The Low Marsh Zone is characterized by the *Ammonia beccarii* Biofacies. A Higher Low Marsh Zone (≈ +0.5 to +0.8m a.m.s.l.) is characterized by the presence of the *Cribroelphidium gunteri* Biofacies, whereas a Lower Low Marsh Zone (≈ 0.0 to +0.5m a.m.s.l.) is delineated by the *Miliammina fusca* Biofacies. The *Trochammina pacifica* Biofacies, as well as the *Miliammina fusca* Biofacies, occur outside the marshes in tidal flats vegetated by *Zostera marina* (eel grass). The *Trochammina pacifica* Biofacies may have developed in response to the high organic content of some sediments.

INTRODUCTION

Unlike the eastern and Gulf coasts of North America, where extensive marine marshes cover large areas of the coastal plain, the Pacific coast is primarily marked by highlands located near the coast. The few marine marshes that are found on the western margin are generally small and confined to alluvial lowland areas where streams discharge (Phleger 1967). The presence of extensive marsh deposits on the Fraser River Delta in southern British Columbia represents a major departure from this general scheme.

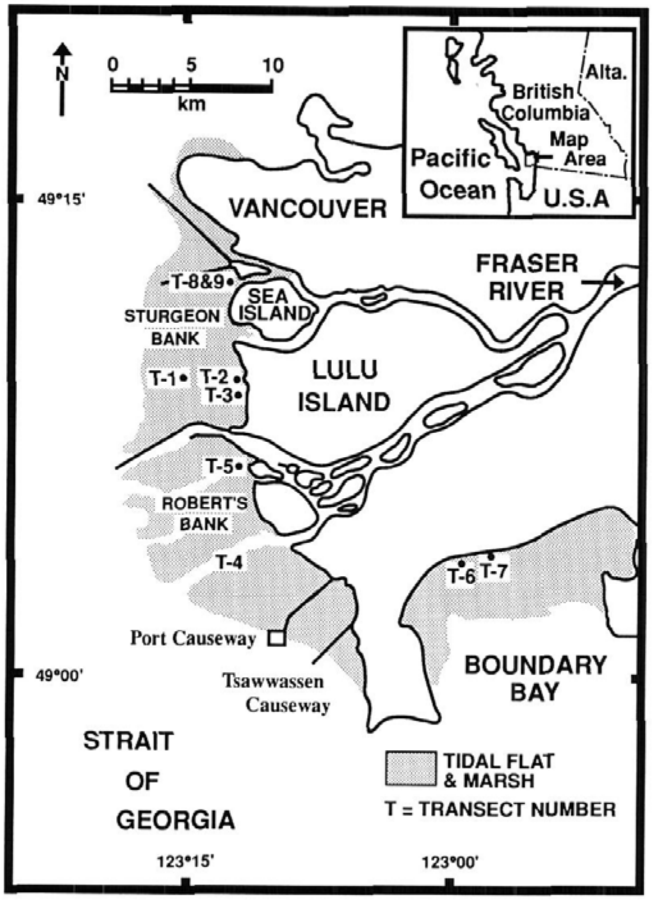
Recently, the Fraser River Delta has been the subject of increased scrutiny, as it is one of the most environmentally sensitive regions of North America. In spring, approximately 300 million sockeye salmon reside in the Delta before migrating to sea; in winter, over 1.5 million ducks and other water fowl inhabit the region. In addition, over half the population of British Columbia lives along the Delta, which is also the site of a multitude of industries. Toxic discharges from these industries, as well as from many land reclamation projects under development along the Delta may very well lead to ecological disaster (Kennedy 1986). Of particular interest to the geologist is the very real potential of a large-scale earthquake, which would not only alter the face of the Delta but also devastate metropolitan Vancouver (Luternauer 1988; McKenna and Luternauer 1987).

Benthic foraminifera have previously been found in distributional biozones in tidal flat/marsh environments. These biozones have been shown to correspond closely with gradations in elevation (Goldstein and Frey 1986; Scott 1976a; Scott and Medioli 1980a). Identification of these biozones down core has proven useful in interpreting depositional environments and in identifying former sea level positions within drill cores (Scott and Medioli 1986; Goldstein 1988).

The purpose of this study is to document fully the foraminiferal fauna characteristic of the Fraser Delta and to identify the surficial tidal flat/marsh foraminiferal biofacies of the Delta system. Data from the Fraser Delta will be compared with previously documented distributional patterns in other North American regions, such as James and Hudson bays (Scott and Martini 1982), Nova Scotia (Scott and Medioli 1980a), Prince Edward Island (Scott et al. 1981), Georgia (Goldstein and Frey 1986), southern California (Scott 1976a,b), the Gulf Coast (Lankford 1959; Phleger 1965), Washington State (Scott 1974), and elsewhere. The baseline data provided by the present study also will be useful in interpreting both the paleoenvironment and sedimentology of cores from the Delta.

Previous Work

Very few studies on Recent shelf and marsh foraminifera have been carried out on the Pacific coast of British Columbia. Cushman (1925) described a few species found in shallow waters (14–45m) in Virago and Queen Charlotte sounds. Cushman and Todd (1947a) also described the Recent fauna from coastal areas of the state of Washington near the British Columbia border. McCulloch (1977) illustrated a few taxa from three stations surrounding Vancouver Harbour. Cockbain (1963) studied the distribution of foraminifera in depths ranging from 112 to 293 meters from the Strait of Georgia. As part of a cursory examination of marsh foraminiferal faunas along the Pacific Coast of North America, Phleger (1967) analysed samples from several localities in British Columbia and the state of Washington. Based on three samples from a marsh located along Phillips Arm, British Columbia, Phleger concluded that the small foraminiferal populations at that location consisted of only two species, *Miliammina fusca* (Brady) 1870, and *Trochammina inflata* (Montagu) 1808. Phleger (1967) also examined the fauna from a marsh skirting Gray's Harbor, Washington. The fauna of the tidal flat fringing this marsh was composed almost exclusively of species of *Elphidium* de Mont-



TEXT-FIGURE 1
Location map of Fraser Delta showing general position of Transects 1–9. Exact localities of samples used in this analysis are given in table 1.

fort 1808. Most marsh samples studied by Phleger were dominated by *Miliammina fusca* and *Jadammina macrescens* (Brady) 1870.

Phleger (1967) also examined 13 samples from marshes located at Sea Island and Smokey Tom Island on the Fraser Delta. Faunas reported at these localities consist entirely of agglutinated taxa that could be divided into two assemblages. The first assemblage, located in the marsh itself, was composed primarily of *Miliammina fusca,* with abundant *Ammobaculites* sp. and *Ammotium salsum* (Cushman and Brönniman) 1948. In addition to being dominated by *Miliammina fusca,* the second assemblage, associated with the tidal flats, also contained a limited number of *Jadammina macrescens.*

In a distributional study of shallow water foraminifera from Samish and Padilla bays, Washington, Scott (1974) recognized six foraminiferal assemblages. Most of these assemblages were dominated by *Trochammina pacifica* Cushman 1925, and varying percentages of *Miliammina fusca.* Jones and Ross (1979) found that the foraminiferal populations in Samish Bay vary seasonally. *Trochammina pacifica* and *Miliammina fusca* make up nearly the entire fauna in the late fall, winter, and early spring, while other species such as *Cribroelphidium excavatum* (Terquem) 1876, and *Ammonia beccarii* (Linné) 1758, dominate the biofacies in the late spring and summer.

More recently, Williams (1989) undertook a study of 24 samples from the tidal flat and marshes of Sturgeon Bank. He identified three well-defined elevation zones within the inter-tidal area. The highest elevation zone, composed almost entirely of *Jadammina macrescens* [identified by Williams as *Polystomammina grisea* (Earland) 1934] was located in higher high water, between +50 and +140cm above mean sea level (a.m.s.l.). *Ammonia beccarii* was most abundant in the narrow second elevation zone between +30 and +50cm a.m.s.l. *Miliammina fusca* dominated the third zone between 0 and +30cm a.m.s.l.

Physiography

The Fraser River, with a mean discharge of 3400m^3/s, is the largest river that reaches the west coast of Canada (Mathews and Shepard 1962). Discharging into the Strait of Georgia, the river forms a delta with a surface area of over 1000km^2 (text-fig. 1). Developed entirely during the 10,000 to 11,000 years following deglaciation in the area, the Delta consists of a triangular area 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 et al. 1983). The subaerial portion of the Delta ranges from one to five meters above mean sea level, and extends approximately 15 to 23km from west to south. The Delta runs from a narrow gap in the Pleistocene uplands at New Westminster and meets the sea along a 40km perimeter. Twenty-seven km of this perimeter face westward, and are adjacent to the 4 main distributary channels of the river. The remaining 13km is separated from the other portion of the perimeter by Point Roberts Peninsula, a former island, and face southward toward Boundary Bay.

The Fraser Delta appears unique among the deltas of the Puget Trough lowlands. Based on a multivariate cluster analysis of the morphological and physical environmental characteristics of 17 deltas from this region, Hutchinson (1988) found that the Fraser Delta represented a distinct cluster. Hutchinson also found the Fraser Delta distinct on the basis of drainage basin size, and the exposure of its delta front.

The sediment discharged on the Fraser Delta is dominated by sand, particularly during freshet, a two to three month period in late spring and early summer (Milliman 1980). During the remainder of the year, when the sedimentation rate decreases, silt and clay form the bulk of the sediment.

Both Sturgeon Bank and Robert's Bank are mantled by fine to medium sand. Sedimentation rates tend to be higher on Sturgeon Bank than on Robert's Bank due to a combination of northward-oriented longshore drift and the Coriolis effect. Exact sedimentation rates, however, have never been determined (Luternauer 1980). The tidal flats extend about 6 km from the landward edge of the Delta to its foreslope and exhibit an average dip of approximately 1.5°. The main portion of the intertidal platform, however, slopes only approximately 0.05°. A discontinuous fringe portion of marsh, underlain primarily by muddy sediments, lies at the landward edges of both Sturgeon and Robert's banks (Luternauer 1980).

The Boundary Bay portion of the Fraser Delta is presently inactive. The Fraser River has not entered the western part of this bay for 5000 years, as evidenced by the lack of any river sediments in the continuous late Holocene organic sequence in

Burns Bog, between Boundary Bay and the Fraser River (Clague et al. 1983). Surface sediments on the Boundary Bay tidal flats consist almost entirely of very fine to fine, well to very well sorted sands that gradually become more fine shoreward. Salt marsh vegetation skirts the shore of the Bay. Sedimentation rates are low (0.42mm/yr), the western part of the salt marsh prograding while the eastern part recedes (Kellerhals and Murray 1969). The maximum tidal range on the Delta is approximately 5m at the mouth of the river, and decreases landward and seasonally in connection with increasing river flow (Ages and Woollard 1976).

Vegetational Characteristics

The tectonically active western continental margin provides few sheltered areas in which fluvial action or longshore drift supply abundant sediment. Hence, marshes along the Pacific coast generally are poorly developed compared with those on the east coast of North America. The marshes of the Fraser River Delta represent the most extensively developed west coast marshes. Plant communities in these marshes are taxonomically and ecologically similar to the estuarine and deltaic marsh plant communities of Washington and Oregon. Hutchinson (1982) found that the distribution of marsh plant species was most closely determined by elevation (*Typha, Potentilla,* and *Distichlis*) and elevation plus salinity (*Scirpus, Carex,* and *Agrostis*). He also noted that variations in vegetation patterns were a function of fluvial regimes that influence salinity and sediment.

