

**LATE CENOZOIC BENTHIC FORAMINIFERA:
TAXONOMY, ECOLOGY AND STRATIGRAPHY**

**In honour of Rolf W. Feyling-Hanssen
on his 75th birthday, July 24th 1993**

edited by

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INTRODUCTION

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The Cushman Foundation for Foraminiferal Research and its scientific colleagues are pleased to honour Rolf W. Feyling-Hanssen on his 75th birthday by this collection of papers that comprise a *Special Publication of the Cushman Foundation for Foraminiferal Research*.

Rolf W. Feyling-Hanssen was a pioneer in the use of quantitative studies of foraminifera in Quaternary stratigraphy and paleoenvironments. As a professor at the University of Aarhus for 23 years, he educated many micropaleontologists who are now scattered all over the world, in scientific institutions and oil companies.

In order to recognize Rolf W. Feyling-Hanssen's remarkable work, we invited a group of his scientific colleagues, including earlier students, in Europe, U.S.A. and Canada to contribute to this special volume with current research papers. Everyone was more than willing to contribute, and this, together with the support by The Board of Directors of the Cushman Foundation for Foraminiferal Research, has made this idea come true.

The taxonomic papers in this volume include the description of one new genus and one new species which are named in honour of Rolf W. Feyling-Hanssen: *Rolfina arnei* Laursen and *Stainforthia feylingi* Knudsen and Seidenkrantz. Several of the ecological and stratigraphical papers deal with topics and methods which have evolved from the "school" of micropaleontology pioneered and taught by Rolf W. Feyling-Hanssen.

We dedicate this special volume "Late Cenozoic Benthic Foraminifera: Taxonomy, Ecology and Stratigraphy" to Rolf W. Feyling-Hanssen in recognition of his inspiring teaching and his scientific contribution to Quaternary foraminiferal stratigraphy.

IN HONOUR OF ROLF W. FEYLING-HANSSSEN

Rolf W. Feyling-Hanssen has been a pioneer in Quaternary micropaleontology at northern high and mid



latitudes. He was among the first to introduce quantitative methods to the study of benthic foraminifera, and he has published a remarkable amount of scientific research through his career as a micropaleontologist, which spans about 40 years.

Feyling-Hanssen was born in Kirkenes in northernmost Norway on July 24, 1918. He graduated from the University of Oslo in 1945 and was subsequently employed at the Geological Survey of Norway for some

years and later at the Paleontological Museum in Oslo. He became a Doctor of Philosophy from the University of Oslo in 1963 on the basis of an extensive study of benthic foraminiferal stratigraphy in the late- and postglacial deposits of the Oslofjord area (published 1964).

During his work in Norway, Feyling-Hanssen also applied micropaleontology to geotechnical studies (e.g., Feyling-Hanssen, 1957). These methods have since been widely used in stratigraphical studies of areas with landslide problems and in geotechnical site investigations for the construction of oil production platforms, pipelines, bridges, tunnels, etc.

In 1965 Feyling-Hanssen moved to Denmark, where he established the Department of Micropaleontology at the University of Aarhus and worked as a professor until his retirement in 1988. During his first years in Århus, Feyling-Hanssen continued his work with the Quaternary stratigraphy of Norway, concentrating his interest on the Jæren area in southwest Norway (e.g., Feyling-Hanssen, 1974). The Quaternary geology of Jæren is quite similar to that of northern Denmark and it was, therefore, natural for him to start his first students in Århus with the investigation of benthic foraminiferal stratigraphy in Vendsyssel, north Denmark (e.g., Feyling-Hanssen, Jørgensen, Knudsen and Andersen, 1971), studies which have been continued by his students for many years. By introducing a field course in north Jutland, Feyling-Hanssen also familiarized most Nordic students and young scientists in the area of Quaternary geology and micropaleontology of this region.

