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ENVIRONMENTAL INDICATOR POTENTIAL OF FORAMINIFERA FROM SAANICH INLET, VANCOUVER ISLAND, BRITISH COLUMBIA, CANADA

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ABSTRACT

Foraminiferal biofacies identified in Saanich Inlet appear to be closely linked to a variety of environmental parameters, including water quality. Five biofacies are defined based on Q-mode cluster analysis and on faunal distribution profiles of foraminifera-bearing surface sediment samples. Biofacies 1 (*Eggerella advena* Biofacies), which occurs in near shore environments near two bays with densely populated shorelines, appears to have an affinity for areas contaminated by sewage outfall and septic system drainage. Biofacies 2 (*Eggerella advena-Spiroplectammina biformis* Biofacies) and 3 (*Miliammina fusca* Biofacies) characterize shallow, brackish waters, and are distributed in shallow bays adjacent to Biofacies 1. Biofacies 4 (*Lobatula fletcheri* Biofacies), the only biofacies dominated by a calcareous fauna, has been subdivided into two sub-biofacies: Sub-biofacies 4A (*Stainforthia feylingi* Sub-biofacies) and 4B (*Buccella frigida* Sub-biofacies). Sub-biofacies 4A occurs in deep water, low oxygen environments, whereas Sub-biofacies 4B characterizes shallow water, normal marine environments. The patchy distribution of Sub-biofacies 4B samples is probably due to vagaries of water circulation in the restricted basin. Biofacies 5 (*Leptohalysis catella-Spiroplectammina biformis* Biofacies) occupies a relatively deeper muddy environment with a high proportion of plant debris and probably relatively lower oxygen levels. Hence, the main environmental control defining the biofacies is water circulation (or lack thereof), which is influenced by the shape of the fiord (presence of the sill).

INTRODUCTION

The economy of southern Vancouver Island, British Columbia, relies heavily on fishing, tourism, and aquaculture, all of which are adversely affected by water pollution. As the population of greater Victoria, the largest city on the island, continues to burgeon, water pollution caused by sewage outfall and industrial waste has become a matter of concern (EVS Environment Consultants, 1996). Encroaching housing developments (Development Services Department of the Cowichan Valley Regional District, oral communication, 1994) also may affect the ecosystem of Saanich Inlet (Fig. 1). Foraminifera are used as indicators of pollution impact, but no work of this type has been carried out on the northwest coast of Canada. Consequently, there is a need for a reconnaissance study of the foraminiferal biofacies in Saanich Inlet in order to establish contemporary baseline conditions in Saanich Inlet.

The application of foraminiferal assemblages and biofacies distributions is a valuable tool for paleoceanographic interpretation of marine sediments (Culver, 1993). Regarding the concerns outlined above, the purposes of this reconnaissance study are to: (1) document foraminiferal distributions in Saanich Inlet and determine the effects of an intermittently anoxic basin on foraminiferal ecology; (2) provide baseline data for a paleoseismic study of sediment cores from Saanich Inlet (Blais, 1995; Blais-Stevens and others, 1997); and (3) assess the environmental impact of industry and urban development on the benthic ecosystem of the fiord.

STUDY AREA

Saanich Inlet, located at the southern end of Vancouver Island (Fig. 1), is 26 km long, up to 8 km wide, and has average and maximum depths of 120 m and 236 m, respectively. It is indented by five bays which receive discharges from small ephemeral streams (Fig. 2). Unlike other inlets in British Columbia, freshwater runoff into Saanich Inlet is negligible as a flushing mechanism (Herlinveaux, 1962). Goldstream River, the only significant stream flowing into the inlet, discharges only a small amount of freshwater ($0.85 m^3$/sec; Herlinveaux, 1962). The main local source of freshwater and sediment is the Cowichan River, which flows into Satellite Channel northwest of the inlet (Fig. 1). A bedrock still at 70 m depth at the mouth of the inlet (Figs. 1 and 2) restricts water circulation, typically creating anoxic conditions below depths of 70–150 m (Carter, 1934; Gross and others, 1963). In late summer or early fall, dense cold water enters the inlet from Haro Strait, flushes the upper part of the anoxic zone, and increases the concentration of dissolved oxygen in the water (Herlinveaux, 1962; Anderson and Devol, 1973; Stucchi and Giovando, 1984). The extent of flushing differs from year to year, and, as a result, the thickness of the anoxic layer is highly variable to the extent that it sometimes does not form (Anderson and Devol, 1973; Stucchi and Giovando, 1984). An example of oxygen replenishment in Saanich Inlet is shown in Figure 3 (Herlinveaux, 1962). Oxygen concentrations decrease with depth throughout the year, except for a short period of time, in late summer when the deeper parts of the basin are flushed.

In the shallower and well-oxygenated areas of the inlet, sediments range from silt to fine sand with gravel in some areas. In the deeper anoxic part of the basin (below 100 m), the sediments are mainly muddy diatomaceous ooze (Fig. 4; Gucluer and Gross, 1964). However, in the central part of the basin, there may be the presence of some sediments coarser than mud due to passive transport caused by slumping of sediments, especially in the southern part of the basin (south of Patricia Bay) where basin walls are steep (Blais, 1995; Blais-Stevens and others, 1997).

Annual water temperatures in the fiord fall within the expected range for fiords in British Columbia (Pickard, 1975).

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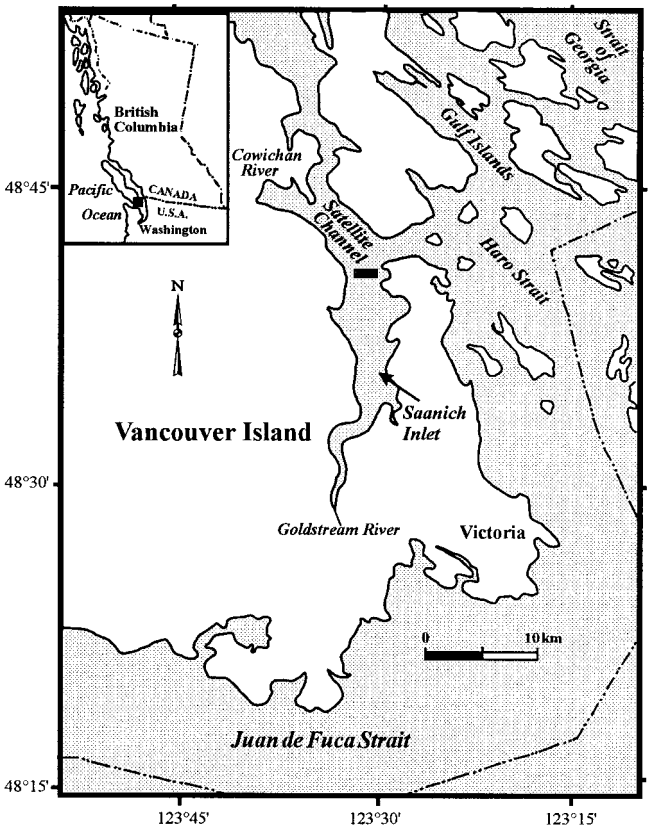


FIGURE 1. Location map, Saanich Inlet, British Columbia. The shaded box locates the bedrock sill at the north end of the Inlet.

At <50 m, temperature changes are seasonal ranging from 5°C in January to 18°C in July. Below 50 m, temperatures are stable at 8–9°C. Observed temperature structure along a longitudinal section of the inlet (Herlinveaux, 1962; Fig. 5) reveals that water temperature varies with depth throughout the inlet. These data indicate that water temperature varies with depth during spring and early summer. However, stratification is well developed by late summer.

Furthermore, data compiled by Herlinveaux (1962) indicate that surface water salinities vary widely compared to those observed in the deeper parts of the basin. These variations appear to reflect the nature of precipitation and local drainage patterns (Herlinveaux, 1962). Waters below the sill appear to be isolated from waters entering the inlet from Satellite Channel (Fig. 6; Herlinveaux, 1962).

PREVIOUS WORK

Until recently, few studies of Recent foraminifera had been carried out along the coast of British Columbia and adjacent Washington state. Most of these studies were of a reconnaissance nature or targeted to specific stratigraphic problems and thus provide little ecological information. Systematic studies on recent shelf foraminifera in the northeast Pacific Ocean along the coast of British Columbia and Washington have been carried out by Cushman (1925), Cushman and Todd (1947), Phleger (1967), McCulloch (1977), and Patterson (1991). As the study of foraminifera developed, many foraminiferal species names were changed, which led to some confusion. In order to standardize nomenclature, and to assist subsequent researchers in the area, Patterson and others (1997) prepared a monograph on the foraminiferal faunas of the British Columbia shelf. Results from several stratigraphic, distributional and paleoenvironmental studies in the region were only of limited use in the Saanich Inlet investigation as none were carried out in fiords (Scott, 1974; Gallagher, 1979; Jones and Ross, 1979; Williams, 1989; Patterson, 1989; 1990; 1991; 1993; Patterson and Cameron, 1991; Jonasson and Patterson, 1992; Snyder and others, 1990 a, b; and Patterson and Luternauer, 1993). However, one distributional study was carried out in Bute and Knight inlets, which are fiords located on the central coast of British Columbia (Schafer and others, 1989). The only foraminiferal distribution study geographically close to Saanich Inlet was carried out by Cockbain (1963) in the Strait of Georgia (Fig. 1).

Studies of diatoms in Saanich Inlet sediments (Gucluer and Gross, 1964; Sancetta and Calvert, 1988; Sancetta, 1989) confirmed that rhythmites in the central anoxic part of the basin are varves. One varve consists of a dark, terrigenous-rich, silty-clay, winter layer and a light, diatom-rich, summer layer. These layers are deposited annually from settling of pelagic matter.

METHODS AND MATERIALS

Fifty-six grab samples were collected from sites distributed throughout the inlet using a Dietz-Lafond grab sampler with a sampling area of 11 × 14.7 cm and a capacity of 480 cm^3; only the top 5 cm were saved for analysis (Fig. 2) with the assumption that biofacies distributions determined for relatively thick (2, 5, and 10 cm deep) sediment layers are more useful analogues of paleoecological applications (Denne and Sen Gupta, 1989; Ozarko and others, 1997). The initial idea was to sample in transects across the basin. However, sampling in the central part of the fiord was not always possible because the grab sampler employed did not always snap shut at greater depths in the soft diatomaceous ooze. Locations of sample sites were determined using a Trimble-NAVTRAC Global Positioning System (GPS) instrument. Sampling depths (in meters below sea level) were recorded with a 200 kHz Ross echosounder at mean low tide (Table 1). After qualitative sedimentological description (Table 1), each sample was immersed in a formalin-Rose Bengal solution (Walton, 1952) for 24 hours to help distinguish live (stained pink) from dead (unstained) specimens. The following day, samples were rinsed through a 0.5 mm screen to remove coarse organic matter and rock fragments and through a 0.063 mm screen to retain the foraminifera. The 0.063–0.50 mm fraction was wet split for quantitative analysis using a wet splitter described by Scott and Hermelin (1993) and preserved in a buffered formalin solution. The amount of sediment retained for examination ranged from 20 to 100 cm^3.