Hutchinson (1982) observed that the flora of the marsh off Lulu Island, adjacent to Sturgeon Bank, represented three distinct biozones (text-fig. 1). The species *Scirpus americanus* (threesquare) and *Scirpus maritimus* (sea bulrush) dominate the low marsh; *Carex lyngbyei* (Lyngbye's sedge), *Triglochin maritimum* (arrowgrass) and *Scirpus maritimus* pervade the middle zone; and *Agrostis alba* (creeping bentgrass), *Potentilla pacifica* (silverweed), *Distichlis spicata* (salt grass), and *Typha latifolia* (cattail) characterize the high marsh.

A cluster analysis of vegetation on 17 deltas in the Puget Trough (Hutchinson 1988), identified three distinct vegetation categories. The Fraser Delta falls into Hutchinson's fairly homogeneous Type B delta grouping, characterized by the relative prominence of *Scirpus*-dominated communities that inhabit low elevations on the marsh platform. *Carex-Triglochin* communities commonly are found in the mid-high marsh of Type B deltas also.

Swinbanks and Murray (1981), determined that the marsh flora of Boundary Bay had a decidedly different character than that of the active margin of the Delta. They divided the marsh into two zones: the upper marsh is dominated by such species as *Atriplex patula* (orache), and *Grindelia integrifolia* (gumweed), and the lower marsh is dominated by more salt-tolerant halophytes such as *Salicornia virginica*, *Salicornia europea* (both species are commonly known as sea asparagus), *Triglochin maritimum* and *Distichlis spicata.* However, Hutchinson (1982), classified *Distichlis spicata* as primarily a high marsh species, and found that *Triglochin maritimum* was more characteristic of middle marsh environments. Because of these apparent inconsistencies, re-examination of the marsh floral zonations of Boundary Bay would seem to be required. In addition, portions of the sandy banks found below mean sea level (b.m.s.l.), outside of the marsh area, are characterized by beds of *Zostera marina* (eel grass).

TABLE 1

Latitude and longitude of sample stations in the marshes and on the tidal flats of the Fraser River Delta. Species names for the floral symbols listed with each station are as follows: AGAL (*Agrostis alba*); ATPA (*Atriplex patula*); CALY (*Carex lyngbyei*); DECE (*Deschampsia caespitosa*); DISP (*Distlichlis spicata*); GRIN (*Grindelia integrifolia*); JUBA (*Juncus balticus*); POPA (*Potentilla pacifica*); SAEU (*Salicornia europea*); SAVI (*Salicornia virginica*); SCAM (*Scirpus americanus*); SCMA (*Scirpus maritimus*); SCVA (*Scirpus validus*); TRMA (*Triglochin maritimum*); TYLA (*Typha latifolia*); ZOMA (*Zostera marina*). (*) Signifies dominant floral species at each station.

Sample Number	Latitude	Longitude	Environment	Vegetation
T1-2	49° 08.91'	123° 12.61'	Marsh	*SCAM; SCMA
T1-3	49° 08.60'	123° 12.49'	Marsh	*SCAM; SCMA
T1-5	49° 08.11'	123° 12.45'	Marsh	*SCAM; SCMA
T1-7	49° 08.02'	123° 13.21'	Marsh	*SCAM; SCMA
T1-9	49° 08.42'	123° 13.59'	Tidal Flat	Absent
T1-10	49° 08.67'	123° 13.60'	Tidal Flat	ZOMA
T1-19	49° 09.72'	123° 12.72'	Marsh	*SCAM; SCMA
T1-20	49° 10.02'	123° 12.89'	Marsh	*SCAM; SCMA
T1-21	49° 09.99'	123° 13.68'	Tidal Flat	ZOMA
T1-28	49° 12.10'	123° 13.17'	Tidal Flat	ZOMA
T1-31	49° 11.78'	123° 13.57'	Marsh	*SCAM; SCMA
T1-33	49° 10.93'	123° 13.53'	Tidal Flat	ZOMA
T1-39	49° 10.49'	123° 15.37'	Tidal Flat	Absent
T1-43	49° 10.48'	123° 13.65'	Tidal Flat	Absent
T2-2	100 m due west of 49° 09.35'	123° 11.70'	Marsh	*SCMA; *TYLA
T2-3	200 m due west		Marsh	*CALY; *DISP; TRMA; POPA; AGAL
T2-4	300 m due west		Marsh	*SCMA; SCAM
T2-5	400 m due west		Marsh	*SCMA; SCAM
T2-6	500 m due west		Marsh	*SCMA; SCAM
T2-7	600 m due west		Marsh	*SCMA; SCAM
T2-10	900 m due west		Marsh	*SCAM
T3-1	49° 12.60'	123° 12.60'	Marsh	*SCAM
T3-2	100 m due east		Marsh	*SCAM
T3-3	200 m due east		Marsh	*SCMA; SCAM
T3-4	300 m due east		Marsh	*SCMA; SCAM
T3-5	400 m due east		Marsh	*SCMA; SCAM
T3-6	500 m due east		Marsh	*SCMA; SCAM
T3-7	600 m due east		Marsh	*SCMA; SCAM
T3-8	700 m due east		Marsh	*SCMA; SCAM
T3-9	800 m due east		Marsh	*CALY; *DISP; TRMA; POPA; AGAL
T3-10	900 m due east		Marsh	*CALY; *DISP; TRMA; *POPA; AGAL
T3-11	1000 m due east		Marsh	*CALY; *DISP; TRMA; *POPA; AGAL
T3-12	1100 m due east		Marsh	TYLA
T4-5	49° 04.86'	123° 11.55'	Marsh	SCAM
T4-20	49° 02.24'	123° 08.75'	Tidal Flat	ZOMA
T4-21	49° 02.32'	123° 07.98'	Tidal Flat	ZOMA
T4-24	49° 01.17'	123° 06.90'	Tidal Flat	ZOMA
T4-25	49° 01.72'	123° 01.72'	Tidal Flat	ZOMA
T5-1	49° 06.35'	123° 11.10'	Marsh	*TYLA
T5-2 (2C)	100 m west		Marsh	*SCVA; CALY
T5-3	200 m west		Marsh	*SCVA; CALY
T5-4	300 m west		Marsh	*CALY; *JUBA; SCVA
T5-5	400 m west		Marsh	*CALY; *JUBA; SCVA
T5-6	500 m west		Marsh	*CALY; *JUBA; SCVA
T5-9	800 m west		Marsh	*JUBA
T5-10	900 m west		Marsh	*JUBA
T5-11	1000 m west		Marsh	*CALY; TRMA
T5-12	1100 m west		Marsh	*SCAM; *SCVA
T6-1	49° 03.65'	123° 10.35'	Marsh	*SAVI; *SAEU; ATPA
T6-2	50 m at 150° SE		Marsh	*SAVI; *SAEU; ATPA
T6-3	100 m at 150° SE		Marsh	*DISP; *SAVI; TRMA; GRIN
T6-4	150 m at 150° SE		Marsh	*DISP; *SAVI; TRMA; GRIN
T6-5	200 m at 150° SE		Marsh	*DISP; *SAVI; TRMA; GRIN
T6-6	250 m at 150° SE		Marsh	*DISP; *SAVI;
T6-7	300 m at 150° SE		Marsh	*DISP; *SAVI TRMA; GRIN
T6-8	350 m at 150° SE		Marsh	*DISP; *SAVI
T7-5	400 m at 330° NW of 49° 03.60'	123° 00.30'	Marsh	*DISP; *SAVI TRMA; GRIN
T7-6	450 m at 330° NW		Marsh	*DISP; *SAVI TRMA; GRIN

TABLE 2

Percent occurrences of benthic foraminifera from Fraser River Delta stations. The "% uncertainty" was calculated for each species utilized in multivariate analysis, designated by (*), of the 60 most populous samples. The computer defined biofacies for each clustered sample and the elevation above mean sea level (a.m.s.l.) of each sample is also shown.

Sample	T3-9	T3-10	T3-11	T3-12	T4-5	T4-20	T4-21	T4-24	T4-25	T5-1	T5-2	T5-3	T5-4	T5-5
Cluster Anal. No.	31	32	33	34	35	36	37	38	39	40	41	42	43	44
Elev. (m)	0.7	0.94	1.2	1.6	0.09	-1.1	-0.5	-1.1	-1.1	1.6	1	0.7	0.63	0.55
Biofacies	5	2	1	1	3	6	6	6	6	1	1	5	5	?
No. of Species	6	4	2	2	4	3	3	2	2	5	4	3	5	3
Total Individuals	1300	808	66	74	131	130	126	46	234	1190	293	134	1502	598
**A. beccarii* %	83.8	-	-	-	5.3	-	-	-	-	-	2.7	97.0	92.8	91.6
% Uncertainty ±	1.0	-	-	-	2.0	-	-	-	-	-	0.9	1.5	0.7	1.1
**C. gunteri* %	-	-	-	-	-	-	-	-	-	-	-	-	-	-
% Uncertainty ±	-	-	-	-	-	-	-	-	-	-	-	-	-	-
**J. macrescens* %	8.6	94.1	97.0	98.6	-	-	-	-	-	94.3	85.0	-	0.7	5.7
% Uncertainty ±	0.8	0.8	2.1	1.4	-	-	-	-	-	0.7	2.1	-	0.2	1.0
**M. fusca* %	6.5	2.5	3.0	1.4	87.8	2.3	1.6	-	7.3	1.0	11.6	2.2	4.8	2.7
% Uncertainty ±	0.7	0.6	2.1	1.4	2.9	1.3	1.1	-	1.7	0.3	1.9	1.3	0.6	0.7
**T. inflata* %	0.3	3.2	-	-	-	-	-	-	-	0.8	0.7	-	-	-
% Uncertainty ±	0.2	0.6	-	-	-	-	-	-	-	0.3	0.5	-	-	-
**T. pacifica* %	-	-	-	-	-	95.4	97.6	96.8	92.7	-	-	-	-	-
% Uncertainty ±	-	-	-	-	-	1.8	1.4	2.6	1.7	-	-	-	-	-
A. exiguus	0.2	-	-	-	6.1	2.3	-	-	-	-	-	-	-	-
A. salsum	-	-	-	-	0.8	-	0.8	-	-	-	-	-	0.3	-
A. fluens	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C. aculeata	-	-	-	-	-	-	-	-	-	-	-	-	-	-
R. columbiensis	-	-	-	-	-	-	-	-	-	-	-	-	-	-
E. advena	-	-	-	-	-	-	-	-	-	-	-	-	-	-
H. advenum	0.6	-	-	-	-	-	-	2.2	-	0.2	-	-	1.5	-
I. limbata	-	-	-	-	-	-	-	-	-	-	-	0.8	-	-
P. ipohalina	-	-	-	-	-	-	-	-	-	-	-	-	-	-
P. limnetis	-	0.3	-	-	-	-	-	-	-	3.7	-	-	-	-
Reophax sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Sample	T5-6	T5-9	T5-10	T5-11	T5-12	T5-2C	T6-1	T6-2	T6-3	T6-4	T6-5	T6-6	T6-7	T6-8	T7-5	T7-6
Cluster Anal. No.	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
Elev. (m)	0.47	0.24	0.17	0.09	0.08	-	-	-	-	-	-	-	-	-	-	-
Biofacies	5	5	5	5	5	5	2	2	2	2	2	2	2	2	2	2
No. of Species	3	2	3	3	3	5	4	4	3	3	4	4	5	6	5	6
Total Individuals	93	148	61	236	73	380	383	2187	120	840	276	288	186	1253	92	157
**A. beccarii* %	51.6	84.5	44.3	51.7	19.2	87.6	-	-	-	-	-	-	0.5	0.2	-	0.6
% Uncertainty ±	5.2	3.0	6.4	3.3	4.6	1.7	-	-	-	-	-	-	0.5	0.1	-	0.6
**C. gunteri* %	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
% Uncertainty ±	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
**J. macrescens* %	7.5	-	-	-	-	6.0	57.2	64.1	30.8	47.4	78.6	94.3	69.4	77.5	62.0	63.7
% Uncertainty ±	2.7	-	-	-	-	1.2	2.5	1.0	4.2	1.7	2.5	1.4	3.4	1.2	5.1	3.9
**M. fusca* %	40.9	15.5	49.2	44.1	78.1	5.8	0.8	2.2	9.2	1.7	5.4	11.0	3.8	1.0	12.0	8.2
% Uncertainty ±	5.1	3.0	6.4	3.2	4.8	4.3	0.5	0.3	2.6	0.5	1.4	1.8	1.4	0.3	3.4	2.2
**T. inflata* %	-	-	-	-	2.7	-	41.3	33.6	60.0	51.0	13.0	4.3	24.2	20.4	25.0	19.1
% Uncertainty ±	-	-	-	-	1.9	-	2.5	1.0	4.5	1.7	2.0	1.2	3.1	1.1	5.2	3.1
**T. pacifica* %	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
% Uncertainty ±	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A. exiguus	-	-	6.6	4.2	-	-	-	-	-	-	-	-	-	-	-	-
A. salsum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A. fluens	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C. aculeata	-	-	-	-	-	0.3	-	-	-	-	-	-	-	-	-	-
R. columbiensis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
E. advena	-	-	-	-	-	-	-	-	-	-	-	-	-	0.2	-	-
H. advenum	-	-	-	-	-	0.3	0.8	0.1	-	-	2.9	0.4	2.2	0.8	1.1	8.3
I. limbata	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
P. ipohalina	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
P. limnetis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Reophax sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