Feyling-Hanssen has a special interest in the Arctic. He participated in his first expedition to Svalbard in the late 1940's, and this and the following Svalbard expeditions resulted in several scientific papers (e.g., Feyling-Hanssen and Jørstad, 1950; Feyling-Hanssen, 1953, 1955, 1965). In the middle of the 1970's Feyling-Hanssen again participated in two expeditions to the Arctic, this time to Baffin Island. His work with the Neogene and Quaternary assemblages there led to fruitful collaboration with many colleagues working in the same field, from Novosibirsk in the east to San Francisco in the west. The Baffin Island expeditions also resulted in several papers (e.g., Feyling-Hanssen, 1976, 1980, 1985). A growing interest in Neogene stratigraphy and in benthic foraminiferal assemblages characterizing deposits around the Pliocene-Pleistocene boundary led to an expansion of the Canadian studies to adjacent areas in north and east Greenland (e.g., Feyling-Hanssen, 1987, 1990; Feyling-Hanssen

and others, 1983, 1989), back to Svalbard (Feyling-Hanssen and Ulleberg, 1984) and into the North Sea area (e.g., Feyling-Hanssen, 1981, 1982; Feyling-Hanssen and Knudsen, 1986).

Feyling-Hanssen's interest in taxonomy is exemplified by his paper "The foraminifer *Elphidium excavatum* (Terquem) and its variant forms" (*Micropaleontology*, 1972) and his work together with Buzas "Emendation of *Cassidulina* and *Islandiella helenae* new species" (*Journal of Foraminiferal Research*, 1976). His interest in systematics clearly influenced his teaching. Because he did not fully agree with Loeblich and Tappan (1964) as to the importance of wall structure for the classification of foraminifera, he wrote his own systematics for his students. His classification partly followed Loeblich and Tappan's, but in some respects it was more influenced by Glaessner's and Pokorny's classifications. Because Feyling-Hanssen's systematic works were written in Danish and never published, they are not known to many micropaleontologists outside Scandinavia, but through these works he certainly has had an important influence on the critical attitudes of his own students.

Feyling-Hanssen was an extremely enthusiastic and hard working scientist, and with this background he has always been a very encouraging teacher and supervisor. He has made the University of Aarhus a center of education and research in micropaleontology. He managed to build up extensive and valuable collections of reprints and foraminiferal reference material, which are continuously consulted by micropaleontologists and students from all the Nordic countries. Several of his many graduate students have become well-known and respected scientists and others are now employed within the oil exploration industry, a field which has always had Feyling-Hanssen's interest.

Feyling-Hanssen had a very special ability to create a pleasant and active atmosphere in his department, both for the students and for the staff. Everybody, colleague or student, who has had the opportunity to stay there, will remember the atmosphere of this work place. The appreciation of this is seen through the many visitors, and through the receipt of many reprints, letters or postcards from colleagues and earlier students. Accordingly, almost all Feyling-Hanssen's earlier students attended his retirement celebrations in 1988.

It is with great pleasure that we present this special volume in honour of Rolf W. Feyling-Hanssen in appreciation of his fundamental contribution to the study of Quaternary foraminiferal stratigraphy and of his encouragement as a teacher.

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***STAINFORTHIA FEYLINGI* NEW SPECIES FROM ARCTIC TO SUBARCTIC ENVIRONMENTS, PREVIOUSLY RECORDED AS *STAINFORTHIA SCHREIBERSIANA* (CZJZEK)**

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ABSTRACT

The name *Stainforthia* (or *Fursenkoina*) *schreibersiana* (Czjzek) has been used for specimens found in Recent and Pleistocene deposits from arctic and subarctic environments as well as Tertiary deposits from Europe. An examination of specimens assigned to *Stainforthia schreibersiana* has revealed that the specimens belong to two different species: the fossil species from European sites of Tertiary age belongs to *Fursen-*

koina acuta (d'Orbigny) (senior synonym to *Fursenkoina schreibersiana* (Czjzek)), while the Recent and Pleistocene cold water specimens are here assigned to the new species *Stainforthia feylingi*. The species is named in honour of Rolf Wilhelm Feyling-Hanssen who has been a pioneer of Quaternary foraminiferal studies in Scandinavia.

INTRODUCTION

The species *Fursenkoina schreibersiana* was first described in 1848 by Czjzek (as *Virgulina schreibersiana*) from the the Miocene of the Vienna Basin. Papp and Schmid (1985), however, showed that *Fursenkoina schreibersiana* is a junior synonym of *Fursenkoina acuta* (d'Orbigny, 1846, as *Polymorphina acuta*), which is also described from the Vienna Basin.