To identify and count live and dead specimens, samples were immersed in water and examined with an Olympus (Model 219142) binocular microscope. Total abundances of live and dead of specimens were tabulated (see Appendix 1 in Blais, 1995). Specimens were considered ''live'' when globules of stained protoplasm were identified. In addition,

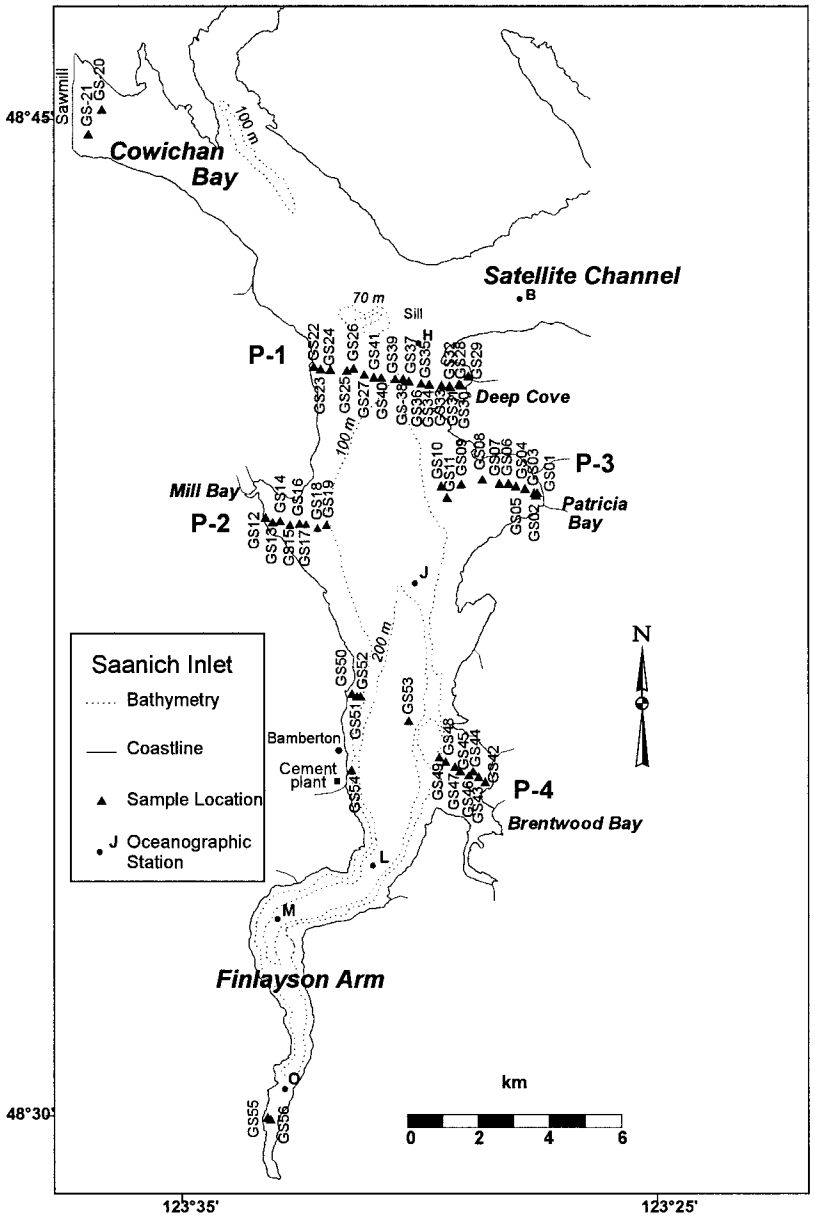


FIGURE 2. Location map of grab sample sites in Saanich Inlet. Stations O, M, L, J, H, and B are from a hydrological study by Herlinveaux (1962). They are referred to in Figs. 3, 5, and 6.

the percent abundance and the percent error for each species were calculated (Appendix 1 in Blais, 1995) using the methods of Patterson and Fishbein (1989) who suggested that these values be included in data compilation to indicate accuracy of species estimates. The percent error (95% confidence level) was calculated using the standard error equation:

$$s_{X_i} = 1.96\sqrt{\frac{X_i[1 - X_i]}{N}}$$

where (N) is the total number of counts, and (X) is the fractional abundance of a species (Patterson and Fishbein, 1989).

A Q-mode cluster analysis was carried out on the total data using a technique that closely emulates results from the statistically significant ''error weighted maximum likelihood'' clustering method of Fishbein and Patterson (1993). This method requires that only the species present in statistically significant (Percent abundance of species > standard error; Fishbein and Patterson, 1993) populations be analyzed. From a total of 96 observed species, the Q-mode cluster analysis was carried out on the 34 statistically significant species using SYSTAT (v. 5.2; SYSTAT Inc. 1992). Euclidean distance correlation coefficients were used to measure similarity between pairs of species, and the Ward's linkage method was utilized to arrange sample pairs and sample groups into a hierarchic dendrogram.

Four faunal distribution profiles of the dominant species

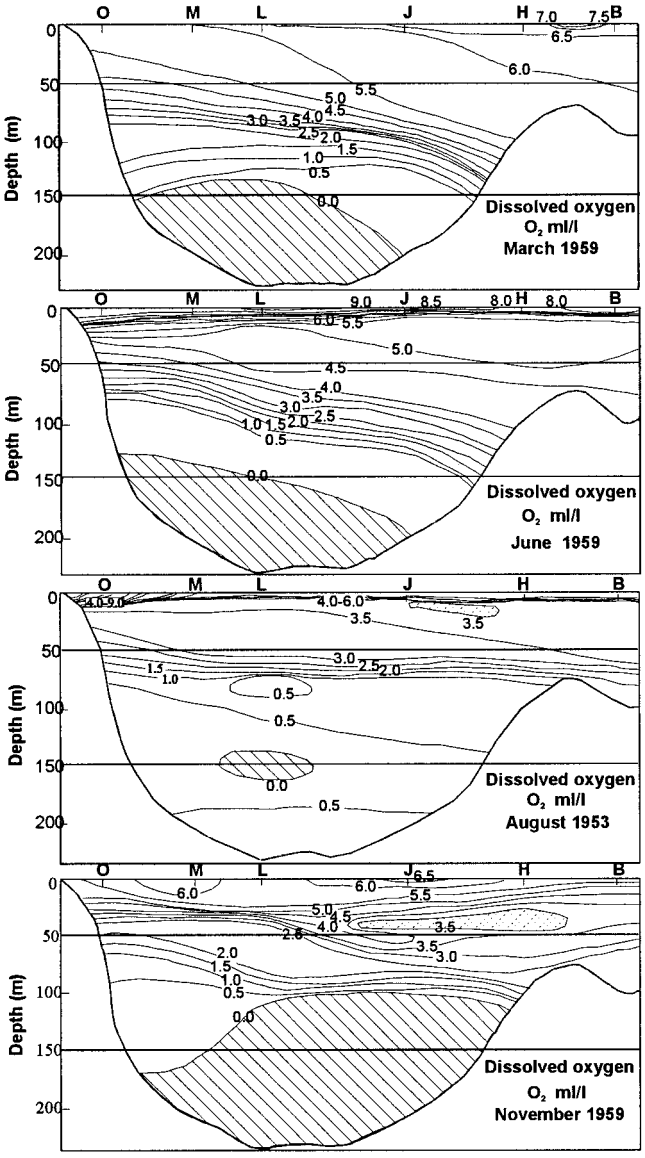


FIGURE 3. Oxygen structure in a longitudinal profile of Saanich Inlet. Stations are plotted on Fig. 2 (modified from Herlinveaux, 1962).

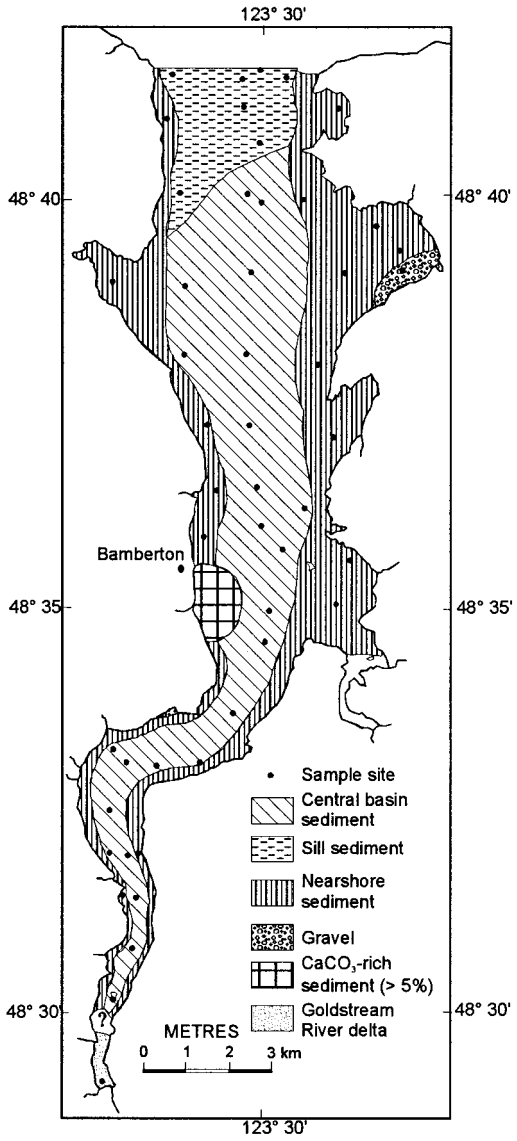


FIGURE 4. Location of surface samples (black dots) and distribution of sediment types in Saanich Inlet. Central basin sediments = silt and clay with abundant diatom frustules. Sill sediments = silt. Nearshore sediments = poorly sorted, fine sand and some gravel. Carbonate-rich sediments = Near limestone quarry in Bamberton (modified from Gucluer and Gross, 1964).

were plotted against sample depth (i.e., water depth) in order to help define, along with the cluster analysis, the ecological parameters.

Selected specimens of common species were mounted, gold coated, and examined using a LECA Cambridge S360 scanning electron microscope at the Geological Survey of Canada, Ottawa.

RESULTS

Species Abundance and Preservation

With the exception of GS-53, collected at 221 m (deepest), all 56 grab samples contain benthic foraminifera. Eight samples with fewer than 100 specimens are not included in Appendix 1 (where relative abundances are tabulated) because species in these samples are rare and are not statistically significant (Patterson and Fishbein, 1989; Fishbein and Patterson, 1993). However, one sample (GS-04) containing fewer than 100 specimens is included because it only contains two species, both of which are statistically significant. Of the 49 samples that are tabulated (Appendix 1 in Blais, 1995), 39 contained specimens with protoplasm that stained with Rose Bengal.

In general, most specimens are well preserved. Some dissolution is indicated by the presence of variably dissolved unstained *Cribroelphidium* spp. tests in 36 of the 49 samples. It is also apparent that some dissolution has taken place on stained specimens of *Cribroelphidium* spp. and *Quinqueloculina* spp. which are partially to completely dissolved, in some cases with only the organic linings remaining. Agglutinated species predominate the foraminiferal fauna of most samples. Only six samples contain relatively more calcareous than agglutinated specimens. However, the

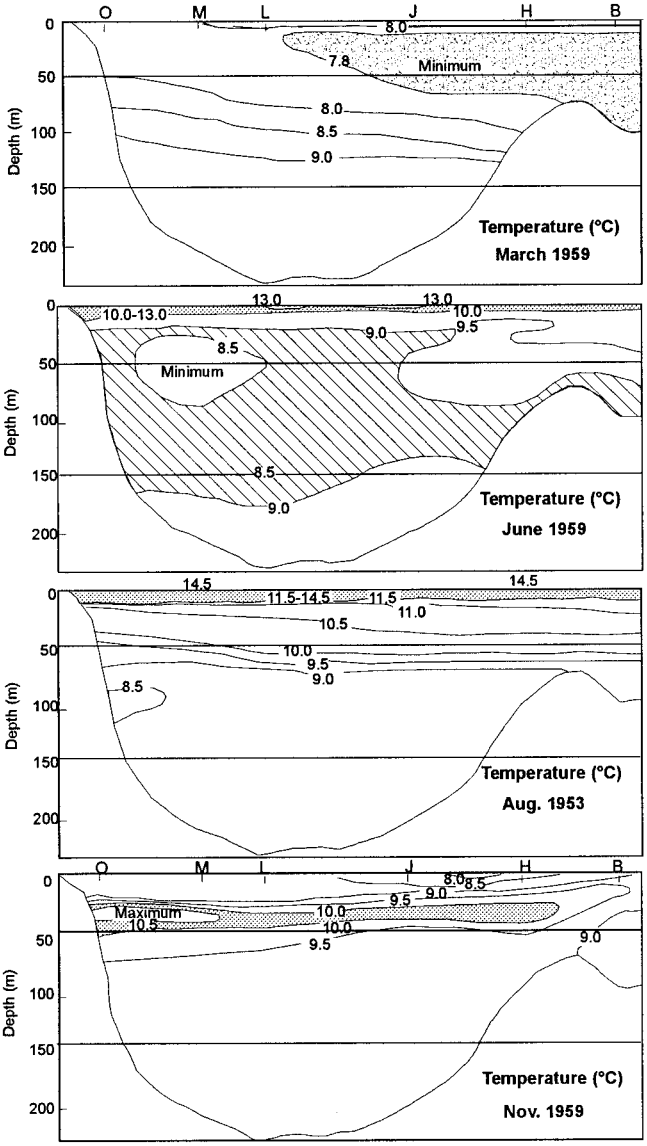


FIGURE 5. Temperature structure in a longitudinal profile of Saanich Inlet. Stations are plotted on Fig. 2 (modified from Herlinveaux, 1962).