METHODS AND MATERIALS

One hundred fifty-one samples were collected in nine transects from the tidal flats and marshes skirting Sturgeon Bank, Robert's Bank, and Boundary Bay (text-fig. 1). Marsh samples from Transects 2, 3, 5, 6, 7, 8, and 9 (table 1) were collected by proceeding on the marsh surface perpendicular to the shore at low tide; material was collected at intervals using the method described by Scott and Medioli (1980a). Sample stations were located by compass and pacing. Transects 2 and 3 were sited in the marsh adjacent to Sturgeon Bank near the terminus of Blundell Rd. Transect 5 spanned the marsh adjacent to the north end of Westham Island on Robert's Bank. Transects 6 and 7 were located in the marsh that borders Boundary Bay near the foot of 72nd St., and Transects 8 and 9 were sited in the marsh bordering Sturgeon Bank near the Iona Island sewage treatment plant. Transects 1 and 4, laid out in a grid pattern covering most of the low tide exposure of Sturgeon and Robert's banks (table 1), were sampled using a Canadian Coast Guard Search and Rescue Hovercraft. The positions of sample stations along Transects 1 and 4 were determined by the hovercraft's onboard navigation system. Predominantly sandy samples from the banks were obtained by a scoop. However, samples from some stations along the seaward edge of the marsh were obtained in the same manner as those from the other marsh transects (table 1). Vertical elevations of sample stations were not measured at the time of collection. Approximate elevations were obtained by reference to topographic maps of the tidal flat and marshes (Swan Wooster Engineering Ltd. 1967). Because the marsh environment mirrors variations in the atmosphere, measurements of marsh temperatures are of limited value and therefore were not made (Scott and Medioli 1980a). Due to technical difficulties, salinity measurements were not obtained. Previous studies have shown that salinity of sample stations may vary greatly depending on the tide and time of year, so spot measurements of salinity in marsh sediments are not useful. For example, salinity measurements of the entire southern Strait of Georgia vary between 24‰ and 29‰. In the marsh these levels fluctuate according to the sample's proximity to the Fraser River and the season during which the sample was collected (Swinbanks and Murray 1981).

Samples for this study were boiled with soda ash to cleanse the foraminiferal tests for examination, and were then rinsed over 500μm sieves to retain coarse material, and 63μm screens to retain the foraminifera. Samples containing excessive amounts of sand were then dried, and the foraminifera separated from the sand by flotation in sodium polytungstate (s.g. 2.28). Previous studies have shown that analysis of the total foraminiferal population, as opposed to only live specimens, is more useful in defining biofacies. Thus, samples were not stained with Rose Bengal (Scott and Medioli 1980b). Samples were then examined under a binocular microscope (generally at 40×) for quantitative analysis of the foraminifera. One hundred of the 151 samples were found to contain at least some foraminifera, and 60 of these samples (table 2) contained populations large enough for statistical analysis (Patterson and Fishbein 1989).

A Q-Mode cluster analysis was performed using the Data, Factor and Cluster Modules of Systat 2 (Wilkinson 1987) on a Macintosh SE personal computer. Initially, the 11 most numerous species contained in the 60 samples were clustered. These included the foraminifers: *Ammobaculites exiguus* Cushman and Brönniman 1948; *Ammonia beccarii*; *Ammotium salsum*; *Cribroelphidium gunteri* (Cole) 1931; *Haplophragmoides manilaensis* Andersen 1953; *Jadammina macrescens*; *Miliammina fusca*; *Pseudothurammina limnetis* (Scott and Medioli) 1980; *Trochammina inflata*; *Trochammina pacifica*, and the arcellacean *Centropyxis aculeata* (Ehrenberg) 1830. Simple correlation coefficients were used to measure similarity between pairs of species, and the centroid linkage method was utilized to arrange sample pairs and sample groups into a hierarchic dendrogram. Following these analyses, to reduce the noise in this large data set, the number of species used was reduced to six. Species were eliminated that strongly covaried with other species. For example, the relative frequency of *Ammobaculites exiguus*, *Ammotium salsum*, and *Miliammina fusca* covaried very closely in most samples. Thus, the statistics

TABLE 2
Continued

Sample	T1-2	T1-3	T1-5	T1-7	T1-9	T1-10	T1-19	T1-20	T1-21	T1-28	T1-31	T1-33	T1-39	T1-43
Cluster Anal. No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Elev. (m)	0.09	0.09	0.09	0.09	-0.4	-0.8	0.09	0.09	-0.5	0	0.09	-0.2	-1.4	-0.8
Biofacies	3	3	3	3	5	5	3	3	3	3	3	3	2	3
No. of Species	5	3	4	3	4	3	5	4	3	4	3	3	4	2
Total Individuals	758	386	455	125	46	135	765	256	211	810	167	162	265	551
**A. beccarii* %	9.6	-	3.5	1.6	60.9	61.5	0.3	0.8	-	0.3	-	2.5	-	0.9
% Uncertainty ±	1.1	-	0.9	1.1	7.2	4.2	0.2	0.6	-	0.2	-	1.2	-	0.4
**C. gunteri* %	-	-	-	-	-	-	-	-	-	-	-	-	-	-
% Uncertainty ±	-	-	-	-	-	-	-	-	-	-	-	-	-	-
**J. macrescens* %	0.3	-	-	-	4.4	-	0.1	-	0.5	-	-	-	72.1	-
% Uncertainty ±	0.2	-	-	-	-	3.0	-	0.1	-	-	-	-	2.8	-
**M. fusca* %	71.2	62.7	36.3	97.6	30.4	37.8	67	94.1	98.1	88.2	92.8	96.9	4.5	99.1
% Uncertainty ±	1.6	2.5	2.3	1.4	6.8	4.2	1.7	1.5	0.9	1.1	2	1.4	1.3	0.4
**T. inflata* %	-	-	-	-	-	-	-	-	-	-	-	-	22.6	-
% Uncertainty ±	-	-	-	-	-	-	-	-	-	-	-	-	2.6	-
**T. pacifica* %	-	-	-	-	-	-	-	-	-	-	-	-	-	-
% Uncertainty ±	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A. exiguus	15.0	33.9	55.6	0.8	4.4	4.4	23.7	3.9	1.4	9.1	6.6	0.6	-	-
A. salsum	3.8	3.4	4.6	-	-	-	9.2	1.2	-	2.5	0.6	-	-	-
A. fluens	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C. aculeata	-	-	-	-	-	-	-	-	-	-	-	-	-	-
R. columbiensis	-	-	-	-	-	-	-	-	-	-	-	-	-	-
E. advena	-	-	-	-	-	-	-	-	-	-	-	-	-	-
H. advenum	-	-	-	-	-	-	-	-	-	-	-	-	0.8	-
I. limbata	-	-	-	-	-	-	-	-	-	-	-	-	-	-
P. ipohalina	-	-	-	-	-	-	-	-	-	-	-	-	-	-
P. limnetis	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Reophax sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Sample	T2-2	T2-3	T2-4	T2-5	T2-6	T2-7	T2-10	T2-11	T3-1	T3-2	T3-3	T3-4	T3-5	T3-6	T3-7	T3-8
Cluster Anal. No.	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Elev. (m)	0.94	0.74	0.63	0.55	0.47	0.4	0.17	0.09	0.09	0.17	0.24	0.32	0.4	0.47	0.55	0.63
Biofacies	1	5	5	4	5	3	3	5	5	3	3	3	3	4	4	5
No. of Species	7	8	7	7	7	5	4	4	4	5	4	5	6	7	13	4
Total Individuals	1420	443	916	1922	1100	2224	413	294	279	593	827	1056	1136	702	1250	525
**A. beccarii* %	0.4	65.2	47.2	14.4	22.5	11.8	1.5	38.4	47.7	4.7	-	1.4	4.6	15.4	10.1	87.8
% Uncertainty ±	0.2	2.3	1.6	0.8	1.3	0.7	0.6	2.8	3.0	0.9	-	0.4	0.6	1.4	0.9	1.4
**C. gunteri* %	-	0.5	3.1	20.0	3.1	-	-	-	-	0.3	-	-	0.2	21.3	15.6	-
% Uncertainty ±	-	0.3	0.6	0.9	0.5	-	-	-	-	0.2	-	-	0.1	1.5	1	-
**J. macrescens* %	69.7	2.3	0.1	0.1	-	-	-	-	-	-	0.1	-	-	0.3	0.6	-
% Uncertainty ±	1.2	0.7	0.1	0.1	-	-	-	-	-	-	0.1	-	-	0.2	0.2	-
**M. fusca* %	12.0	16.7	45.4	55.3	65.7	75.6	76.3	56.1	48	73.2	60.1	50	60.0	54.7	59.7	10.9
% Uncertainty ±	0.9	1.8	1.6	1.1	1.4	0.9	0.2	2.9	3	1.8	0.2	1.5	1.5	1.9	1.4	1.4
**T. inflata* %	-	12.2	-	-	-	-	-	-	0.4	-	-	-	-	-	0.1	-
% Uncertainty ±	-	1.6	-	-	-	-	-	-	0.4	-	-	-	-	-	0.1	-
**T. pacifica* %	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
% Uncertainty ±	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A. exiguus	-	1.8	2.3	5.7	8.0	12.1	21.3	5.0	3.9	19.1	36.8	46.4	30.1	5.3	11.4	1.0
A. salsum	-	-	0.2	4.8	0.7	0.3	1	0.7	-	2.7	2.9	2.3	4.8	3	2.1	0.4
A. fluens	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.1	-
C. aculeata	1.3	-	-	0.1	-	-	-	-	-	-	-	-	-	-	0.1	-
R. columbiensis	-	-	-	-	-	0.2	-	-	-	-	-	-	-	-	-	-
E. advena	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
H. advenum	8.2	1.3	1.5	-	-	-	-	-	-	-	-	-	-	-	-	-
I. limbata	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.1	-
P. ipohalina	0.3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
P. limnetis	8.2	-	-	-	0.2	-	-	-	-	-	-	-	-	-	0.1	-
Reophax sp.	-	-	-	-	*0.2*	-	-	-	0.4	-	-	0.2	0.4	-	0.2	-

associated with *Miliammina fusca* alone, were sufficient to represent this relationship.