The species has been described from Tertiary and Lower Pleistocene deposits in the Mediterranean region and from the Oligocene and Miocene in northern and central Europe (e.g., Cushman, 1937, as *Virgulina schreibersiana* (part); Longinelli, 1956, as *Virgulina schreibersiana*; Toering and van Voorthuysen, 1973, as *Stainforthia schreibersiana*; Hageman, 1979, as *Fursenkoina schreibersiana*; Papp and Schmid, 1985, as *Fursenkoina acuta*; Rupp, 1986, as *Fursenkoina acuta*; Rasmussen, 1986, as *Fursenkoina schreibersiana*; Laursen, 1992, as *Stainforthia schreibersiana*).

The name *Stainforthia schreibersiana* (or *Fursenkoina schreibersiana*) has, however, also been used for specimens recorded from arctic to subarctic environments of Pleistocene to Recent age (e.g., Nørvang, 1945; Feyling-Hanssen, 1964; Nagy, 1965; Knudsen, 1982; Knudsen and Nordberg, 1987; Hald and Vorren, 1987; Bergsten, 1991).

The wide stratigraphical and ecological range thus indicated has led to a re-examination of recent and fossil specimens from northern Europe and from the Arctic. The specimens have been compared with holotype material of *Fursenkoina acuta*.

This study has led to a division of the specimens into two species: the fossil species from European sites of Tertiary age belong to *Fursenkoina acuta* (d'Orbigny), while the Recent and Pleistocene cold water specimens are assigned to the new species *Stainforthia feylingi*. The purpose of the present paper is, thus, to describe the new species and the criteria for distinguishing it from other species, and to give an indication of the stratigraphical and ecological distribution of the species.

The systematic allocation of the species is made in accordance with Loeblich and Tappan (1988).

SYSTEMATIC DESCRIPTION

Suborder ROTALIINA Delange and Hérouard,
1896

Superfamily TURRELLINACEA Cushman, 1927

Family STAINFORTHIIDAE Reiss, 1963

Genus STAINFORTHIA Hofker, 1956

***Stainforthia feylingi* n.sp.**

Pl. 1, Figs. 1-32; Pl. 2, Figs. 1-6, 8

- Virgulina schreibersiana* Czjzek—FEYLING-HANSEN, 1964, p. 309, pl. 14, figs. 19–21.—NAGY, 1965, p. 120, pl. 1, fig. 30.—FEYLING-HANSEN and others, 1971, p. 240, pl. 7, figs. 6–8.
- Virgulina* species—FEYLING-HANSEN, 1954, p. 193, pl. 1, figs. 23, 24.
- Stainforthia schreibersiana* (Czjzek)—MICHELSEN, 1967, p. 226–227, pl. 2, fig. 12.—ELVERHØI and others, 1980, pl. 1, figs. 8, 9.
- Fursenkoina fusiformis* (Williamson)—SCHRÖDER-ADAMS and others, 1990, p. 34, pl. 6, fig. 17.—SCOTT and VILKS, 1991, p. 30, pl. 4, fig. 11 (not pl. 2, fig. 8).

Derivatio Nominis. Name given in honour of Dr. Rolf W. Feyling-Hanssen, who has been a pioneer of Quaternary foraminiferal studies in Scandinavia.

Diagnosis. Slender, elongate, fusiform *Stainforthia* with a very thin, translucent wall and a small loop-shaped depressed aperture with a serrate lip at the face of the final chamber.

Description. Test narrow, elongate, fusiform, three to four times as long as broad, ovate in section, and bluntly pointed at both ends. Seven to eleven, high, narrow, and slightly inflated chambers. The chambers triserially arranged in the early stages, later biserially arranged and often slightly twisted. Sutures are distinct, oblique, and depressed. Wall very thin, fragile, translucent, calcareous, hyaline, and optically indistinctly radial. Surface smooth, very fine and densely perforate, rounded pores. Aperture depressed in an elongate, often rather narrow loop extending from the base of the final chamber and across the face of the final chamber. The depressed aperture is bordered by a serrate lip which may be prolonged to a broader flap on one side extending over part of the aperture.

Dimensions. Holotype: length, 0.51 mm; breadth, 0.19 mm; thickness, 0.15 mm.

Other material (adult specimens, average value in brackets): length, 0.40–0.60 mm (0.46 mm); breadth, 0.13–0.20 mm (0.15 mm); thickness, 0.10–0.15 mm (0.12 mm).

Variation. The species shows little variation. The magnitude of the twist of the test varies from only a few to about 90 degrees, the aperture varies between open and more narrow and the broadness of the bordering lip may vary between a mere lip to a narrow flap (Pl. 2, Figs. 1–6). Some specimens have an imperforate area in the upper part of each chamber below the suture of the succeeding chamber. This character seems to vary geographically as there is a tendency for a high number of specimens with an imperforate band at the Canadian North Pacific coast, whereas it is seldom in the North Atlantic region (J.-P. Guilbault, oral communication, 1993).