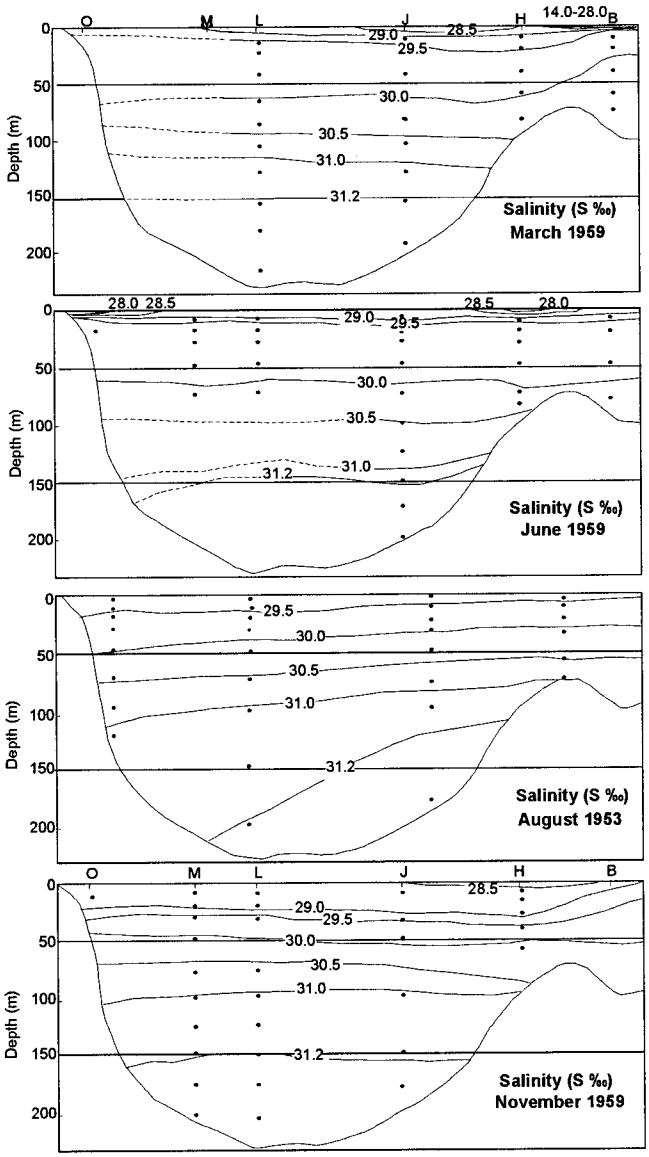


FIGURE 6. Salinity structure in a longitudinal profile of Saanich Inlet. Stations are plotted on Fig. 2 (modified from Herlinveaux, 1962).

calcareous faunas are more diverse than agglutinated faunas in those instances where they dominate an assemblage. No planktic foraminifera are observed in any of the samples.

Percent Live vs. Water Depth

The percentage of ''live'' specimens relative to total (''live'' and dead) abundance (Table 1) is plotted against water depth of sample (Fig. 7). The scattergram reveals a negative relationship, indicating that the deeper the water, the lower the percentage of ''live'' specimens. Furthermore, in those samples collected at greater depths (73–97 m), only trace abundances of ''live'' specimens were found (*Trochammina pacifica* and *Spiroplectammina biformis*).

FAUNAL DISTRIBUTION OF DOMINANT SPECIES

To examine faunal changes with water depth across the fiord, cumulative abundances of numerically dominant foraminiferal species (''live'' and dead), i.e., dominant in at least one sample (in Blais, 1995), are plotted against depth in four profiles (Figs. 8, 9, 10, and 11), which are identified on Figure 2. Five samples (GS-20, 21, 54, 55, and 56; Fig. 2) are not in line with the profiles and have therefore been excluded.

Bays/Shore

Eggerella advena generally dominates the assemblages in Deep Cove (Profile 1; Fig. 8) and Patricia Bay (Profile 3; Fig. 10), and one assemblage in Mill Bay (Profile 2; Fig. 9), three bays subject to septic tank drainage, agricultural runoff, and sewage discharge (EVS Consultants, 1996); only trace amounts of other species are present in these areas. In one portion of Patricia Bay, at water depths shallower <12 m and adjacent to the mouth of an ephemeral stream (Fig.

TABLE 1. List of samples with their location, depth, brief qualitative sediment description (not using Wentworth scale) and total percent of live specimens. In the last column, the samples with no number have less than 100 specimens and are not included in the scattergram of Figure 7. Sample GS-04 is included because it is statistically significant (Fishbein and Patterson, 1989).

Sample	Latitude °W	Longitude °N	Depth (m)	Description	Total % live
GS01	48°39.37″	123°26.83″	1	Grey coarse sand	—
GS02	48°39.37″	123°26.90″	3	Grey coarse sand high organics	12.5
GS03	48°39.33″	123°26.86″	6	Grey coarse sand high organics	15
GS04	48°39.43″	123°27.11″	12	Olive coarse sand	48
GS05	48°39.47″	123°27.32″	15	Olive coarse sand	36
GS06	48°39.51″	123°27.49″	20	Olive coarse sand	48.3
GS07	48°39.51″	123°27.70″	26	Olive coarse sand	33.1
GS08	48°39.57″	123°28.09″	23	Olive coarse sand	19.2
GS09	48°39.50″	123°28.57″	36	Olive coarse sand	8
GS10	48°39.47″	123°29.03″	72	Sand and mud	—
GS11	48°39.30″	123°28.90″	73	Olive coarse sand	1.4
GS12	48°39.92″	123°33.08″	5	Sand and mud	23.5
GS13	48°38.93″	123°32.89″	15	Olive coarse sand	23.7
GS14	48°38.90″	123°32.67″	13	Coarse sand	1
GS15	48°38.94″	123°32.55″	21	Medium-coarse olive sand	4.6
GS16	48°38.95″	123°32.43″	34	Medium-coarse olive sand	14.8
GS17	48°38.90″	123°32.12″	42	Medium-coarse olive sand	21.2
GS18	48°38.72″	123°31.77″	90	Olive mud	—
GS19	48°38.79″	123°31.72″	90	Olive mud	0
GS20	48°45.14″	123°36.75″	53	Olive mud high organic content	0
GS21	48°44.77″	123°37.05″	40	Olive mud high organic content	0
GS22	48°41.27″	123°31.95″	19	Olive coarse sand	44.6
GS23	48°41.23″	123°31.79″	67	Olive mud high organic content	0
GS24	48°41.22″	123°31.57″	72	Olive mud and sand	0
GS25	48°41.21″	123°31.19″	73	Olive-grey mud and sand	0
GS26	48°41.24″	123°31.04″	73	Olive mud and sand	0.8
GS27	48°41.15″	123°30.79″	76	Olive mud and sand	1.6
GS28	48°40.99″	123°28.58″	18	Coarse dark grey sand	0
GS29	48°41.13″	123°28.41″	2	Coarse sand	—
GS30	48°41.01″	123°28.62″	25	Olive coarse sand	46.6
GS31	48°40.98″	123°28.84″	30	Medium-coarse olive sand	40.1
GS32	48°40.96″	123°28.82″	30	Medium-coarse olive sand	12
GS33	48°40.99″	123°29.02″	41	Medium-coarse olive sand	20.6
GS34	48°41.00″	123°29.30″	49	Medium-coarse olive sand	23.2
GS35	48°41.02″	123°29.49″	57	Medium-coarse olive sand	5.9
GS36	48°41.02″	123°29.49″	56	Medium-coarse olive sand	2.1
GS37	48°41.05″	123°29.77″	95	Olive mud high organic content	1.2
GS38	48°41.09″	123°29.90″	97	Olive mud and sand	1.5
GS39	48°41.08″	123°30.08″	112	Olive mud high organic content	0
GS40	48°41.10″	123°30.40″	84	Olive mud and sand	0.5
GS41	48°41.11″	123°30.57″	78	Olive mud and sand	5.6
GS42	48°35.02″	123°28.03″	10	Coarse sand and mud	38
GS43	48°35.10″	123°28.18″	44	Coarse sand and mud	23.3
GS44	48°35.18″	123°28.30″	52	Olive mud high organic content	3.2
GS45	48°35.18″	123°28.60″	78	Olive mud high organic content	2
GS46	48°35.12″	123°28.40″	62	Olive mud + high organic content	0
GS47	48°35.25″	123°28.72″	42	Medium-coarse olive sand	7
GS48	48°35.32″	123°28.93″	62	Sand and mud	—
GS49	48°35.39″	123°29.08″	31	Coarse sand and mud	0.3
GS50	48°36.34″	123°31.08″	2	Olive-grey coarse sand	80.7
GS51	48°36.30″	123°30.97″	35	Coarse sand	—
GS52	48°36.30″	123°30.88″	74	Olive coarse sand and mud	10.8
GS53	48°35.82″	123°30.87″	221	Black mud and H2S odor	0
GS54	48°35.20″	123°31.09″	88	Light grey med. sand	0.2
GS55	48°29.97″	123°33.01″	16	Medium-coarse olive sand	30.2
GS56	48°29.94″	123°32.94″	14	Coarse sand + high org. content	0.9

2), *Miliammina fusca* dominates the agglutinated foraminiferal assemblages (Profile 3; Fig. 10).

In samples dominated by agglutinated species, *Leptohalysis catella* is present at water depths greater than 20 m and *Spiroplectammina biformis* occurs only in trace abundances (all profiles; Figs. 8, 9, 10, and 11).

In samples consisting mainly of calcareous foraminifera, *Buccella frigida* predominates the assemblages from shallow depths (<20 m; Profiles 1, 2, and 4; Figs. 8, 9, and 11, respectively). At depths of 20-50 m, *Buccella frigida* and *Stainforthia feylingi* occur in approximately equal abundances (Profile 4; Sample GS-49; Fig. 11).

Where dissolved *Cribroelphidium* spp. dominates an assemblage at depths of less than 5 m, it is represented by a substantial number (percentage) of live specimens (Appendix 1 in Blais, 1995). Samples GS-12 and −50; Profiles 2

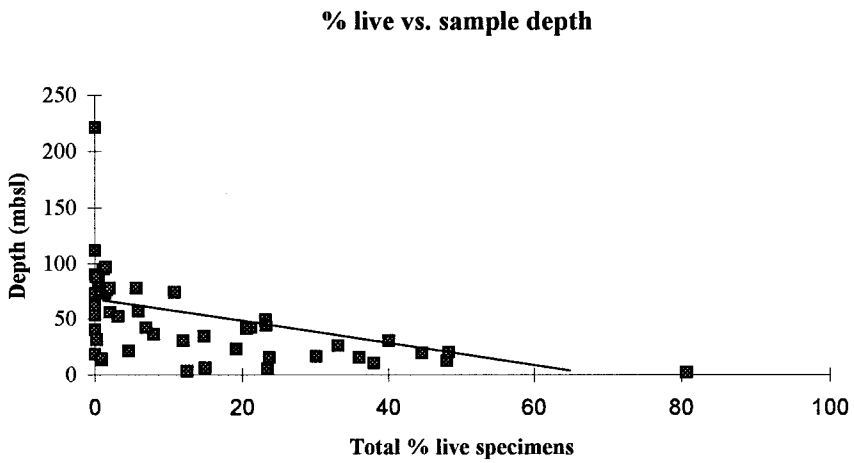


FIGURE 7. Scattergram of the total percent abundance of live specimens versus sample depth. ''Best-fit'' regression line shows negative relationship as calculated by Delta Graph version 3.0 (for Apple Macintosh). Correlation coefficient (r) = −0.533.

and 4; Figs. 9 and 11, respectively. On the other hand, dissolved ''dead'' *Cribroelphidium* spp. are found in most of the deeper samples (>5 m).

Basin Trough

Leptohalysis catella and *Spiroplectammina biformis* are the most abundant species in dominantly agglutinated assemblages from water depths >57 m (Profile 1; Fig. 8; Samples GS-40, 38, and 35). *S. biformis* is present in most samples collected for this study and it increases in abundance at depths greater than 30 m (all profiles; Figs. 8, 9, 10, and 11). At water depths >50 m, calcareous assemblages are characterized by an abundance of *Stainforthia feylingi* (Profile 2; Fig. 9; sample GS-54, not included in the profiles).

Dissolved specimens of *Cribroelphidium* spp. become more abundant with increasing depth, with the exception of sample GS-40 (depth 84 m; Profile 1; Fig. 8) which contains none. Although *Cribroelphidium* spp. is a significant component of deeper water assemblages, it dominates only in samples GS-26 and −27 at depths of 73 m and 76 m, respectively (Profile 1; Fig. 8).