Prior to obtaining a clustering of the condensed data set, a principal component analysis was performed on the raw data utilizing a covariance matrix of the six species and a varimax rotation. The principal component analysis transformed the set of observed species into a different set of variables (principal components). Each principal component represents a linear combination of the observed variables, maximally discriminates among the samples under study, and is not correlated with any other principal component. In addition, none of the data are eliminated from the data set either after one component has been identified, or prior to the identification of the next component. Each case (sample) in the component was ranked either positively or negatively (table 3). The higher the score, the more highly the sample is ranked within the positive or negative assemblage of each principal component. Following this examination, a Q-Mode cluster analysis was carried out using the first four principal components and centroid linkage. These first four principal components explained 97.77% of the data.

Scanning electron micrographs were taken using Polaroid PN 665 film on a Jeol JSM-U3 Scanning electron microscope in the Department of Biology at Carleton University. The location map and all text-figures were prepared using various CAD programs on Macintosh SE and IIcx personal computers.

RESULTS

Vegetational Distribution

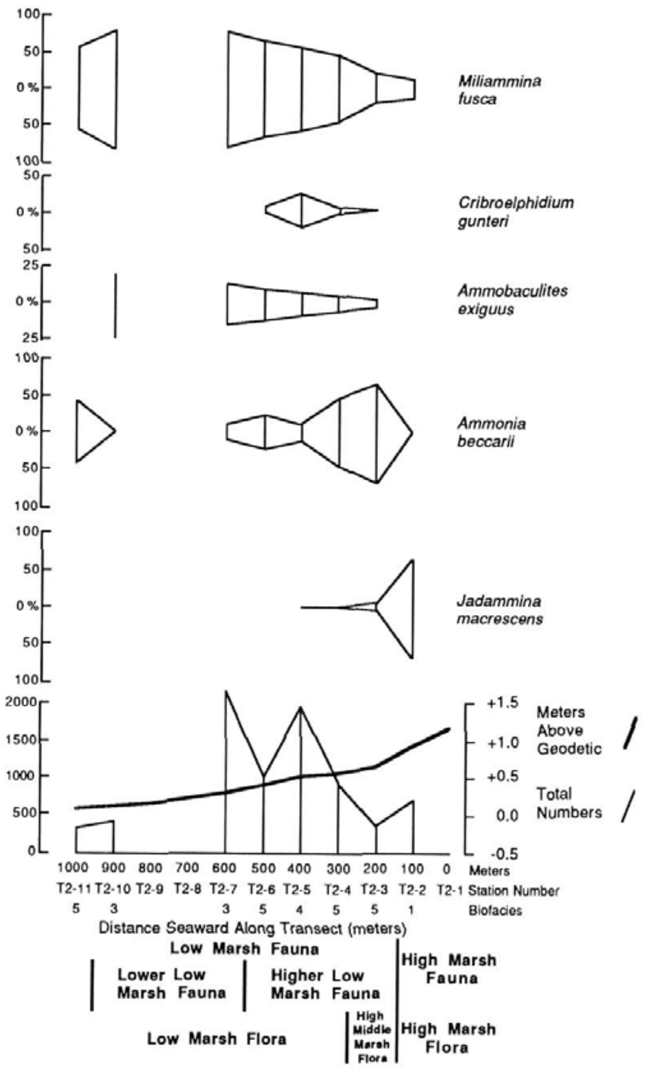
Samples collected from Transects 2 (T-2) and 3 (T-3) may be mapped into the three vegetation zones identified by Hutchinson (1982; table 1; Figures 2, 3). Samples T2-1, T2-2, and T3-12 are characterized by the presence of *Typha latifolia*, which indicates a high marsh environment. The vegetation at T2-3 and T3-9 through T3-11 represents mixed middle/high marsh specimens. In these samples the high marsh species *Distichlis spicata* and middle marsh species *Carex lyngbyei* are dominant. Samples T2-4 through T2-10, and T3-1 through T3-8, are dominated by the low marsh plant species *Scirpus americanus*, and *Scirpus maritimus*.

The floral distribution observed along Transect 5 (T-5) (from the margin of Robert's Bank) is less well delineated, but also may be divided into three zones (table 1; text-fig. 4). Sample T5-1 is characterized by the high marsh species *Typha latifolia*. Samples T5-2 through T5-11 are dominated variously by *Scirpus validus, Carex lyngbyei, Juncus balticus, Scirpus americanus*, and *Scirpus maritimus*. These species indicate a low to middle marsh character for these samples. Samples T5-12 and T5-13 are dominated by *Scirpus americanus* and *Scirpus validus* indicating a low marsh vegetational zone.

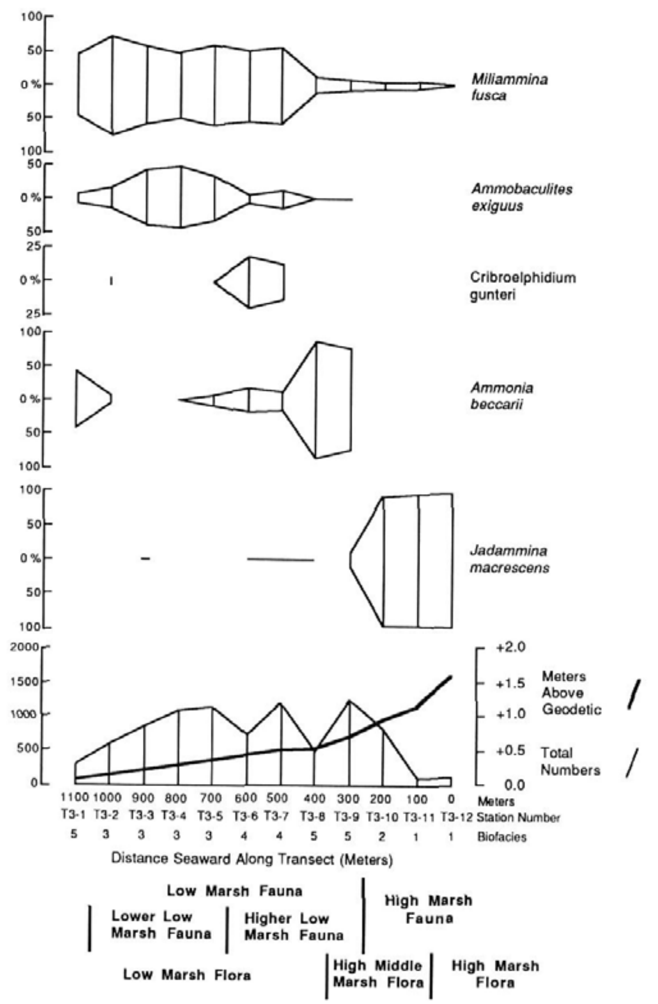
Samples collected from Transects 6 (T6) and 7 (T7) in Boundary Bay were from sites entirely dominated by *Distichlis spicata, Triglochin maritimum, Grindelia integrifolia, Salicornia virginica*, and *Salicornia europea*, species characteristic of both lower and high marsh zones of Swinbanks and Murray (1981) (table 1; text-fig. 5).

Foraminiferal Distribution

Twenty-four species of benthic and planktonic foraminifera were identified from 100 samples. As discussed above, the 60 most populous samples, and the six most numerous species, *Ammonia beccarii*, *Cribroelphidium gunteri*, *Jadammina macrescens*, *Miliammina fusca*, *Trochammina inflata*, and *Trochammina pacifica*, were utilized to define the biofacies (table 2). In general, the nonvegetated, primarily sandy sediments of the banks were devoid of foraminifera, whereas the marsh samples commonly yielded very large assemblages. The Q-Mode multivariate cluster analysis defined six distinct foraminiferal biofacies from the marsh and tidal flat samples obtained from the Fraser Delta (text-fig. 6). These six biofacies are denominated for their most characteristic species, as follows: Biofacies 1 - *Jadammina macrescens*; Biofacies 2 - *Jadammina macrescens* and *Trochammina inflata;* Biofacies 3 - *Miliammina fusca;* Biofacies 4 - *Cribroelphidium gunteri;* Biofacies 5 - *Ammonia beccarii*; and Biofacies 6 - *Trochammina pacifica*.



TEXT-FIGURE 2
Relative fractional abundance and total foraminiferal populations along Transect 2, collected from the marsh flanking Sturgeon Bank on the Fraser River Delta. The elevation above mean sea level, computer designated biofacies, and floral and foraminiferal zonation is also indicated for each sample station.



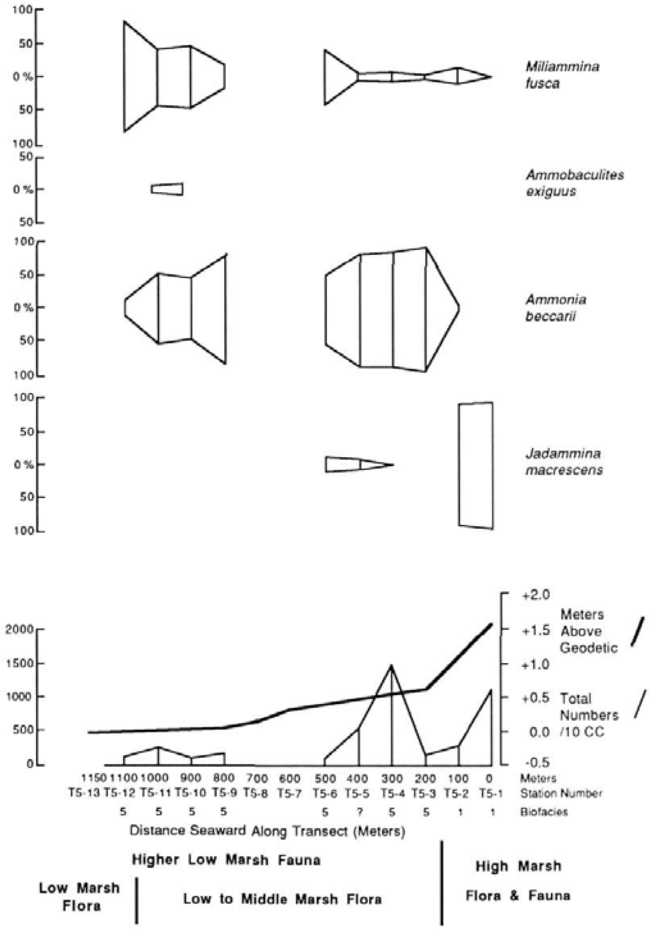
TEXT-FIGURE 3
Relative fractional abundance and total foraminiferal populations along Transect 3, collected from the marsh flanking Sturgeon Bank, Fraser River Delta. The elevation above mean sea level, computer designated biofacies, and floral and foraminiferal zonation is also indicated for each sample station.