Type Level. Late Glacial; Zone Am (Feyling-Hanssen, 1964).

Type Locality. Onsøy, Østfold (Oslo Fjord region, Norway), boring 86, 18.0 m below surface, 13-21.0. Material first described by Feyling-Hanssen (1964).

Holotype (Pl. 1, Fig. 18). Specimen MGUH no. 22096 from Onsøy, Østfold (Oslo Fjord region, Norway), boring 86, 18.0 m below surface, 13-21.0. Housed at the Department of Earth Sciences, University of Aarhus.

Paratypes (Pl. 1, Figs. 19–31). Four specimens (Paratypes 1–4; MGUH nos. 22097–22100) from Onsøy, Østfold (Oslo Fjord region, Norway), boring 86, 18.0 m below surface, sample no. 13-21.0; two specimens (Paratypes 5–6; MGUH nos. 22101–22102) from Valle, Sarpsborg, boring 27, 3.65 m below surface, sample no. O 287-28; two specimens (Paratypes 7–8; MGUH nos. 22103–22104) from Solberga (Sweden) 23.00–23.05 m below surface; two specimens (Paratypes 9–10; MGUH nos. 22105–22106) from Core PC 10-1 (the Kattegat), 30–33 cm below sea floor. All are housed at the Department of Earth Sciences, University of Aarhus.

Additionally, two specimens (Paratypes 11–12; nos. P52869–P52870) from Onsøy, Østfold (Oslo Fjord region, Norway), boring 86, 18.0 m below surface, sample no. 13-21.0, are housed at the Natural History Museum, London, United Kingdom, and two specimens (Paratypes 13–14; U.S. National Museum nos. 477218–477219) from Onsøy, Østfold (Oslo Fjord region, Norway), boring 86, 18.0 m below surface, sample no. 13-21.0, are housed at the Smithsonian Institution, Washington, D.C., U.S.A.

Affinities. *Stainforthia feylingi* shows clear affinity to *Stainforthia fusiformis* (Williamson, 1858) (Pl. 3, Figs. 1–7, 16–17), but the latter species has a shorter test, more inflated chambers, and a shorter, elliptical aperture placed at the terminal end of the test. It is also more distinctly optically radial.

Stainforthia feylingi differs from *Stainforthia concava* (Höglund, 1947, as *Virgulina concava*) (Pl. 3, Figs. 12–13) and *Stainforthia loeblichii* (Feyling-Hanssen, 1954, as *Virgulina loeblichii*) (Pl. 2, Fig. 7; Pl. 3, Fig. 14) as these species have less elongated, globular chambers which are arranged more tortuously, and the loop of their depressed aperture is broader and longer. Furthermore, they are also more distinctly optically radial.

Stainforthia feylingi clearly differs from *Fursenkoina acuta* (d'Orbigny, 1846) (= *F. schreibersiana* (Czjzek, 1848)) (Pl. 1, Fig. 33; Pl. 3, Figs. 8–11, 18) in its smaller, more slender test, and less twisted and irregular chamber arrangement. Furthermore, the aperture of *Fursenkoina acuta* is a long narrow slit partly covered by an apertural lip and *F. acuta* is distinctly optically granular.

Stainforthia feylingi differs from *Fursenkoina? ska-*

gerakensis (Höglund, 1947, as *Virgulina skagerakensis*) (Pl. 3, Figs. 15, 19) as the latter species has more globular chambers arranged biserially and is only very slightly twisted (usually about 90°). In addition, *F. skagerakensis* often has a basal spine and a narrow slit-like aperture covered by an apertural lip. It must be mentioned that *Fursenkoina? skagerakensis* is clearly optically radial whereas the genus *Fursenkoina* is defined as optically granular (Loeblich and Tappan, 1988). The shape of the aperture, however, suggests affiliation to the genus *Fursenkoina* rather than to *Stainforthia*.

Cassidelina profunda Saidova (1975) (see Loeblich and Tappan, 1988, pl. 565, no. 3) differs from *Stainforthia feylingi* by its biserial arrangement of chambers and by having a more pointed initial end, often with a basal spine. A basal spine has not been observed in *S. feylingi*. Furthermore, the spoon-like toothplate of *Cassidelina* almost closes its apertural opening (Loeblich and Tappan, 1988, p. 513).