CLUSTER ANALYSIS

Q-mode cluster analysis on the foraminiferal data (total abundance = ''live'' and dead) for 34 statistically significant species (Appendix 1 in Blais, 1995), yields six clusters (Fig. 12). These clusters (Table 1) are the: (1) *Eggerella advena* Cluster, (2) *Eggerella advena-Spiroplectammina biformis* Cluster, (3) *Miliammina fusca* Cluster, (4) *Lobatula fletcheri* Cluster divided into two sub-clusters based on dominant species: (4A) *Stainforthia feylingi* and (4B) *Buccella frigida*, (5) dissolved *Cribroelphidium-Spiroplectammina biformis-Leptohalysis catella* Cluster, and (6) *Spiroplectammina biformis-Leptohalysis catella* Cluster. In Clusters 2, 3

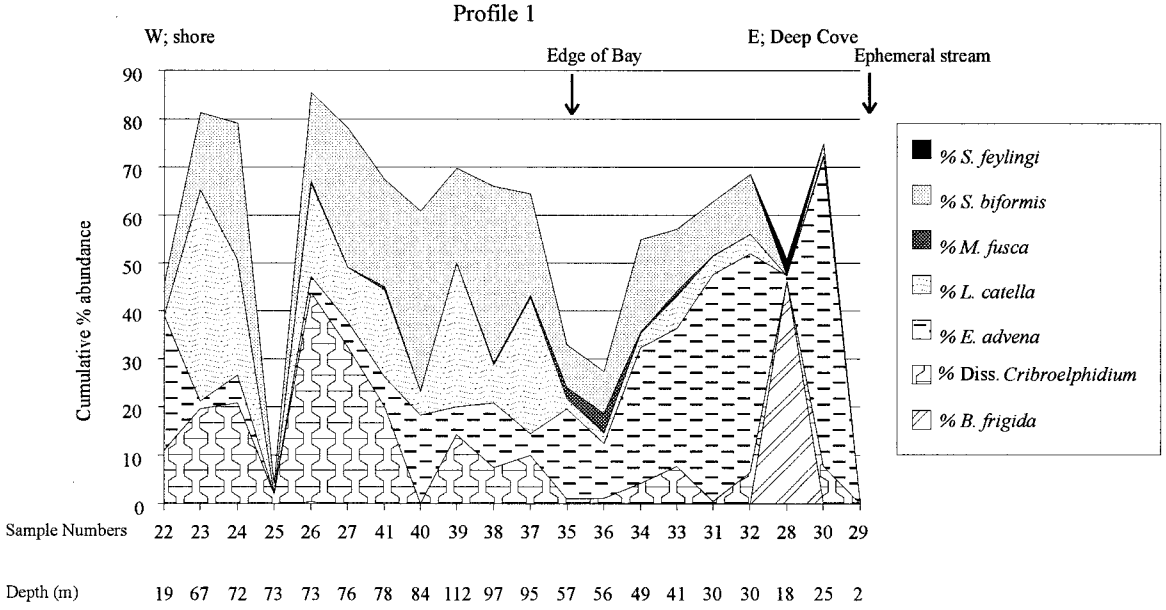


FIGURE 8. Profile 1: Cumulative percent abundance of the dominant foraminiferal species plotted against sample depth. See Figs. 2 and 13 for location of profile.

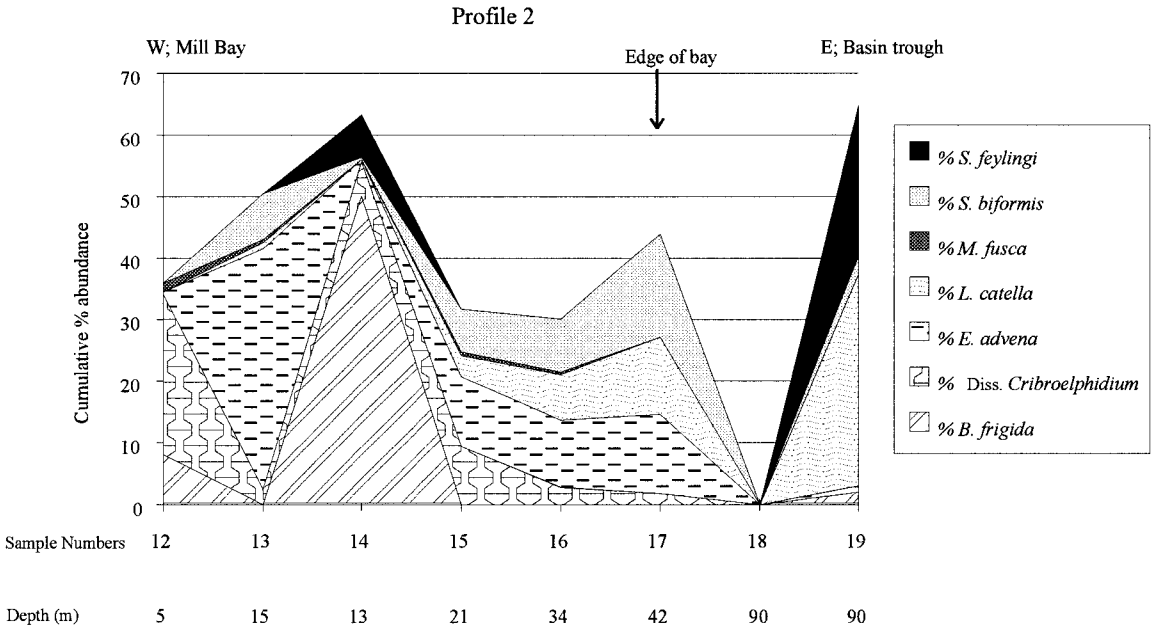


FIGURE 9. Profile 2: Cumulative percent abundance of the dominant foraminiferal species plotted against sample depth. See Figs. 2 and 13 for location of profile.

and 5, some samples are anomalously distributed within a cluster because of their characteristic taxa.

BIOFACIES

Five biofacies (as defined by Bates and Jackson, 1987; p. 232) are defined on the basis of characteristic taxa identified in a cluster analysis and faunal distribution profiles. Table 2 summarizes the biofacies, i.e., their most dominant species, assemblages, and, respective depth ranges, and the environment in which they are found.

Biofacies 1: Eggerella advena *Biofacies*

This biofacies, which is also represented by Cluster 1 (Fig. 12), is characterized by *Eggerella advena*, with relative abundances ranging from 64.3% to 89% within the four samples (Profiles 1 and 3; Figs. 8 and 10, respectively). The foraminiferal diversity of this biofacies is low. Samples that represent the biofacies range in depth from 15 to 26 m, are composed of gray sands, and are located in Patricia Bay and in Deep Cove on the eastern shore of Saanich Inlet near a highly populated area of the coast.

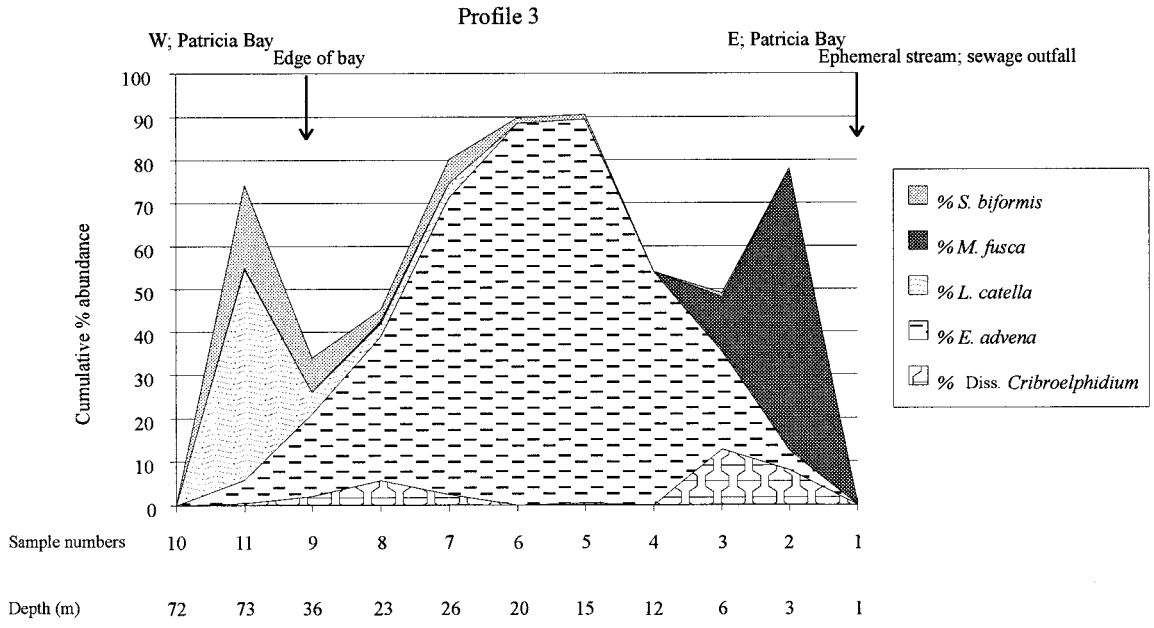


FIGURE 10. Profile 3: Cumulative percent abundance of the dominant foraminiferal species plotted against sample depth. See Figs. 2 and 13 for location of profile.

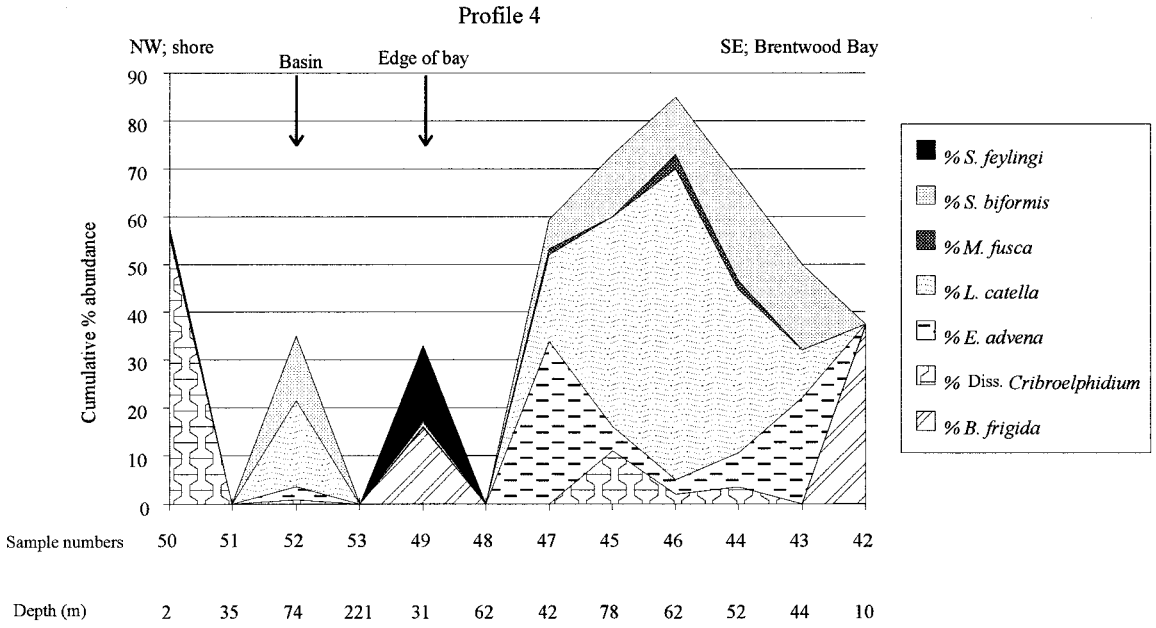


FIGURE 11. Profile 4: Cumulative percent abundance of the dominant foraminiferal species plotted against sample depth. See Figs. 2 and 13 for location of profile.

Biofacies 2: Eggerella advena-Spiroplectammina biformis *Biofacies*

Biofacies 2, which is represented by Cluster 2 (excluding sample GS-52 as discussed below), is dominated by *Eggerella advena* and *Spiroplectammina biformis.* Biofacies 2 has a slightly greater foraminiferal diversity than Biofacies 1 (Appendix 1 in Blais, 1995). Samples of Biofacies 2 consist of olive coarse sand, are found at depths ranging from 12 to 57 m, and are located in the all the sampled bays (Profiles 1 to 4; Figs. 8, 9, 10, and 11, respectively).

Biofacies 3: Miliammina fusca *Biofacies*

Biofacies 3, which is represented by Cluster 3 (excluding sample GS-25 as discussed below; Fig. 12), is characterized by relatively high abundances (12.8% to 65%) of *Miliammina fusca.* Samples from Biofacies 3 are coarse sands with abundant plant debris at water depths of 3 to 14 m.

Biofacies 4: Lobatula fletcheri *Biofacies*

This biofacies, which is represented by Cluster 4 (Fig. 12) is dominated by a calcareous fauna; *Lobatula fletcheri* is the only species that occurs in every sample. The biofacies is subdivided into two sub-biofacies, 4A and 4B, on the basis of taxonomic composition.

Sub-biofacies 4A: Stainforthia feylingi *Sub-biofacies*

Sub-biofacies 4A, which is also represented by Sub-cluster 4A, is dominated by *Stainforthia feylingi* and is found at much greater depths (ca. 90 m) than Sub-biofacies 4B (10–31 m; Fig. 12).

Sub-biofacies 4B: Buccella frigida *Sub-biofacies*

Sub-biofacies 4B, which is represented by sub-cluster 4B (Fig. 12), is dominated by *Buccella frigida.* The samples from this sub-biofacies are sandy and distributed within the bays along the margins of Saanich Inlet (Fig. 13; Profiles 1, 2, and 4; Figs. 8, 9 and 11, respectively).