The *Jadammina macrescens* Biofacies is characterized by relative abundances of that species which range from 69.7 to 98.6% (68.5 to 100.0% considering standard error) of the sample. *Pseudothurammina limnetis* and the arcellacean *Centropyxis aculeata* also are present in some samples (tables 2, 4; text-fig. 6). This biofacies occurs at the highest elevations, nearest to the shore in marsh transects T2, T3, and T5 (text-figs. 2, 3, and 5). Elevations ranged from +0.9 to +1.6m a.m.s.l. (text-fig. 7).

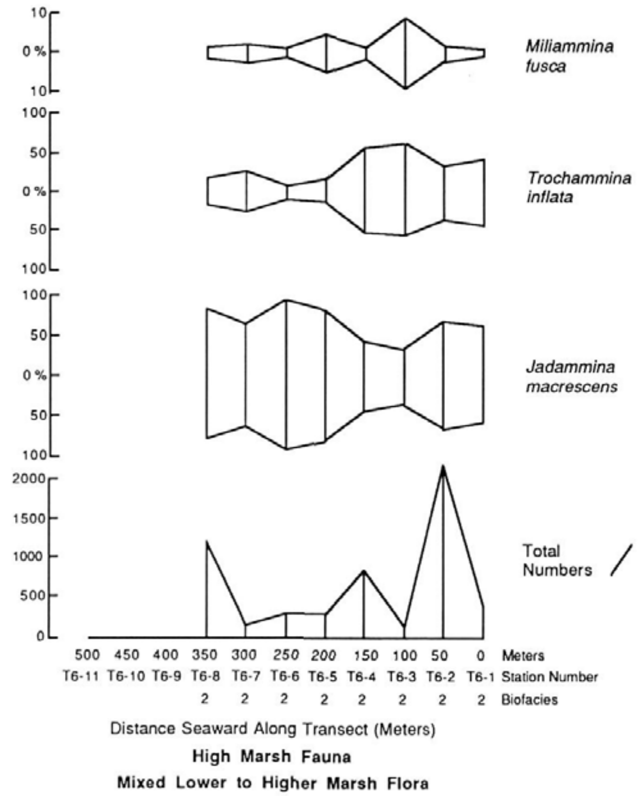
The *Jadammina macrescens/Trochammina inflata* Biofacies (2) clustered very closely with the *Jadammina macrescens* Biofacies due to its high proportion of *Jadammina macrescens* (30.8 to 94.3%; 26.6 to 95.7% considering standard error). However, Biofacies 2 also included 3.2 to 60.0% *Trochammina inflata* (tables 2, 4; text-fig. 6). Biofacies 2 numerically dominates all samples of Transect 6 in Boundary Bay, and a single sample from Transect 2 at an elevation of +0.9m a.m.s.l. (text-figs. 2, 4, and 7). Unfortunately, elevational data are not available for Transect 6. Sample T1-39, collected from a sandy environment on Sturgeon Bank at an elevation of 1.4m b.m.s.l. also is associated with this biofacies (table 4; text-fig. 6). Because the sand-dominated bank environment is very unstable, the presence of this high marsh biofacies at such a low elevation is probably explained by transport.

The *Miliammina fusca* Biofacies (3) is characterized by relative abundances of *M. fusca* that comprise 36.3 to 99.1% (34.0 to 99.5% considering standard error) of the assemblages identified in samples from elevations of –0.8 to +0.4m a.m.s.l. (tables 2, 4; text-figs. 6, 7). Significant numbers of *Ammobaculites exiguus* and *Ammotium salsum* are also found in these samples. This biofacies is found along the seaward edges of Transects 2 and 3, as well as in samples from Transects 1 and 4, which were collected along the seaward edges of marshes adjacent to Sturgeon and Robert's banks (text-figs. 1, 2, and 3).

The *Cribroelphidium gunteri* Biofacies (4) is represented by only 3 samples: T2-5, T3-6, and T3-7 obtained from Transects



TEXT-FIGURE 4
Relative fractional abundance and total foraminiferal populations along Transect 5, collected from the marsh flanking Robert's Bank on the Fraser River Delta. The elevation above mean sea level, computer designated biofacies, and floral and foraminiferal faunal zonation is also indicated for each sample station.



TEXT-FIGURE 5
Relative fractional abundance and total foraminiferal population found along Transect 6, collected from the marsh flanking Boundary Bay on the Fraser River Delta. The computer designated biofacies, and floral and foraminiferal faunal zonation is also indicated for each sample station.

2 and 3 on Sturgeon Bank (tables 2, 4; text-figs. 4, 5, 6). Although the *Miliammina fusca* population (54.7 to 59.7%; 52.8 to 61.1% considering standard error) of these samples is close to that identified in samples characteristic of the *M. fusca* Biofacies, Biofacies 4 is readily distinguishable from Biofacies 3 by its large proportion of *Cribroelphidium gunteri* (15.6 to 21.3%; 14.6 to 22.8% considering standard error; table 3). In addition, samples associated with Biofacies 4 are found at a slightly higher elevation (+0.5 to +0.6m a.m.s.l.) than those included in the *Miliammina fusca* Biofacies (text-fig. 7).

The *Ammonia beccarii* Biofacies (5) is characterized by relative abundances of *Ammonia beccarii* from 19.2 to 97.0% (14.6 to 98.5% considering standard error; tables 2, 4; text-fig. 6). Biofacies 5 is found along Transects 2, 3, and 5 on both Sturgeon Bank and Robert's Bank (text-figs. 2, 3, 4). This biofacies exhibits a wide distribution of elevations which range from +0.1m a.m.s.l. at the seaward edge of the marsh, to +0.7m a.m.s.l. at the top of the low marsh. The range in elevation of Biofacies 5 partially overlaps that of Biofacies 3 — the *Miliammina fusca* Biofacies (–0.8 to +0.4 a.m.s.l) — and encompasses completely the elevational range of Biofacies 4, the *Cribroelphidium gunteri* Biofacies (+0.5 to +0.6m a.m.s.l.). This overlapping results in a somewhat patchy occurrence of these three biofacies which is particularly noticeable along Transects 2 and 3.

The *Trochammina pacifica* Biofacies (6) consists almost exclusively of *Trochammina pacifica* (92.7 to 97.6%; 91.0 to 99.4% considering standard error). It is restricted to 4 sample stations between the Robert's Bank Port Causeway and the Tsawwassen Causeway (text-fig. 1). The biofacies occurs at elevations between 1.1 and 0.5m b.m.s.l. (tables 2, 4; text-fig. 7). *Trochammina pacifica* is found only in the samples representing Biofacies 6.

Despite the richly organic sediment, foraminifera are almost entirely absent from Transects 8 and 9 in the patchy marsh adjacent to the Iona Sewage Treatment Plant. This lack of fauna is probably closely related to the presence of more than a meter of unconsolidated black, anaerobic sludge due to hydrotroilite (FeS). Bandy et al. (1964) observed a similar "dead zone", almost devoid of foraminifera, in the sludge immediately surrounding the Los Angeles County sewage outfall at Whites Point, California.

DISCUSSION

As reported in marshes elsewhere (Scott 1976a; Scott and Medioli 1980a, 1986; Scott et al. 1981; Goldstein and Frey 1986), the foraminiferal biofacies observed in the marshes and

TABLE 3
Varimax rotated scores of the first four principal components of raw data using covariance matrix of the six most definitive species (variables) and 60 most populous samples (cases) from the Fraser River Delta. The resulting data was used in the multivariate analysis to generate a cluster dendrogram.

	Rotated Principal Component Loadings			
Cluster Analysis Number (CAN) and Transect Station	PC 1	PC 2	PC 3	PC 4
CAN 1 (T1-2)	0.988	0.087	-0.111	0.022
CAN 2 (T1-3)	0.996	0.068	0.022	0.015
CAN 3 (T1-5)	0.992	0.084	-0.073	0.020
CAN 4 (T1-7)	0.996	0.070	0.006	0.016
CAN 5 (T1-9)	0.294	0.121	-0.945	0.057
CAN 6 (T1-10)	0.394	0.188	-0.896	0.056
CAN 7 (T1-19)	0.997	0.066	0.018	0.015
CAN 8 (T1-20)	0.996	0.069	0.014	0.015
CAN 9 (T1-21)	0.996	0.068	0.022	0.015
CAN 10 (T1-28)	0.996	0.068	0.019	0.015
CAN 11 (T1-31)	0.996	0.068	0.022	0.015
CAN 12 (T1-33)	0.996	0.072	-0.003	0.016
CAN 13 (T1-39)	-0.152	-0.952	0.180	0.184
CAN 14 (T1-43)	0.996	0.070	0.011	0.015
CAN 15 (T2-2)	0.026	-0.987	0.065	-0.006
CAN 16 (T2-3)	0.009	0.185	-0.951	0.177
CAN 17 (T2-4)	0.616	0.201	-0.758	0.066
CAN 18 (T2-5)	0.918	0.251	-0.134	0.118
CAN 19 (T2-6)	0.942	0.142	-0.302	0.044
CAN 20 (T2-7)	0.985	0.094	-0.131	0.023
CAN 21 (T2-10)	0.996	0.071	0.003	0.016
CAN 22 (T2-11)	0.790	0.161	-0.586	0.045
CAN 23 (T3-1)	0.638	0.180	-0.743	0.055
CAN 24 (T3-2)	0.995	0.079	-0.041	0.018
CAN 25 (T3-3)	0.997	0.066	0.022	0.015
CAN 26 (T3-4)	0.996	0.072	-0.000	0.016
CAN 27 (T3-5)	0.994	0.082	-0.052	0.020
CAN 28 (T3-6)	0.903	0.264	-0.144	0.128
CAN 29 (T3-7)	0.959	0.191	-0.069	0.091
CAN 30 (T3-8)	-0.071	0.170	-0.980	0.053
CAN 31 (T3-9)	-0.135	0.066	-0.987	0.055
CAN 32 (T3-10)	-0.113	-0.982	0.079	0.012
CAN 33 (T3-11)	-0.098	-0.982	0.067	-0.008
CAN 34 (T3-12)	-0.116	-0.980	0.066	-0.008
CAN 35 (T4-5)	0.995	0.078	-0.038	0.018
CAN 36 (T4-20)	-0.195	0.227	0.252	-0.892
CAN 37 (T4-21)	-0.203	0.226	0.251	-0.891
CAN 38 (T4-24)	-0.175	0.229	0.253	-0.895
CAN 39 (T4-25)	-0.142	0.232	0.255	-0.899
CAN 40 (T5-1)	-0.121	-0.980	0.070	-0.003
CAN 41 (T5-2)	-0.001	-0.989	0.042	-0.000
CAN 42 (T5-3)	-0.171	0.161	-0.970	0.051
CAN 43 (T5-4)	-0.144	0.156	-0.975	0.052
CAN 44 (T5-5)	-0.175	0.101	-0.977	0.051
CAN 45 (T5-6)	0.521	0.062	-0.848	0.055
CAN 46 (T5-9)	-0.010	0.174	-0.982	0.054
CAN 47 (T5-10)	0.643	0.174	-0.704	0.050
CAN 48 (T5-11)	0.558	0.183	-0.805	0.054
CAN 49 (T5-12)	0.967	0.109	-0.220	0.028
CAN 50 (T5-2C)	-0.139	0.097	-0.983	0.052
CAN 51 (T6-1)	-0.272	-0.782	0.283	0.379
CAN 52 (T6-2)	-0.225	-0.875	0.241	0.296
CAN 53 (T6-3)	-0.172	-0.338	0.382	0.593
CAN 54 (T6-4)	-0.284	-0.620	0.334	0.483
CAN 55 (T6-5)	-0.106	-0.981	0.129	0.094
CAN 56 (T6-6)	-0.131	-0.981	0.083	0.018
CAN 57 (T6-7)	-0.170	-0.942	0.184	0.204
CAN 58 (T6-8)	-0.188	-0.957	0.158	0.151
CAN 59 (T7-5)	-0.042	-0.936	0.216	0.242
CAN 60 (T7-6)	-0.082	-0.964	0.169	0.179
Percent of Variance Explained	42.632	25.018	22.898	7.222

tidal flats of the Fraser Delta may be grouped according to absolute elevation. Within the marsh fringing the Delta (with a lowermost elevation of approximately mean sea level), a High Marsh Zone (≈ +0.8 to +1.6m a.m.s.l.) and a Low Marsh Zone (0.0 to +0.8m a.m.s.l.), can be recognized (text-fig. 7). Within the Low Marsh Zone, a Higher Low Marsh Zone (≈ +0.5 to +0.8m a.m.s.l.) and a Lower Low Marsh Zone (≈ 0.0 to +0.8m a.m.s.l.) can also be identified. In addition, in certain areas of the tidal flats, a fauna similar to that of the Lower Low Marsh Zone is found.