STRATIGRAPHY AND ECOLOGY

Stainforthia feylingi has been documented from deposits from the Early Pleistocene (Tjörnes, Iceland: Eiriksson and others, 1992, as *Stainforthia schreibersiana*) to Recent.

An exact record of the recent distribution of *Stainforthia feylingi* is hampered because of the confusion with *Fursenkoina acuta* (d'Orbigny)/*F. schreibersiana* (Czjzek), *Stainforthia fusiformis* (Williamson), and to some extent with *Stainforthia concava* (Höglund).

Stainforthia feylingi is normally found in Recent arctic to cold boreal environments. In the North Atlantic region it has been recorded in arctic and subarctic waters from Greenland, Canada, Spitsbergen, the Norwegian continental margin, and the Arctic Ocean at water depths between a few meters and several thousand meters (Nørvang, 1945, as *Virgulina schreibersiana*; Nagy, 1965, as *V. schreibersiana*; Elverhøi and others, 1980, as *S. schreibersiana*; Schröder-Adams and others, 1990, as *Fursenkoina fusiformis*; Scott and Vilks, 1991, as *F. fusiformis* (part)). The specimens described from the North Sea area (e.g., Murray, 1971) presumably belong to *Stainforthia concava* (Höglund). *Stainforthia feylingi* has a wide distribution in the North Pacific, and it is often the dominant species on the west coast of Canada, also in boreal waters. In the Hecate Strait off British Columbia it thrives at bottom water temperatures of 8–9°C throughout the year (R. T. Patterson, oral communication, 1993).

Fossil specimens of *Stainforthia feylingi* have been described from late glacial deposits from Scandinavia

(Feyling-Hanssen, 1964; Michelsen, 1967; Feyling-Hanssen and others, 1971; Knudsen, 1982; Hald and Vorren, 1987; Knudsen and Nordberg, 1987; Bergsten, 1991, all as *Stainforthia* or *Virgulina schreibersiana*) and from the North Pacific (Patterson, 1993, as *Stainforthia* sp.). Some of these records show increasing numbers in Allerød sediments, decreasing again in the Younger Dryas (Knudsen, 1982; Bergsten, 1991). The species has also been observed from the Saalian-Eemian transition (Seidenkrantz, 1993) and from deposits of Boreal age in Scandinavia (Seidenkrantz and Knudsen, in press).

The relatively high frequency of *Stainforthia feylingi* in fossil deposits reflecting a transitional environment between arctic and boreal conditions may indicate that it is especially tolerant of unstable conditions.

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PLATE I

Scanning electron microscope photographs. **1–17** *Stainforthia feylingi*. **1–8** Specimens from the Late Pleistocene at Onsøy, Østfold (Oslo Fjord region, Norway) (MGUH nos. 22109–22116), **1–2** ×90, **3–4** ×110, **5–6** ×120, **7** ×110, **8** ×80. **9–11** Specimens from the Late Pleistocene from Valle, Sarpsborg (Oslo Fjord region, Norway) (MGUH nos. 22117–22119), **9** ×120, **10–11** ×100. **12–13** Specimens from the Late Pleistocene from Solberga (Sweden) (MGUH nos. 22120–22121), **12** ×160, **13** ×110. **14–16** Specimens from the Early Holocene in Boring PC 10-1, Kattegat (Scandinavia) (MGUH nos. 22122–22124), **14** ×85, **15** ×100; **16** ×80. **17** Specimen from the Late Saalian at Anholt (Denmark) (MGUH no. 22125), ×125. Light microscope photographs, ×90. **18–32** *Stainforthia feylingi*. **18** Holotype (MGUH no. 22096). **19, 20** Paratypes 1–2 (MGUH nos. 22097–22098). **21–31** Paratypes 4–14 (MGUH nos. 22100–22106; NMH nos. P52869–P52870; U.S. National Museum nos. 477218–477219). **32** Specimen from Onsøy, Østfold (Oslo Fjord region, Norway), boring 86, 18.0 m below surface, sample no. 13-21.0 (MGUH no. 22107). **33** *Fursenkoina acuta* (d'Orbigny) (MGUH no. 22108) from the Baden-Sooss quarry (south of Vienna, Austria), of Badenian (Middle Miocene) age.