Biofacies 5: Leptohalysis catella-Spiroplectammina biformis *Biofacies*

This biofacies includes samples from Clusters 5 and 6 (Fig. 12), which have similar foraminiferal content, average depth, and sediment texture. Cluster 5 contains a higher abundance of dissolved *Cribroelphidium* spp. and less plant debris than Cluster 6.

Biofacies 5, dominated by *Leptohalysis catella* and *Spiroplectammina biformis,* occurs at water depths from 40 to 112 m, deeper than all other biofacies except 4A (Table 2). Samples consist of olive mud with the exception of sample GS-11, which is olive sand. Some samples contain high proportions of plant debris. Most of the samples are from the basin trough distant from shoreline and bay environments (Fig. 13). Those samples collected within bays came from depths of 40 m or more (Figs. 8, 9, 10, and 11).

DISCUSSION

PERCENT LIVE VS. SAMPLE DEPTH

As mentioned above, the percentage of live specimens relative to the total assemblage decreases with depth (Fig. 7). Although the percentage of live specimens depends on the abundance of dead specimens, which in turn, can be affected by factors, such as production rates, sedimentation rates, and preservation of tests, the scarcity of living foraminifera at greater depths may also reflect a decrease in dissolved oxygen with depth in the seawater (Fig. 3). Furthermore, at greater depths, only trace amounts of live species (*T. pacifica* and *S. biformis*) which can tolerate a wide range of marine conditions (Murray, 1991) are found. Thus,

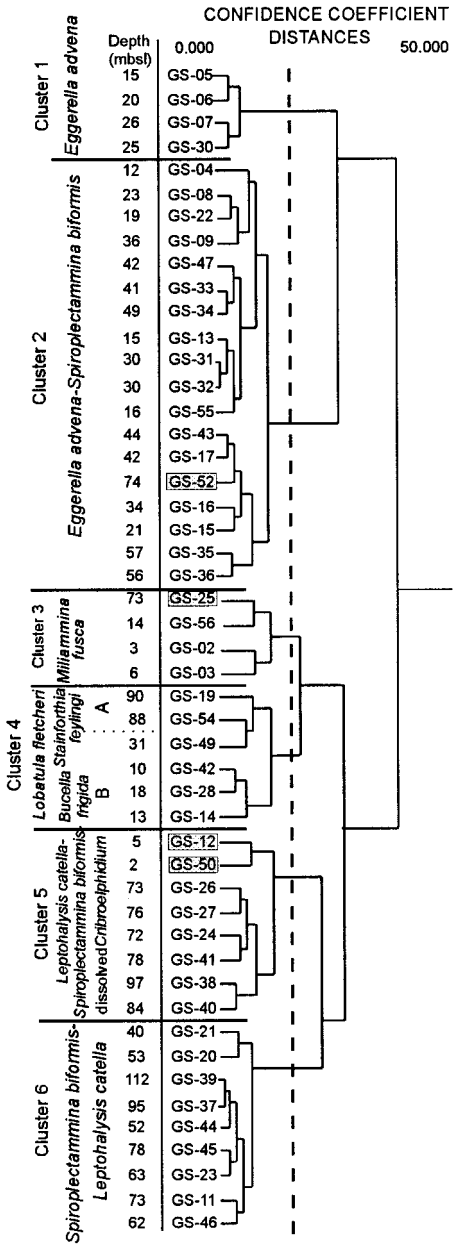


FIGURE 12. Q-mode cluster dendrogram defining six clusters. Cluster 4 is divided into two sub-clusters: 4A and 4B. Dashed line defines confidence level. Shaded boxes indicate anomalous clustering.

living conditions at greater depths seem to be strained considering the low abundance of live specimens and the types of species observed.

BIOFACIES

Eggerella advena dominates the low-diversity Biofacies 1 assemblage at shallow depths near a highly populated area of the coast. Patricia Bay and Deep Cove are densely populated with septic systems that may be contaminating the groundwater discharging into the inlet along with agricultural runoff (EVS Environment Consultants, 1996). Furthermore, water quality analyses of Saanich Inlet show that after a period of rainfall, Deep Cove and Patricia Bay have the highest fecal coliform concentrations in the inlet and often exceed the swimming criterion of 200 MPN/100 ml (Drinnan and others, 1995). In addition, the highest levels of fecal coliform were found in sources entering Deep Cove, Patricia Bay, Brentwood Bay, and Mill Bay. Moreover, data presented by Calder and Mann (1995) show that most shellfish harvest areas found along all the bays and some of the shoreline have been closed since 1987 due to concentrations of fecal coliform exceeding the accepted level of 43 MPN/100 ml.

Although sewage discharge may cause an increase in foraminiferal diversity in warm climates (Yanko and others, 1994), along the coast of California sewage reduces the diversity of the foraminiferal biofacies and favors a dramatic increase of agglutinated taxa such as *Eggerella advena* and *Trochammina pacifica* (Watkins, 1961; Bandy and others, 1964a, b; Murray, 1991). Similar foraminiferal biofacies have been reported from Atlantic Canada, the Fraser River delta, and southeast Norway (Schafer and Cole, 1974; Patterson, 1990; Alve 1993, respectively). Schafer and Cole (1974) reported foraminiferal diversity decreases and assemblages are dominated by *Eggerella advena,* along with *Miliammina fusca,* near a pulpmill effluent outfall on the Atlantic coast, Baie des Chaleurs, Gulf of St. Lawrence. Patterson (1990) attributed a dramatic increase in the abundance of *Trochammina pacifica* and a lowered foraminiferal diversity in Fraser River delta in tidal flats to high levels of organic mud. Alve (1993) reported that one of the most abundant taxa found near sewage outfalls is *Eggerrella advena.* A species known to tolerate slightly brackish water conditions that are generally found near sewage outfalls (Murray, 1991). Hence, contamination of the water in Saanich Inlet because of sewage discharge, agricultural runoff, and septic system leakage likely is responsible for this low diversity foraminiferal biofacies.

Biofacies 2 is characterized by high abundances of *Eggerella advena* and *Spiroplectammina biformis. Spiroplectammina biformis,* which can tolerate a wide range of marine conditions (Murray, 1991), increases in abundance with depth along Profiles 1 to 4 (Figs. 8, 9, 10, and 11, respectively). The association of *Eggerella advena,* which is known to tolerate brackish waters (Murray, 1991), with *Spiroplectammina biformis* transends the depth range of Biofacies 1 (15–26 m) and becomes Biofacies 2 (12–57 m), yet both biofacies still characterize shallow waters. Biofacies 2 is found in nearshore portions of bays and near the mouths of freshwater streams on the distal side of Biofacies 1 (e.g., Fig. 13). Thus, both brackish water conditions and contamination of the water likely play a role in the distribution of Biofacies 2, which is reflected by its close association with Biofacies 1.

Sample GS-52 is excluded from Biofacies 2 even though it falls within Cluster 2 (Fig. 12). Its high abundance of *Spiroplectammina biformis* (13.4%) and significant concentration of *Eggerella advena* (2.7%) seem to indicate the reason for its presence in Cluster 2. However, the high abundance of *Leptohalysis catella* (17.9%), similar fossil assemblage to Biofacies 5, and its greater depth (74 m; Profile 4; Fig. 11) reflect conditions of Biofacies 5 as discussed below. Since this sample falls within two possible groups, it was not assigned to a specific biofacies.

TABLE 2. List of biofacies and their assemblage, sediment texture, depth range, and the environment in which they are found.

Biofacies	Assemblage	Sediment texture	Depth range (m)	Environment
Biofacies 1	*Eggerella advena** *Trochammina pacifica* *Trochammina rotaliformis*	Grey coarse sand	15–26	Bay/sewage outfall
Biofacies 2	*Eggerella advena**- *Spiroplectammina biformis** *Reophax scorpiurus*; *Trochammia pacifica* *Trochammia rotaliformis*	Olive coarse sand	12–57	Bay
Biofacies 3	*Miliammina fusca** *Eggerella advena*; *Saccammina cf. atlantica*	Coarse sand high organics	3–14	Bay/ephemeral stream outlet
Biofacies 4	*Lobatula fletcheri**			
Subiofacies 4a	*Stainforthia feylingi** *Leptohalysis catella*; *Lobatula fletcheri*	Mud and sand	88–90	Basin trough
Subiofacies 4b	*Bucella frigida** *Cribroelphidium excavatum* *Lobatula fletcheri*; *Valvulineria arctica*	Coarse sand	10–31	Bay
Biofacies 5	*Leptohalysis catella**- *Spiroplectammina biformis** *Eggerella advena* *Haplophragmoides columbiensis* *Trochammina rotaliformis*	Olive mud + medium sand; some with abundant organics	40–112	Basin trough Bay/high organics

Note: The asterisk indicates the most characteristic species.

Miliammina fusca characterizes brackish waters with salinities less than 20‰ (Scott and others, 1980; Alve, 1990) and abundant plant debris on the sediment surface (Alve, 1990). Biofacies 3 comprises three nearshore samples, two in Patricia Bay and one near the mouth of Goldstream River. These three occur near samples from Biofacies 1 and 2 (Fig. 13). This association provides further evidence that the near shore environments of Patricia Bay and Goldstream River outlet are brackish water environments probably rich in organic debris. *Eggerella advena* can tolerate brackish waters. However, when the water becomes too brackish, *Miliammina fusca* will dominate the foraminiferal assemblage especially close to a zone of freshwater discharge (Scott and others, 1980).

Sample GS-25 grouped within Cluster 3, but it does not contain *Miliammina fusca,* therefore is excluded from Biofacies 3. This sample contains abundant *Discammina compressa* and *Saccammina* cf. *atlantica,* which are common to some samples from Cluster 3 and Biofacies 3 (Appendix 1 in Blais, 1995). *Discammina compressa* should not be considered as an indicator of brackish waters because it is identified in a variety of marine environments (Schröder, 1986; Loeblich and Tappan, 1987). *Saccammina* lives in a temperate to cold inner shelf (0–100 m) setting (Murray, 1991). Because all samples from this study were collected within a temperate, inner shelf oceanographic setting, *Saccammina* should not be considered as an indicator of any particular environment in Saanich Inlet. Thus, sample GS-25 remains anomalously linked to Cluster 3, but lacks some key taxa indicative of the environment of Biofacies 3, and it is geographically associated with samples assigned to Biofacies 5 (Fig. 13; Table 1). One reason for its anomalous association with Cluster 3 could be that the total count is too low for the fractional abundance of many species to be statistically significant (Fishbein and Patterson, 1989).

The assemblage from sample GS-19 (Profile 2; Fig. 10) of Sub-biofacies 4A is characterized by an abundance of *Stainforthia feylingi* and has low species diversity. The sample comes from a muddy substrate at a depth of approximately 90 m. *S. feylingi* is a newly named species, considered conspecific in many studies with specimens assigned to *Fursenkoina fusiformis.* It normally occurs in arctic to cold boreal environments (Knudsen and Seidenkrantz, 1994). A similar foraminiferal assemblage from Drammensfjord, southeast Norway was described by Alve (1990). Alve reported that an assemblage dominated by *S. fusiformis* characterizes a low oxygen environment (towards the redox cline) with a muddy organic substrate and salinities exceeding 30‰. *S. fusiformis* may be conspecific with *F. fusiformis* (Alve, 1990, p. 681), which would make it conspecific with *S. feylingi* (Knudsen and Seidenkrantz, 1994). This issue aside, the foraminiferal assemblages from Drammensfjord and Saanich Inlet reflect similar environmental conditions including deep water, low oxygen, salinities close to 30‰, and a muddy substrate (Figs. 3 and 6).

Other studies document that *S. feylingi* is dominant in deep estuarine environments in eastern Canada (Miller and others, 1982) and coastal fiords in northern Europe (Murray, 1985).

Sample GS-54 in Sub-biofacies 4A is not from a muddy substrate but rather from a sandy one and it has a relatively high foraminiferal diversity. Nevertheless, the dominance of *Stainforthia feylingi* in this sample suggests low-oxygen conditions like those reported from a similar environment in Norway (Alve, 1990). The small number of live foraminifera in this sample (0.2%) may also likely be the result of low-oxygen conditions. The light color of the sediment and the greater foraminiferal diversity in sample GS-54 may be related to the proximity of the sample site to a cement plant (also called limestone quarry) which is responsible for the high amounts of $CaCO_3$ in the adjacent waters (Fig. 13; Gucluer and Gross, 1964).