In the marshes flanking both Sturgeon Bank (Transect 2 and Transect 3; text-figs. 2, 3) and Robert's Bank (Transect 5; text-fig. 4), the High Marsh Zone is dominated by the *Jadammina macrescens* Biofacies (1). The probable High Marsh Zone marsh associated with Boundary Bay (Transect 6; text-fig. 5) is dominated by the *Jadammina macrescens/Trochammina inflata* Biofacies (2). Foraminiferal samples representing the High Marsh Zone of Sturgeon and Robert's banks also correspond very closely to Hutchinson's (1982) floral High Marsh Zone, which is dominated by species such as *Typha latifolia* and *Distichlis spicata*.

In samples collected along Transect 6, the elevation associated with the *Jadammina macrescens/Trochammina inflata* Biofacies, could not be determined. The vegetation that characterizes this transect is of limited use in estimating the elevation, as it consists of an indeterminate mix of low (*Salicornia virginica,* and *Salicornia europea*) and high (*Carex lyngbyei, Distichlis spicata, Grindelia integrifolia,* and *Triglochin maritinum*) marsh species (Swinbanks and Murray 1981). However, several lines of evidence support a high marsh interpretation for the *Jadammina macrescens/Trochammina inflata* Biofacies. *Jadammina macrescens* is primarily a high marsh species. Because this species is very abundant in samples associated with the *Jadammina macrescens/Trochammina inflata* Biofacies (30.8 to 94.3%; 26.6 to 95.7% considering standard error), this biofacies probably represents a high marsh elevation. Corroboration of this placement is provided by an elevation of +0.94m a.m.s.l. recorded for a *Jadammina macrescens/Trochammina inflata* Biofacies-dominated station in the high marsh of Sturgeon Bank (T3-10). In addition, this biofacies characterizes the High Marsh Zone identified in southern California (Scott 1976a).

The existence of two High Marsh Zone biofacies from the Fraser Delta may be related to differences in salinity. Hutchinson (1982) reported that because of the freshwater influence of the Fraser River, salinities are low in the marshes that flank Sturgeon and Robert's banks, where the *Jadammina macrescens* Biofacies dominates the High Marsh Zone. Salinities in the marsh flanking Boundary Bay, where the *Jadammina macrescens/Trochammina inflata* Biofacies dominates the High Marsh Zone, are most likely higher due to the isolation of this marsh from the River (text-fig. 1). Similar situations have been documented in marshes in Holland (Phleger 1970) and California (Scott 1976a) where a *Jadammina macrescens/Trochammina inflata*-dominated high marsh biofacies is associated with high, marine-like salinities.

Although not quantified, the phenotypic variation in the populations of *Jadammina macrescens* on Sturgeon and Robert's banks and in Boundary Bay suggests the presence of a salinity gradient between the two areas. Specimens of *Jadammina macrescens* from Sturgeon and Robert's banks have fewer supplementary areal apertures than those obtained from Boundary Bay. Based on a study of *Jadammina macrescens* in marshes of Nova Scotia, Scott and Medioli (1980a) reported that this species is more likely to develop supplementary areal apertures under higher salinity conditions.

The high marsh foraminiferal fauna identified from the Fraser Delta is similar to high marsh faunas in Southern California (Scott 1976a), Holland (Phleger 1970) and Nova Scotia (Scott and Medioli 1980a). For example, the *Jadammina macrescens* Biofacies of Sturgeon and Robert's banks, characterized by *Jadammina macrescens* and *Pseudothurammina limnetis*, indicates low salinities and is most similar to biofacies identified from the high marshes of Nova Scotia. Similarly, the *Jadammina macrescens/Trochammina inflata* Biofacies found in the marsh fringing Boundary Bay is similar to higher salinity high marsh faunas of California and Holland.

The *Ammonia beccarii* Biofacies — Biofacies 5 — dominates the entire Low Marsh Zone of both Robert's and Sturgeon banks, an area ranging from ≈0.0 to +0.8m a.m.s.l. (text-fig. 7). Although *Ammonia beccarii* best characterizes this biofacies, several other species (e.g. *Miliammina fusca)* also occur in these samples. The Low Marsh Zone identified in this study overlaps entirely the floral Lower and Middle Marsh Zone posited by Hutchinson (1982). Although variable, the vegetation characterizing the *Ammonia beccarii* Biofacies consists primarily of *Carex lyngbyei, Distichlis spicata, Scirpus americanus,* and *Juncus balticus.*

A Higher Low Marsh Zone also can be discerned in Transects 2 and 3 on Sturgeon Bank where the *Cribroelphidium gunteri* Biofacies prevails (text-figs. 2, 3, 7). The faunal makeup of these samples is similar to that of the *Ammonia beccarii* Biofacies, except that *Cribroelphidium gunteri* replaces *Ammonia beccarii.* The presence of significant numbers of calcareous species in the low marsh is similar to assemblages from marshes located in Matagorda Bay and Galveston Bay in south Texas (Phleger 1965, 1966), southern Holland (Phleger 1970), and southern California (Scott 1976a). However, calcareous foraminifera generally are found only in low marsh biofacies in eastern Canadian marshes where they make up a large part of the living population but only a small part of the total foraminiferal assemblage (Scott and Medioli 1980a). Scott and Medioli found high populations of calcareous foraminifera in the summer but low populations in the winter, presumeably when the combination of lowered temperatures and low salinity precluded production of carbonate. They also determined that calcareous species contribute relatively little to the total assemblage because these tests dissolve soon after death in the low pH marsh sediments.

A Lower Low Marsh Zone can be identified within the Low Marsh Zone in certain areas where the *Miliammina fusca* Biofacies (3) prevails, although this Biozone also continues below the lowermost edge of the marsh (–0.8 to +0.4m a.m.s.l.; text-fig. 7). The vegetation of the *Miliammina fusca* Biofacies sites is dominated by low marsh plant species (Hutchinson 1982) such as *Scirpus americanus* and *Scirpus maritimus* in the marsh proper above m.s.l., and by *Zostera marina* in areas below m.s.l. The *Miliammina fusca* Biofacies generally is found only in areas on tidal flats where *Zostera marina* was present to stabilize the substrate. Similar foraminiferal distributions to that identified in the *Miliammina fusca*-dominated Lower Low Marsh Zone of the Fraser Delta have been observed in other marshes throughout the world, including Bottsand Lagoon, Kiel, Germany (Lutze 1968), the James River Estuary, Virginia (Ellison and Nichols 1976), Barnstable Marsh, Massachusettes, and in marshes located in Nova Scotia (Scott and Medioli 1980a) and Prince Edward Island (Scott et al. 1981).

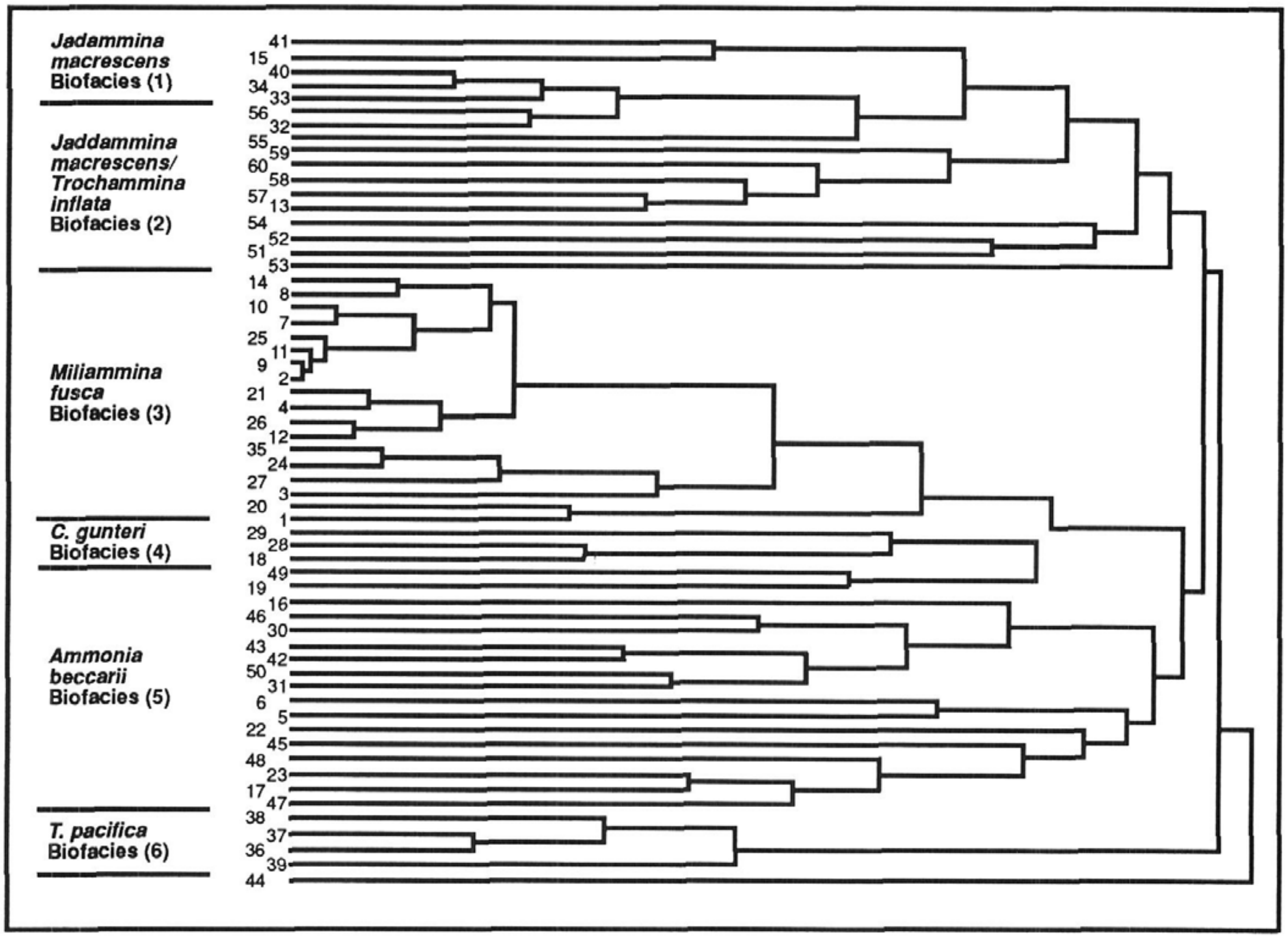
TABLE 4
Ranges of observed percent occurrence, including calculated percent uncertainty, of principal species within each biofacies.