Sub-biofacies 4B is dominated by *Buccella frigida,* which is indicative of normal, temperate marine waters

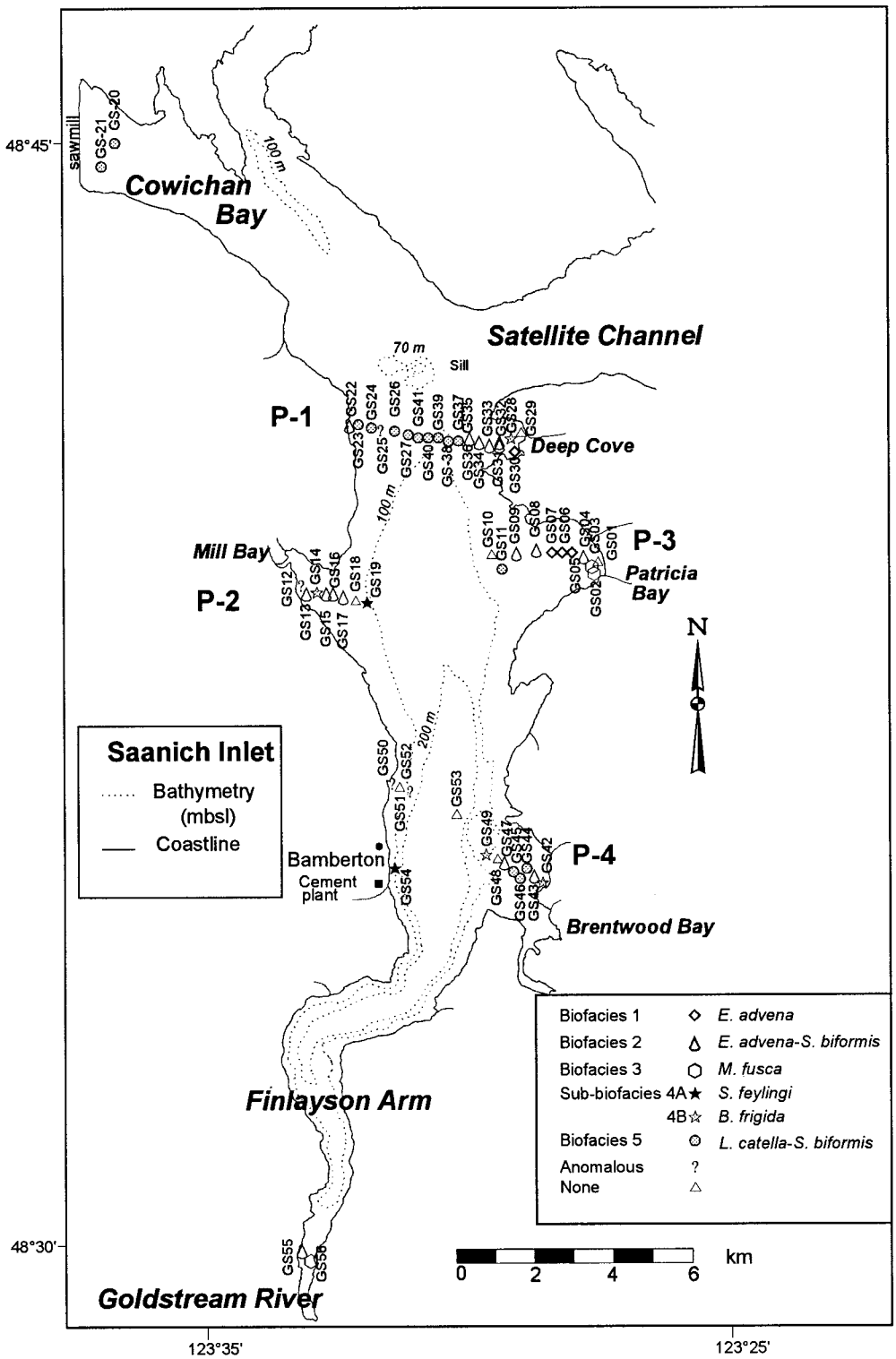


FIGURE 13. Distribution of foraminiferal biofacies in Saanich Inlet defined by Q-mode cluster analysis and the distribution profiles of the dominant species (P-1 to P-4; Figs. 8 to 11). The triangle (△) indicates that there were not enough specimens in the sample to assign it to a biofacies. The question mark (?) indicates that the sample was anomalously clustered in the dendrogram and could not conclusively be assigned to a biofacies based on other criteria, including, dominant fauna, depth of sample, sediment texture.

(Murray, 1991). This calcareous biofacies, which indicates relatively higher salinities, is isolated among agglutinated biofacies that reflect brackish waters in shallow nearshore environments. Such heterogeneity in the spatial distribution of species (Buzas, 1968) has been previously observed and is referred to as patchiness. It is the result of daily temporal and spatial fluctuations of physical environmental parameters, such as salinity, temperature, oxygen concentrations,

predation, etc. (Schröder, 1986; Kaminski and others, 1988). Others have usually described patchiness on a centimetre-scale, such as within a single box core (Schröder, 1986; Kaminski and others, 1988). However, in this case, patchiness occurs on a larger scale. Patchiness is not unexpected in Saanich Inlet because of its restricted water circulation pattern due to the bedrock sill located at the mouth of the inlet.

As mentioned above, *Spiroplectammina biformis* increases with depth along sample profiles. In addition, *Leptohalysis catella* becomes more common in agglutinated assemblages with increasing depth, except where *S. biformis* dominates (Profile 1; Fig. 8). Therefore, high numbers of *L. catella* and *S. biformis* may signal low oxygen levels in deeper water. Another possible factor influencing Biofacies 5 could be passive transport (Schafer and others, 1989), which would not be related to lower oxygen levels at greater depths, but mainly due to slumping of sediments. This was documented in cored sediments from the central part of the basin collected below this (Blais, 1995; Blais-Stevens and others, 1997). However, if it were the case, a mixture of both shallow brackish water and deeper water specimens would be expected (Blais, 1995; Blais-Stevens and others, 1997) along with many broken ones and even freshwater specimens (thecamoebians; R. T. Patterson, oral communication, ODP Legs 169S, Saanich Inlet; Schafer and others, 1989). Thus, samples from Biofacies 5 do not reflect typical fossil assemblages produced from passive transport in Saanich Inlet.

Differences in sediment texture most likely explain the statistical distinction between Clusters 5 and 6. The sediments containing Clusters 5 and 6 comprise olive mud with some sand, but samples of Cluster 6 contain a higher proportion of plant debris. However, the results are not clear enough to separate Clusters 5 and 6 into two biofacies.

Samples GS-20 (53 m) and GS-21 (40 m) contain high amounts of plant debris, probably related to a nearby sawmill on the shore of Cowichan Bay (Fig. 13). A high proportion of plant debris, a muddy substrate, and probably relatively lower oxygen levels seem to create ideal conditions for *Leptohalysis catella.*

Samples GS-12 (5 m) and GS-50 (2 m) are anomalously grouped with Cluster 5 and are excluded from Biofacies 5. Both samples are characterized by a high percentage of live dissolved *Cribroelphidium* spp., in contrast to deeper water samples containing dead *Cribroelphidium* spp. The clustering of these samples with deep-water samples of Biofacies 5 is due to dissolution of *Cribroelphidium* specimens. However, no distinction of live versus dead was made for the clustering computer program, only total (live and dead) abundances were used. Furthermore, the absence of *Leptohalysis catella* in these shallow-water samples and the predominantly calcareous fauna (in Blais, 1995) clearly differentiate them from other Biofacies 5 samples.

Environmental Control of the Biofacies

In Saanich Inlet, water circulation (or lack thereof) is likely the main environmental control, which is in turn responsible for variations of environmental parameters such as salinity, oxygen, temperature, etc. Thus, the bathymetry of the fiord (i.e., presence of the sill) controls water circulation and mixing in the basin. Other environmental controls are surface land drainage, sewage contamination, and sediment texture, but these are also influenced by the intensity of water circulation and mixing in the basin. For example, water contamination occurs in two bays of the inlet and defines a biofacies. However, if water circulation were not restricted, contamination might not affect foraminiferal assemblages since point source concentrations would be diluted to a greater degree than observed in this study.

Hence, foraminiferal biofacies indicate that, at shallow depths (above the sill), surface waters are oxygenated and brackish with isolated areas of contamination or higher salinity. At greater depths (below the sill), biofacies seem to reflect a low oxygen and higher salinity environment.

CONCLUSIONS

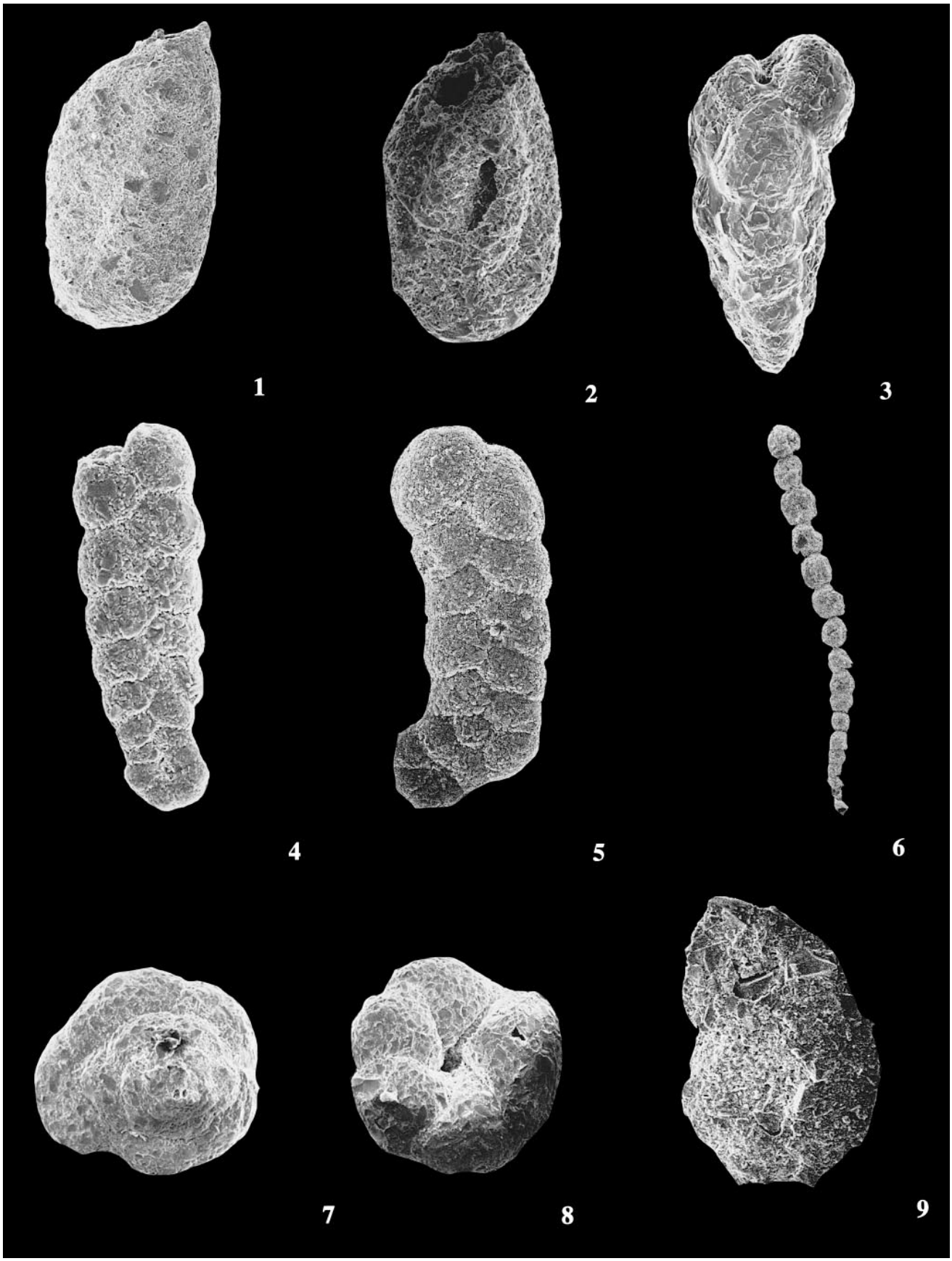
A reconnaissance study on foraminiferal distributions in Saanich Inlet, a fiord with restricted water circulation, shows that:

1) The percentage of live foraminifera decreases with increasing depth, probably due to decreasing oxygen concentration.

2) The main environmental control is water circulation that is influenced by the shape of the fiord (i.e., presence of the sill). Related to water circulation are different environmental parameters, including salinity, oxygen and temperature, that may explain most of the clustering and the distribution of the dominant foraminiferal fauna. Other environmental controls are surface land drainage, contamination, and sediment texture, but these are also affected by the degree of water circulation in the basin.

3) Certain foraminiferal species are closely linked to specific environmental parameters. *Eggerella advena* indicates contamination and brackish water conditions. *Miliammina fusca* probably reflects brackish water conditions. *Leptohalysis catella* reflects deep water, relatively lower oxygen concentrations, high organic content, and a muddy (with some sand) substrate. Similarly, *Stainforthia feylingi* indicates deep water and, probably, low oxygen concentrations. *Buccella frigida* is indicative of normal, temperate marine conditions.

4) Using distribution profiles of dominant species and Q-mode cluster analysis, five foraminiferal biofacies of distinct geographic distribution are defined. These are: 1—*Eggerella advena* Biofacies of shallow near shore environments near sewage outfalls, agricultural runoff, and septic system drainage; 2—*Eggerella advena-Spiroplectammina biformis* Biofacies and 3—*Miliammina fusca* Biofacies, located close to Biofacies 1 at shallow depths in brackish bays. Although there is relatively little freshwater runoff into Saanich Inlet, Biofacies 1, 2, and 3 indicate that localized ephemeral runoff affects the foraminiferal distribution; 4—*Lobatula fletcheri* Biofacies, subdivided into: 4A—*Stainforthia feylingi* Sub-biofacies dominant at greater depths where oxygen levels are low; and 4B—*Buccella frigida* Sub-biofacies at shallow depths within the bays of the inlet, probaby reflecting poor mixing of normal marine seawater because of restricted circulation; 5—*Leptohalysis catella-Spiroplec-*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tammina biformis Biofacies found at greater depths far from shore.

Plans for the construction of 5000 houses with tertiary sewage treatment (septic systems) are under consideration (Development Services Department of the Cowichan Valley Regional District, oral communication, 1994) in the Bamberton area (Fig. 13). The present foraminiferal study identifies a low-diversity foraminiferal assemblage (Biofacies 1) that occurs in areas impacted by Sewage outfall, agricultural runoff, or septic system drainage. Septic pollution appears to reduce the diversity of foraminiferal assemblages and establish conditions that favor just a few opportunistic, pollution-tolerant taxa. This suggests that the planned expansion of septic system drainage could greatly impact water quality in Saanich Inlet.

FAUNAL REFERENCE LIST

In the abbreviated list of species given below, names enclosed by square brackets indicate the original generic designations. Original references are cited from the Catalogue of Foraminifera (Ellis and Messina, 1940 and supplements). Plate and figure numbers refer to taxa illustrated here.

ORDER FORAMINIFERIDA

Alveolophragmium crassimargo (Norman), 1892. [*Haplophragmium crassimargo*].
Alveolopragmium jeffreysi (Williamson), 1858. [*Nonionina jeffreysi*].
Ammodiscus incertus (d'Orbigny), 1839. [*Operculina incerta*].
Astrononion gallowayi Loeblich and Tappan, 1953.
Atlantiella atlantica (F. L. Parker), 1952. [*Trochamminella atlantica*], (Pl. 2, Fig. 3).
?*Bathysiphon* sp. 1.
Remarks: Fine-grained agglutinated tube.
?*Bathysiphon* sp. 2.
Remarks: Coarse-grained agglutinated tube.
Bolivina compacta Sidebottom, 1905.
Bolivina minuta Natland, 1938.
Bolivina vaughani Natland, 1938.
Bolivinellina pacifica (Cushman and McCulloch), 1942. [*Bolivina acerosa* var. *pacifica*], (Pl. 2, Fig. 3).
Buccella frigida (Cushman), 1922. [*Pulvinulina frigida*], (Pl. 2, Figs. 7, 8).
Buccella inusitata Andersen, 1952.
Buliminella elegantissima (d'Orbigny), 1839. [*Bulimina elegantissima*], (Pl. 2, Fig. 2).
Cassidulina limbata Cushman and Hughes, 1925.
Cassidulina reniforme (Nörvang), 1945. [*Cassidulina crassa* d'Orbigny var.].
Cibicides sp. 1.
Cibicides sp. 2.
Cribroelphidium sp.
Remarks: Partially to completely dissolved.
Cribroelphidium bartletti (Cushman), 1933. [*Elphidium bartletti*].
Cribroelphidium excavatum (Terquem), 1876. [*Polystomella excavata*].
Cribroelphidium foraminosum (Cushman), 1939. [*Elphidium hughesi* var. *foraminosum*].
Cribroelphidium frigidum (Cushman), 1933. [*Elphidium frigidum*].
Cribroelphidium groenlandica (Cushman), 1933. [*Elphidium groenlandica*].
Cribroelphidium microgranulosum (Galloway and Wissler), 1927. [*Themeon microgranulosum*].
Cribroelphidium hallandense (Brotzen), 1943. [*Elphidium hallandense*].
Cribroelphidium tumidum (Natland), 1938. [*Elphidium tumidum*].
Cribrostomoides sp.
Cribrostomoides wiesneri (Parr), 1950. [*Labrospira wiesneri*].
Cuneata arctica (Brady), 1881. [*Reophax arctica*].
Discammina compressa (Goës), 1882. [*Lituolina irregularis* var. *compressa*], (Pl. 1, Fig. 9).
Discorbis sp.
Dyocibicides biserialis Cushman and Valentine, 1930. (Pl. 2, Figs. 4, 5).
Eggerella advena (Cushman), 1922. [*Verneuilina advena*], (Pl. 1, Fig. 3).
Elphidiella hannai Cushman and Grant, 1927.
Elphidium crispum (Linné).
Epistominella pacifica (Cushman), 1927. [*Pulvinulina pacifica*].
Epistominella vitrea Parker, 1953.
Favulina melo (d'Orbigny), 1839. [*Oolina melo*], (Pl. 2, Fig. 6).
Fissurina lucida (Williamson), 1848. [*Entosolenia marginata* (Montagu) var. *lucida*].
Fissurina marginata (Montagu), 1803. [*Vermiculum*], (Pl. 2, Fig. 9).
Fissurina vitreola (Buchner), 1940. [*Lagena vitreola*].
Haplophragmoides sp.
Haplophragmoides canariensis (d'Orbigny), 1839. [*Nonionina canariensis*].
Haplophragmoides columbiensis Cushman, 1925.
Haplophragmoides tenuum (Cushman), 1927. [*Haplophragmoides tenuis*].
Homalohedra borealis (Loeblich and Tappan), 1954. [*Oolina borealis*].
Hyalinonetrion gracile (O. G. Costa), 1856. [*Amphorina gracilis*].
Hyperammina friabilis Brady, 1884.
Islandiella norcrossi (Cushman), 1933. [*Cassidulina norcrossi*].
Lagena sp. 1.
Lagena sp. 2.
Remarks: Partially to almost completely dissolved.
Lagena dorseyae McLean, 1956.
Lagena laevis (Montagu), 1803. [*Vermiculum laeve*].
Lagena sulcata (Walker and Jacob), 1798. [*Serpula* (*lagena*) *sulcata*].
Leptohalysis catella (Höglund), 1947. [*Reophax catella*], (Pl. 1, Fig. 6).
Lobatula fletcheri (Galloway and Wissler), 1927. [*Cibicides fletcheri*].
Lobatula mckannai (Galloway and Wissler), 1927. [*Cibicides mckannai*].
Miliammina fusca (Brady), 1870. [*Quinqueloculina fusca*], (Pl. 1, Figs. 1, 2).
Miliolinella subrotunda (Montagu), 1803. [*Vermiculum subrotundum*].
Nodosaria emphysaocyta Loeblich and Tappan, 1953.
Nonionella auricula Heron-Allen and Earland, 1930.
Nonionella stella Cushman and Moyer, 1930.
Nonionella turgida Williamson, 1858.

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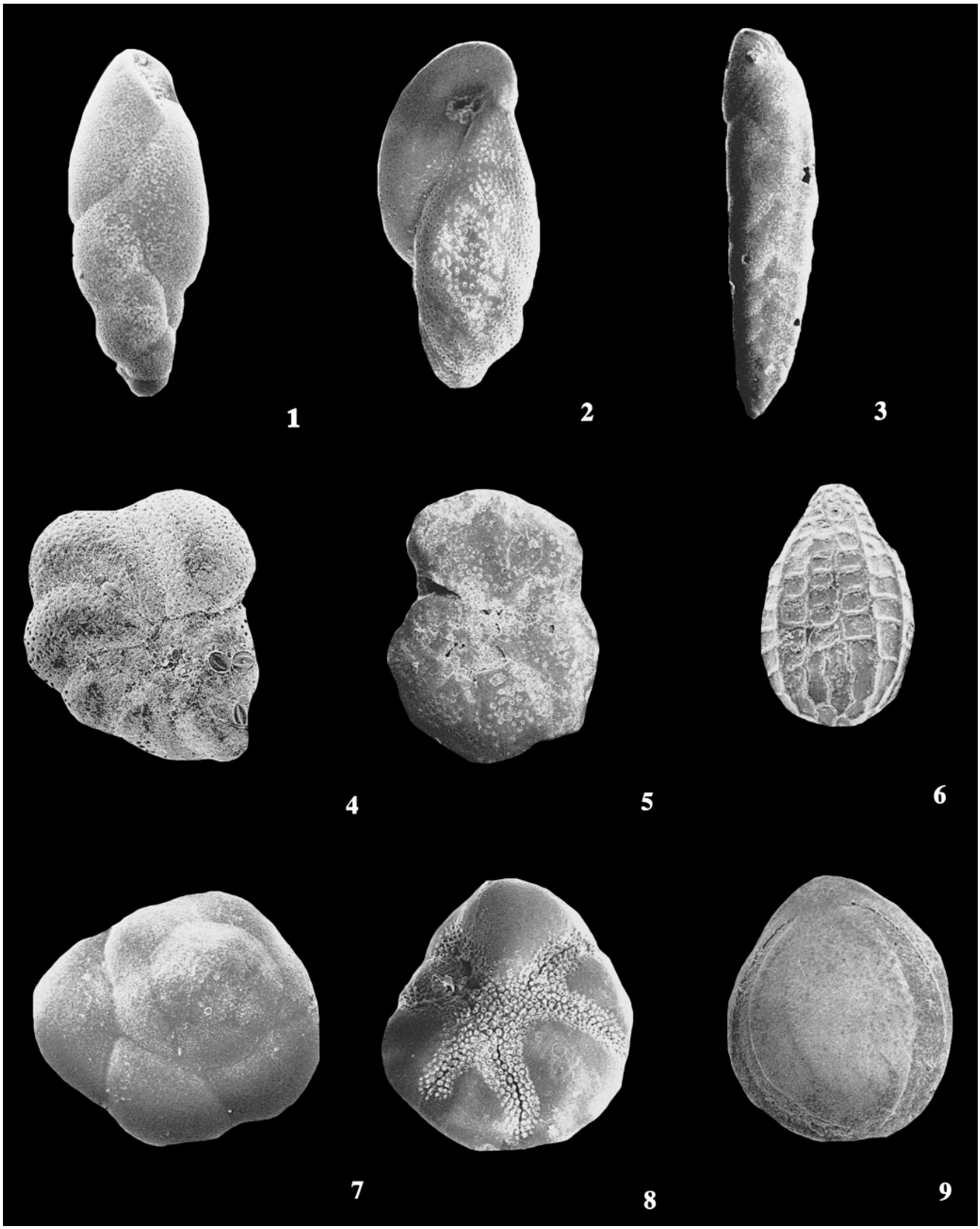
PLATE 1

1, 2 *Miliammina fusca* (Brady). **1** Side view of hypotype from station GS-55, ×240. **2** Side view of hypotype from station GS-03, slightly broken, showing quinqueloculine chamber arrangement and part of the apertural opening at the top, ×300. **3** *Eggerella advena* (Cushman). Side view of hypotype from station GS-04 showing triserial chamber arrangement, ×380. **4, 5** *Spiroplectammina biformis* (Parker and Jones). **4** Side view of hypotype from station GS-24 showing chambers with initial coiling and later biserial arrangement, ×380. **5** side view of hypotype from station GS-46 with chambers anomalously bent in the early biserial arrangement, ×400. **6** *Leptohalysis catella* (Höglund). Longitudinal section of hypotype from GS-24 showing beaded chamber arrangement gradually increasing in size, ×380. **7, 8** *Trochammina discorbis* Earland. **7** Dorsal view of hypotype from station GS-05 showing coarsely agglutinated wall, ×320. **8** Ventral view of hypotype from station GS-47 showing deep umbilicus, ×320. **9** *Discammina compressa* (Goës). Side view of hypotype from station GS-25 showing coarsely agglutinated wall, ×140.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Nonionellina labradorica (J. W. Dawson), 1860. [*Nonionina scapha* var. *labradorica*].
Procerolagena sp.
Procerolagena wiesneri (Parr), 1950. [*Lagena striata*].
Pseudononion bassispinata (Cushman and Moyer), 1930. [*Nonion pizarrensis* var. *basispinata*].
Pygmaeoseistron hispidum (Reuss), 1863. [*Lagena hispida*].
Quinqueloculina sp. d'Orbigny, 1826.
Remarks: Partially to almost completely dissolved.
Quinqueloculina arctica Cushman, 1933.
Quinqueloculina seminula (Linné). [*Serpula seminulum*].
Reophax curtus Cushman, 1920.
Reophax gracilis (Kiaer), 1900. [*Nodulina gracilis*].
Reophax scorpiurus de Montfort, 1808.
Rosalina columbiensis (Cushman), 1925. [*Discorbis columbiensis*].
Saccammina atlantica (Cushman), 1944. [*Proteonina atlantica*].
Saccammina cf. *atlantica.*
Remarks: Fusiform agglutinated foraminifera with one chamber.
Saccammina sphaerica Brady, 1871.
Siphonaperta stalkeri (Loeblich and Tappan), 1953. [*Quinqueloculina stalkeri*].
Spirilina arctica Cushman, 1933.
Spiroplectammina biformis (Parker and Jones), 1878. [*Textularia biformis*], (Pl. 1, Figs. 4, 5).
Spirosigmoilina tenuis (Czjzek), 1848. [*Quinqueloculina tenuis*].
Stainforthia feylingi Knudsen and Seidenkrantz, 1993. (Pl. 2, Fig. 1).
Textularia earlandi Parker, 1952.
Trochammina charlottensis Cushman, 1925.
Trochammina discorbis Earland, 1934. (Pl. 1, Figs. 7, 8).
Trochammina inflata (Montagu), 1808. [*Nautilus inflatus*].
Trochammina nana (Brady), 1881. [*Haplophragmium nana*].
Trochammina pacifica Cushman, 1925.
Trochammina rotaliformis Wright, 1911.
Remarks: Specimen is abnormally large.
Trochammina cf. *squamata* Wright in Heron-Allen and Earland, 1911.
Trochammina squamata Parker and Jones, 1860.
Trochamminopsis pusilla (Höglund), 1947. [*Trochammina quadriloba*].
Valvulineria sp.
Valvulineria arctica Green, 1960.