Species \ Biofacies	1 *J. macrescens* Biofacies	2 *J. macrescens T. inflata* Biofacies	3 *M. fusca* Biofacies	4 *C. gunteri* Biofacies	5 *A. beccarii* Biofacies	6 *T. pacifica* Biofacies
A. beccarii	0.0-3.6	0.0-1.2	0.0-12.5	9.2-16.8	14.6-98.5	-
C. gunteri	0.0-3.6	0.0-7.6	0.0-0.5	14.6-22.8	0.0-3.7	-
J. macrescens	68.5-100.0	26.6-95.7	0.0-1.0	0.0-0.8	0.0-9.4	-
M. fusca	0.0-13.5	0.3-15.4	34.0-99.5	52.8-61.1	0.9-82.9	0.0-9.0
T. inflata	0.0-1.2	2.6-64.5	-	0.0-0.2	0.0-13.8	-
T. pacifica	-	-	-	-	-	91.0-99.4

The *Trochammina pacifica* Biofacies (6) is found only in the sheltered area between the Robert's Bank Port Causeway and the Tsawwassen Causeway on the southern portion of Robert's Bank (text-fig. 1). With the exception of some *Miliammina fusca* Biofacies-dominated stations located below m.s.l., samples ranging from -0.5 and -1.1m b.m.s.l., obtained from the area between these two causeways represent the only foraminifera-bearing nonmarsh samples (text-fig. 7). Similar to the *Miliammina fusca* Biofacies-dominated samples obtained from tidal flats away from the marsh, *Trochammina pacifica* Biofacies-dominated samples are found only in sediment stabilized by vegetation, usually *Zostera marina* (eel grass). The shifting sand substrate and the relatively high sedimentation rates of the open bank areas of the Delta are not conducive to development of large *in situ* foraminiferal populations. Development of a *Trochammina pacifica* Biofacies in the area between these causeways is probably a fairly recent phenomenon, related to the construction of the flanking causeways. The presence of a *Trochammina pacifica* Biofacies in this area, as opposed to the *Miliammina fusca* Biofacies that occurs at similar elevations elsewhere on the Delta, probably is due to the high level of organic mud in sediment of this area. Watkins (1961) found a significant increase in the proportion of *Trochammina pacifica* in highly organic sediments surrounding the Orange County, California, ocean sewer outfall. He also observed that *Trochammina pacifica* in this area tended to live in shallower waters than normal. In addition, Bandy et al. (1965) found that *Trochammina pacifica* was 2 to 1600 times more abundant than usual in the vicinity of the Los Angeles city (Hyperion) sewage outfall. However, Scott (1974), who also found great numbers of *Trochammina pacifica* in Samish Bay, Washington, found no such relationship.

The foraminiferal distributional patterns identified in the present study compare favorably with those obtained by Williams (1989). However, Williams recognizes fewer biofacies than reported here. In addition, there is considerable difference in the absolute elevation postulated for biofacies identified in both studies. These differences can be attributed primarily to the fact that Williams (in press) studied only samples from Sturgeon Bank and used fewer samples (24) in his data set.

Results of the present study cannot properly be compared to Phleger's (1967) reconnaissance of Fraser Delta marshes, other than that both studies report many of the same species. As Phleger collected only a very small number of samples (13) from a broad area, he was unable to recognize the detailed foraminiferal distributional patterns in the Delta.



TEXT-FIGURE 6
Q-Mode dendrogram showing 60 most populous samples from the tidal flats and marshes of the Fraser Delta, divided into six distinct biofacies.

CONCLUSIONS

1. Six well-defined biofacies are recognized from the tidal flats and marshes fringing the Fraser Delta. As has been observed for marsh areas elsewhere, the distribution of the biofacies populating the Delta is determined primarily by elevation. Salinity and organic content of the substrate are also important. Foraminiferal faunas generally are well developed only in areas where vegetational cover is sufficient to stabilize the substrate.

2. Based on the foraminiferal biofacies, the marsh can be divided into a High Marsh Zone and a Low Marsh Zone. The Low Marsh Zone can further be divided into a Higher Low Marsh Zone and a Lower Low Marsh Zone in some areas.

3. Although not directly measured, salinity differences between the marshes fringing the active margin of the Fraser Delta and those bordering Boundary Bay may explain the presence of different high marsh zone faunas in the two areas.

4. The high organic content in the substrate may explain why the *Trochammina pacifica* Biofacies occurs only in the sheltered area between the Roberts Bank Port Causeway and the Tsawwassen Causeway.

5. As previous studies have shown, the distribution of foraminiferal biofacies in the sediments of the Fraser Delta are determined by elevation, salinity, and organic content, hence these assemblages may be useful in estimating paleoenvironmental conditions and former sea levels in core samples from the Delta.

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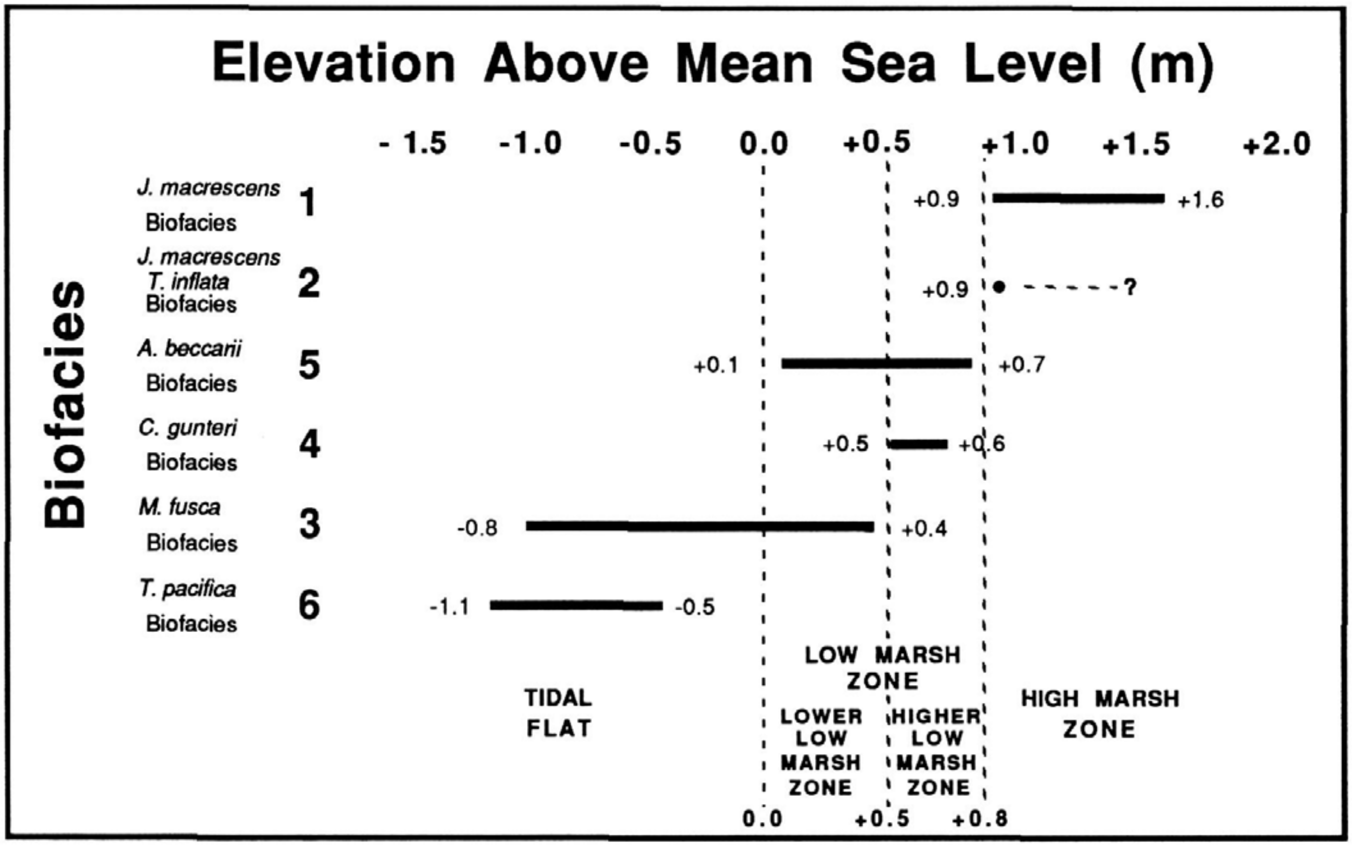

TEXT-FIGURE 7
Elevational range above mean sea level of the samples comprising the six foraminiferal biofacies as defined by multivariate analysis. The corresponding marsh and tidal flat zonations are also indicated.

final preparation of samples for examination, and Ian Hutchinson, Department of Geography, Simon Fraser University, Burnaby, British Columbia, for identifying the vegetation characterizing the sample stations. I would also like to thank A.R.L., H.T.L., and David B. Scott, Centre for Marine Geology, Dalhousie University, Halifax, Nova Scotia for assisting in the identification of some taxa, and Sanping Chen, Statistical Consulting Centre, Carleton University, for assisting with the multivariate analysis. Finally, I wish to thank D.B.S., A.R.L., H.T.L., and Gail B. Patterson, Esq., Blanc Gilburne Williams & Johnson, Los Angeles, California, for critically reviewing the manuscript.

FAUNAL LIST

Order FORAMINIFERIDA EICHWALD 1830

Ammobaculites exiguus Cushman and Brönniman
Plate 1, figure 2

Ammobaculites exiguus CUSHMAN and BRÖNNIMAN 1948a, p. 38, pl. 7, figs. 7, 8.

Ammonia beccarii (Linné)
Plate 2, figures 4, 5

Nautilus beccarii LINNÉ 1758, p. 710.

Ammotium salsum (Cushman and Brönniman)
Plate 1, figure 3

Ammobaculites salsus CUSHMAN and BRÖNNIMAN 1948b, p. 16, pl. 3, figs. 7–9.

Angulogerina cf. *A. fluens* Todd

Angulogerina fluens TODD, in CUSHMAN and TODD 1947b, p. 67, pl. 16, figs. 6, 7 (nomen nudum).

Angulogerina fluens TODD, in CUSHMAN and McCULLOCH 1948, p. 288.

Cribroelphidium gunteri (Cole)
Plate 2, figures 1, 2

Elphidium gunteri COLE 1931, p. 34, pl. 4, figs. 9, 10.

Eggerella advena (Cushman)

Verneuilina advena CUSHMAN 1922, p. 141.

Haplophragmoides manilaensis Andersen
Plate 2, figures 3, 6

Haplophragmoides manilaensis ANDERSEN 1953, p. 22, pl. 4, figs. 8a, b.

Islandiella limbata (Cushman and Hughes)

Cassidulina limbata CUSHMAN and HUGHES 1925, p. 12, pl. 2, fig. 2.

Jadammina macrescens (Brady)
Plate 2, figures 7–9

Trochammina inflata (Montagu) var. *macrescens* H.B. BRADY, in G.S. BRADY and ROBERTSON 1870, p. 290, pl. 11, figs. 5a–c.