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REFERENCES

ANDERSON, J. J., and DEVOL, A. H., 1973, Deep water renewal in Saanich Inlet, an intermittently anoxic basin: Estuarine and Coastal Marine Science, v. 1, p. 1–10.

ALVE, E., 1990, Variations in estuarine foraminiferal assemblages with diminishing oxygen conditions in Drammensfjord, SE Norway: Paleoecology, Biostratigraphy, Paleoceanography and Taxonomy of Agglutinated Foraminifera, NATO Series, C, Mathematical and Physical Sciences, v. 327, p. 661–694.

———, 1993, Benthic foraminiferal responses to estuarine pollution: A review: Geological Society of America, Abstracts with Programs, v. 25, p. A-137.

AQUATIC SCIENCE CONSULTANTS LIMITED, 1995, Saanich Inlet study synthesis workshop, Information package, April 25–26: hosted by Ministry Lands and Parks of British Columbia, Saanich Native Heritage Society, and Institute of Ocean Sciences, 46 p.

BANDY, O. L., INGLE, J. C., and RESIG, J. M., 1964a, Foraminifera, Los Angeles County outfall area, California: Limnology and Oceanography, v. 9, p. 124–137.

———, ———, and ———, 1964b, Foraminiferal trends, Laguna Beach outfall area, California: Limnology and Oceanography, v. 9, p. 112–123.

BATES, R. L. and JACKSON, J. A., 1987, Glossary of geology, Third edition: American Geological Institute, Alexandria, Virginia, 788 p.

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

BLAIS-STEVENS, A., CLAGUE, J. J., BOBROWSKY, P. T., and PATTERSON, R. T., 1997, Late Holocene sedimentation in Saanich Inlet, British Columbia, and its paleoseismic implications: Canadian Journal of Earth Sciences, v. 34, p. 1345–1357.

BUZAS, M. A., 1968, On spatial distribution of foraminifera: Contributions from the Cushman Foundation for Foraminiferal Research, v. 19, p. 1–11.

CALDER, A. M. and MANN, G. S., 1995, Saanich Inlet Study: Synthesis workshop summary, April 25/26, 1995; compiled by EVS Consultants ans Sea Science; Water quality Branch, Environmental Protection Department, B.C. Ministry of Environment, Lands and Parks.

CARTER, N. M., 1934, Physiography and oceanography of some British Columbia fiords: Proceedings of the Fifth Pacific Science Congress, Pacific Science Association, Vancouver, B.C., 1933, v. 1, p. 721–733.

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., 1993, Foraminifera, *in* Lipps, J. E. (ed.), Fossil pro-

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PLATE 2

1 *Stainforthia feylingi* Knudsen and Sidenkrantz. Side view of hypotype from station GS-49 showing porous wall and part of the apertural opening at top, ×550. **2** *Buliminella elegantissima* (d'Orbigny). Side view of hypotype from station GS-32 showing apertural opening and porous test, ×400. **3** *Bolivinellina pacifica* (Cushman and McCulloch). Side view of hypotype from station GS-49 showing slightly broken elongate test, ×130. **4, 5** *Dyocibicides biserialis* Cushman and Valentine. **4** Dorsal view of hypotype from station GS-42 showing coiling in early chamber arrangement, ×150. **5** Ventral view of holotype from station GS-42 showing coarsely perforate wall, ×160. **6** *Favulina melo* (d'Orbigny). Side view of hypotype from station GS-24 showing elevated ridges forming polygonal reticulations, ×360. **7, 8** *Buccella frigida* (Cushman). **7** Dorsal view of hypotype from station GS-14 showing lobulate but rounded periphery, ×320. **8** Ventral view of hypotype from station GS-14 showing numerous pustules concentrated along incised sutures, ×320. **9** *Fissurina marginata* (Montagu). Side view of hypotype from station GS-49 showing narrow marginal keel, ×340.

karyotes and protists: Blackwell Scientific Publications, p. 203–247.

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

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

DENNE, R. A. and SEN GUPTA, B. K., 1989, Effects of taphonomy and habitat on the record of benthic foraminifera in modern sediments: Palaios, v. 4, p. 414–423.

DRINNAN, R. W., EMMETT, B., HUMPHREY, B., AUSTIN, B., and HULL, D. J., 1995, Saanich Inlet Study: Water use inventory and water quality assessment; Water quality Branch, Environmental Protection Department, B.C. Ministry of Environment, Lands and Parks.

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

EVS ENVIRONMENT CONSULTANTS, 1996, Saanich Inlet study: Synthesis report, British Columbia, Environment, Lands and Parks, Water Quality Branch, Victoria.

FISHBEIN, E., and PATTERSON, R. T., 1993, Error weighted maximum likelihood (EWML): a new statistically based method to cluster quantitative micropaleontological data: Journal of Paleontology, v. 67, p. 475–485.

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

GROSS, M. G., GUCLUER, S. M., CREAGER, J. S., and DAWSON, W. A., 1963, Varved marine sediments in a stagnant fjord: Science, v. 141, p. 918–919.

GUCLUER, S. M. and GROSS, M. G., 1964, Recent marine sediments in Saanich Inlet, a stagnant marine basin: Limnology and Oceanography, v. 9, p. 359–376.

HERLINVEAUX, R. H., 1962, Oceanography of Saanich Inlet in Vancouver Island, British Columbia: Journal of Fisheries Research Board of Canada, v. 19, no. 1, p. 1–37.

JONASSON, K., and PATTERSON, R. T., 1992, Preservation potential of salt marsh foraminifera from the Fraser River Delta, British Columbia: Micropaleontology, v. 38, p. 289–301.

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

KAMINSKI, M. A., GRASSLE, J. F., and WHITLASH, R. B., 1988, Life history and recolonisation among agglutinated foraminifera in the Panama Basin: Abhandlungen der Geologischen Bundesanstalt, v. 41, p. 229–243.

KNUDSEN, K. L. and SEIDENKRANTZ, M.-S., 1994, *Stainforthia feylingi:* New species from Arctic to Subarctic environments, previously recorded as *Fursenkoina schreibersiana* (Czjzek): Contributions from the Cushman Foundation of Foraminiferal Research, Special Publication, no. 32, p. 5–13.

LOEBLICH, A. R., JR and TAPPAN, H., 1987, Foraminiferal genera and their classification [2 volumes]: Van Norstrand Reinhold Company, New York, 2047 p.

MCCULLOCH, I. A., 1977, Qualitative observations on Recent foraminiferal tests with emphasis on the eastern Pacific [3 pts.]: University of Southern California, Los Angeles, 1078 p.

MILLER, A. A. L., MUDIE, P. J., and SCOTT, D. B., 1982, Holocene history of Bedford Basin, Nova Scotia: foraminifera, dinoflagellate, and pollen records: Canadian Journal of Earth Sciences, v. 19, p. 2342–2367.

MURRAY, J. W., 1985, Recent foraminifera from the North Sea (Forties and Ekofisk areas) and the continental shelf west of Scotland: Journal of Micropaleontology, v. 4, p. 117–125.

———, 1991, Ecology and paleoecology of benthic foraminifera: John Wiley and Sons Inc., New York, 397 p.

OZARKO, D. L., PATTERSON, R. T., and WILLIAMS, H. F. L., Marsh foraminifera from Nanaimo, British Columbia (Canada): Implications of infaunal habitat and taphonomic biasing, Journal of Foraminiferal Research, v. 27, no. 1, p. 51–68.

PATTERSON, R. T., 1989, Neogene foraminiferal biostratigraphy of the southern Queen Charlotte Basin: *In* Contributions to Canadian Paleontology, Geological Survey of Canada, Bulletin 396, p. 229–265.

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

———, 1991, Three new species of Holocene benthic foraminifera from the Queen Charlotte Basin-Hecate Strait region of coastal British Columbia: Transactions of the American Microscopical Society, v. 110, p. 354–360.

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

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

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

———, and LUTERNAUER, J. L., 1993, Holocene foraminiferal faunas from cores collected on the Fraser River delta, British Columbia: A paleoecological interpretation: *In* Current Research, Part A, Geological Survey of Canada, Paper 93-1A, p. 245–254.

———, BURBIDGE, S. M., and LUTERNAUER, J. L., 1997, An atlas of common Quaternary shelf benthic foraminiferal species from off the coast of Canada: Geological Survey of Canada Bulletin 503, 92 p.

PHLEGER, F. B., JR., 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.

PICKARD, G. L., 1975, Annual and longer term variations of deepwater properties in the coastal waters of southern British Columbia: Journal of Fisheries Research Board of Canada, v. 32, p. 1561–1587.

SANCETTA, C., 1989, Processes controlling the accumulation of diatoms in sediments: A model derived from British Columbian fiords: Paleoceanography, v. 4, p. 235–251.

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

SCHAFER, C. T., and COLE, F. E., 1974, Distributions of benthonic foraminifera: their use in delimiting local nearshore environments: *In* Offshore Geology of Eastern Canada, Geological Survey of Canada, (B. R. Pelletier, ed.), v. 1, p. 103–108.

———, COLE, F. E., and SYVITSKI, J. P. M., Bio- and Lithofacies of modern sediments in Knight and Bute Inlets, British Columbia: Palaios, v. 4., p. 107–126.

SCHRÖDER, C. J., 1986, Deep-water arenaceous foraminifera in the Northwest Atlantic Ocean: Canada Department of Fisheries and Oceans, Canadian Technical Report of Hydrography and Ocean Sciences, no. 71, 193 p.

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

———, and HERMELIN, J. O. R., 1993, A device for precision splitting of micropaleontological samples in liquid suspension: Journal of Paleontology, v. 67, p. 151–154.

———, SCHAFER, C. T., and MEDIOLI, F., 1980, Eastern Canadian estuarine foraminifera: A framework for comparison: Journal of Foraminiferal Research, v. 10, p. 205–234.

SNYDER, S. W., HALE, W. R., and KONTROVITZ, M. 1990a, Distributional patterns of modern benthic foraminifera of the Washington shelf: Micropaleontology, v. 36, p. 245–258.

———, ———, and ———, 1990b, Assessment of postmortem transportation of modern benthic foraminifera of the Washington shelf: Micropaleontology, v. 36, p. 259–282.

STUCCHI, D. J. and GIOVANDO, L. F., 1984, Deep water renewal in Saanich Inlet, B.C.: Proceedings of a multidisciplinary symposium on Saanich Inlet, 2nd February, 1983 (S. K. Juniper and R. O. Brinkhurst, eds.), Canadian Technical report of hydrography and Ocean Sciences no. 38, Institute of Ocean Sciences, Department of Fisheries and Oceans, Sidney, B.C., p. 7–15.

WALTON, W. R., 1952, Techniques for recognition of living foraminifera: Cushman Foundation for Foraminiferal Research, v. 3, p. 56–60.

WATKINS, J. G., 1961, Foraminiferal ecology around the Orange County, California, ocean sewer fall: Micropaleontology, v. 7, p. 199–206.

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.

YANKO, V., KRONFELD, J., and FLEXER, A., 1994, Response of benthic foraminifera to various pollution sources: Implications for pollution monitoring, Journal of Foraminiferal Research, v. 24, p. 1–17.

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