Jadammina polystoma BARTENSTEIN and BRAND 1938, p. 381, 382, tfs. 1, 2.

Miliammina fusca (Brady)
Plate 1, figure 4

Quinqueloculina fusca H.B. BRADY in G.S. BRADY and ROBERTSON 1870, p. 47, pl. 11, figs. 2, 3.

Polysaccammina ipohalina Scott

Polysaccammina ipohalina SCOTT 1976b, p. 318, pl. 2, figs. 1–4.

Pseudothurammina limnetis (Scott and Medioli)
Plate 1, figure 1

Thurammina (?) *limnetis* SCOTT and MEDIOLI 1980a, p. 43, 44, pl. 1, figs. 1–3.

Reophax sp.

Trochammina inflata (Montagu)
Plate 1, figures 8–10

Nautilus inflatus MONTAGU 1808, p. 81, pl. 18, fig. 3.

Trochammina pacifica Cushman
Plate 1, figures 5–7

Trochammina pacifica CUSHMAN 1925, p. 39, pl. 6, fig. 3a–c.

Rosalina columbiensis (Cushman)

Discorbis columbiensis CUSHMAN 1925, p. 43, pl. 6, figs. 13a–c.

Order ARCELLINIDA Kent 1880

Centropyxis aculeata (Ehrenberg)

Arcella aculeata EHRENBERG 1830, p. 91.

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PLATE 1

1 *Pseudothurammina limnetis* (Scott and Medioli). Dorsal view of specimen with two apertural openings (GSC 95453) from Station T2-2, ×400.

2 *Ammobaculites exiguus* (Cushman and Brönniman). Side view of hypotype (GSC 95454) showing initial planispiral coiling and later uniserial stage, from Station T2-4, ×175.

3 *Ammotium salsum* (Cushman and Brönniman). Side view of slightly damaged hypotype (GSC 95455) from Station T2-4, showing planispiral coiling arrangment, ×350.

4 *Miliammina fusca* (Brady). Side view of hypotype (GSC 95456) from Station T4-20 showing quinqueloculine chamber arrangment, ×125.

5–7 *Trochammina pacifica* Cushman. 5, Dorsal view of typical coarsely agglutinated hypotype (GSC 95457) from T4-20 showing trochospiral coiling, ×175; 6, Umbilical view of a second hypotype (GSC 95458) from T4-20, with only chambers of final whorl visible, ×200; 7, Edge view of hypotype of figure 5, showing flattened trochospiral coiling, ×175.

8–10 *Trochammina inflata* (Montagu). 8, Dorsal view of hypotype (GSC 95459) from Station T5-5 showing finely agglutinated surface texture, ×175; 9, Ventral view of same, ×180; 10, Edge view of a second hypotype (GSC 95460) also from Station T5-5, showing flattened trochospiral coiling, ×180.

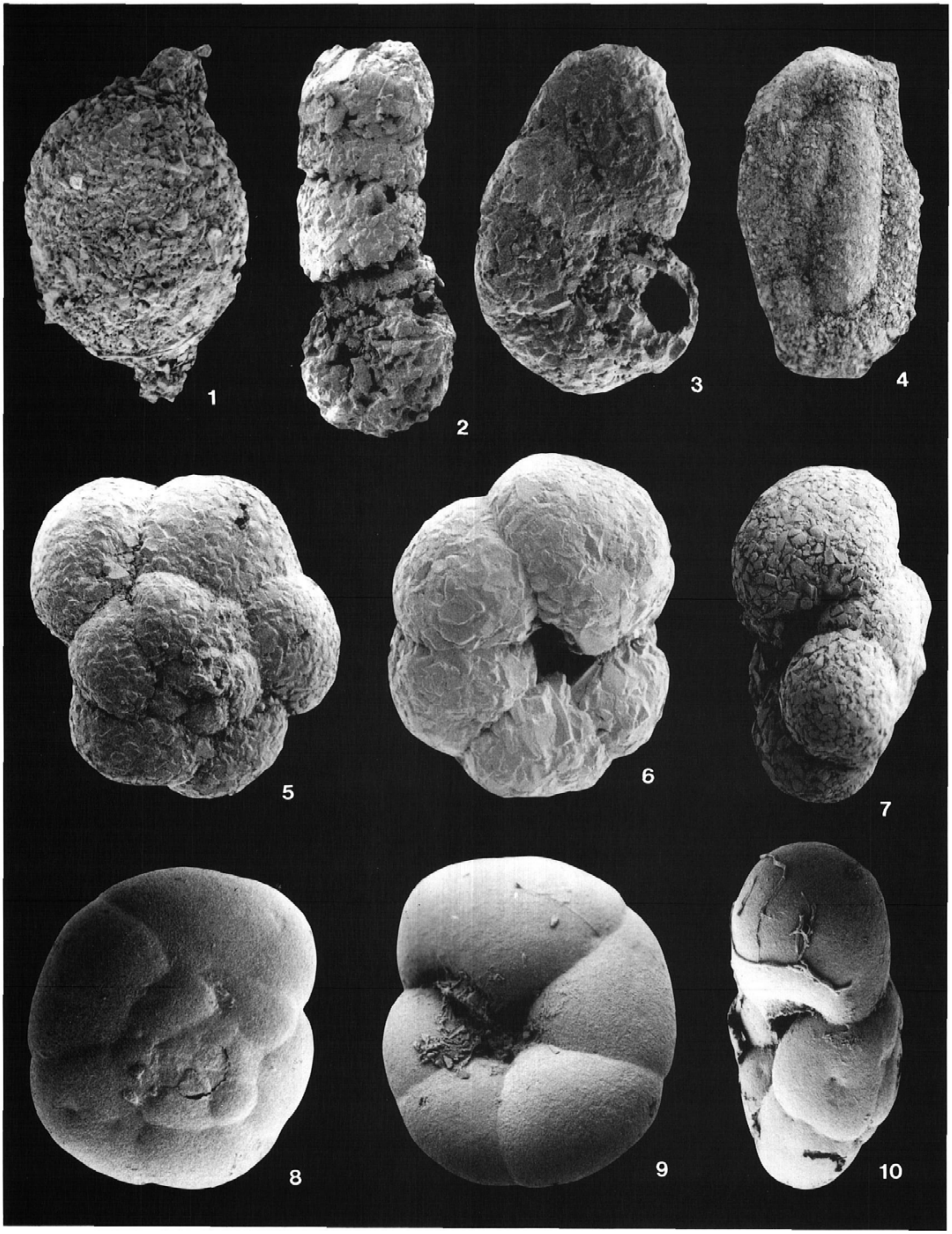
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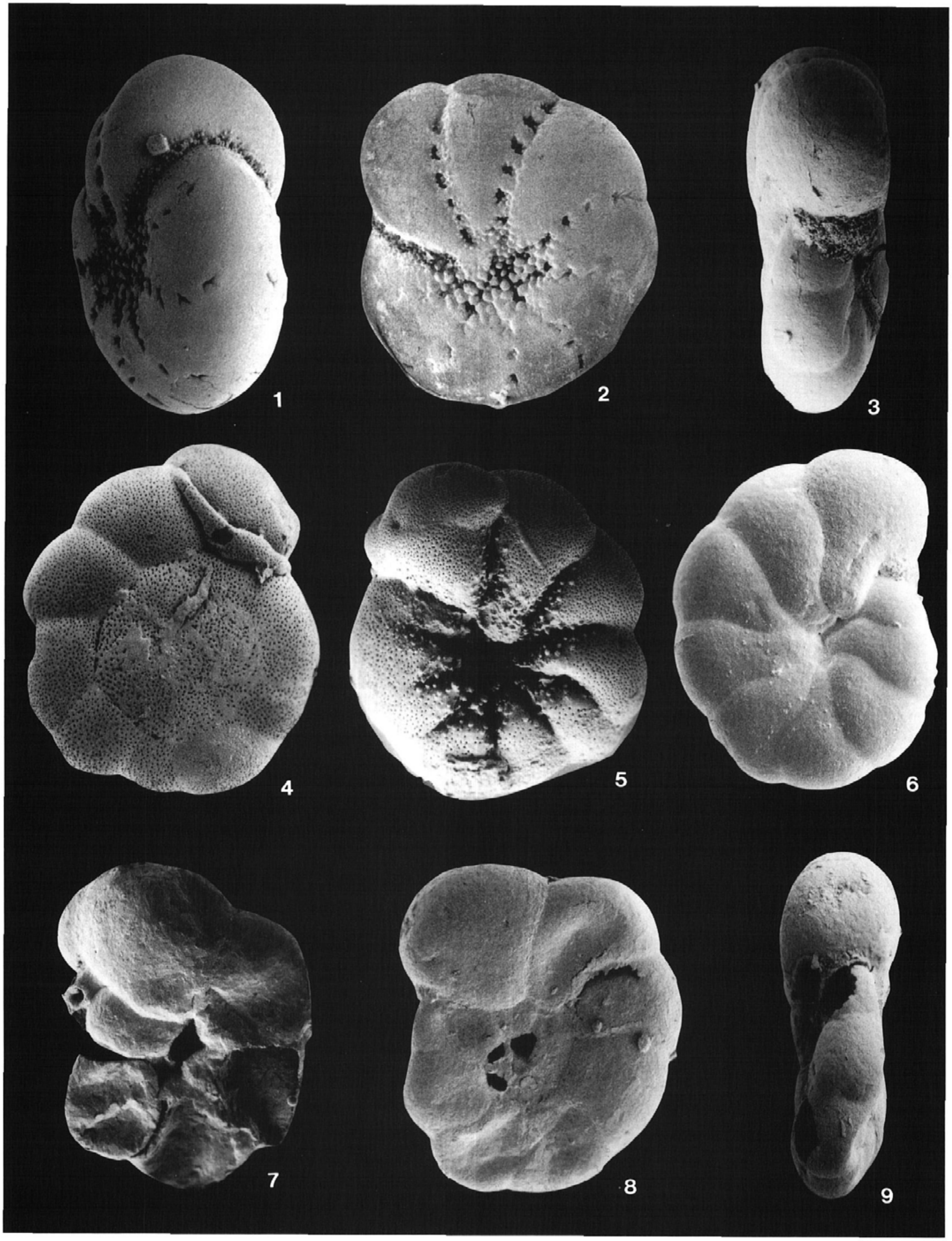
PLATE 2

1, 2 *Cribroelphidium gunteri* (Cole). 1, Apertural view of hypotype (GSC 95461) from Station T3-6 showing compressed, planispirally coiled test, ×400; 2, Side view of same hypotype showing concentrations of pustules along sutures and particularly in the umbilical region, ×425.

3, 6 *Haplophragmoides manilaensis* Andersen. 3, apertural view of planispirally coiled hypotype (GSC 95462) from Station T2-4, ×200; 6, Side view of same hypotype showing smoothly agglutinated surface and depressed, recurved sutures, ×180.

4, 5 *Ammonia beccarii* (Linné). 4, Dorsal view of coarsely perforate hypotype (GSC 95463) from T2-4 with adnormal penultimate chamber, ×200; 5, Ventral view of same specimen showing complex umbilical region typical of genus, ×200.

7-9 *Jadammina macrescens* (Brady). 7, Side view of slightly collapsed hypotype (GSC 95464) from Station T2-2, showing supplementary tubulated areal aperture, ×250; 8, Side view of a second hypotype (GSC 95465) from Station T1-39, ×250; 9, Apertural view of same hypotype showing absence of tubulated areal supplementary aperture in this phenotype, ×280.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