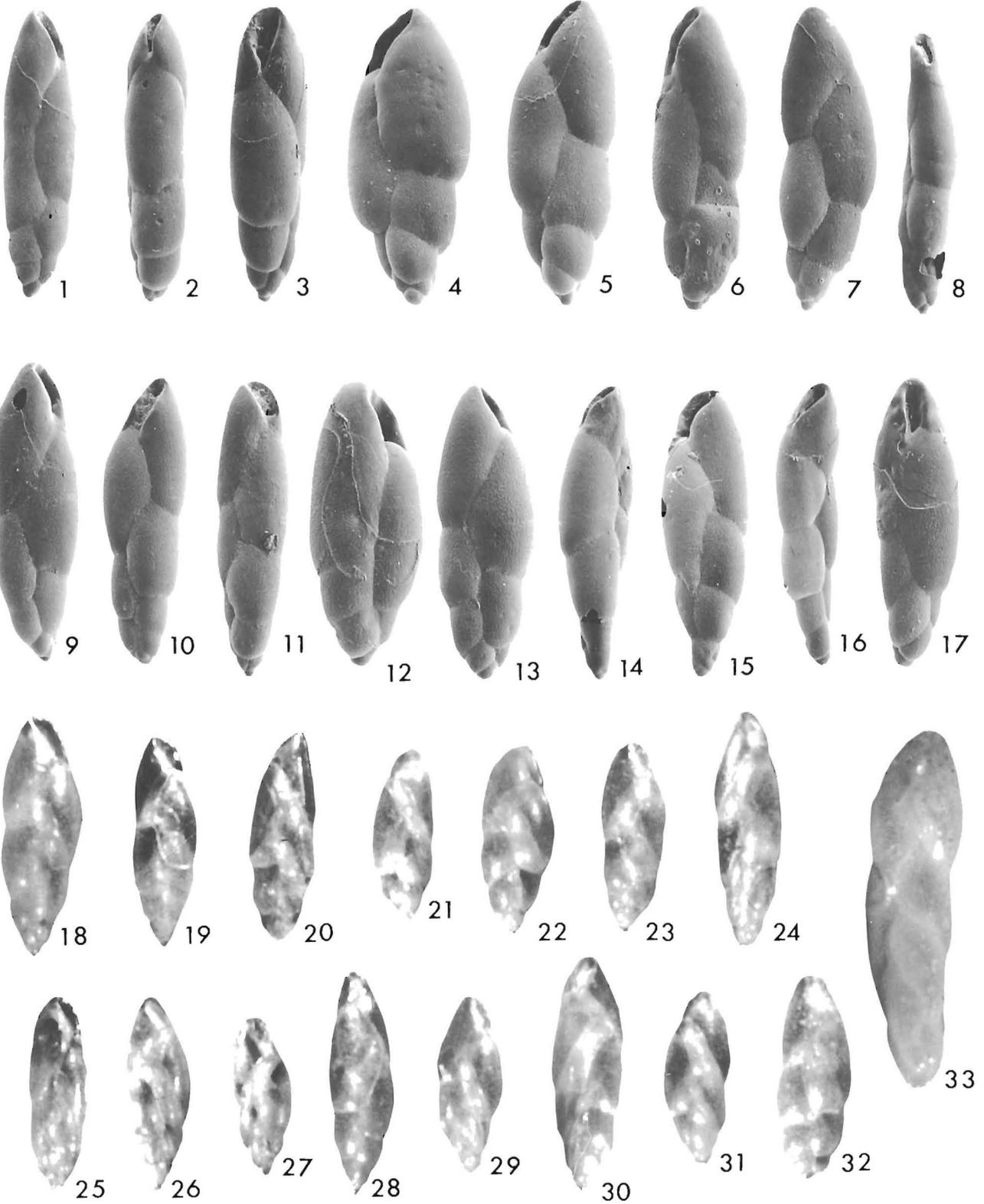


PLATE 2

Scanning electron microscope photographs. 1-7 Apertural sections. 1-6 *Stainforthia feylingi* (MGUH nos. 22125, 22111, 22109, 22113, 22110, 22124), 1 × 460, 2 × 380, 3 × 330, 4 × 350, 5 × 450, 6 × 400. 7 *Stainforthia loeblichii* (MGUH no. 22139), × 350. 8 Pores of *Stainforthia feylingi* (MGUH no. 22141), × 1,200.

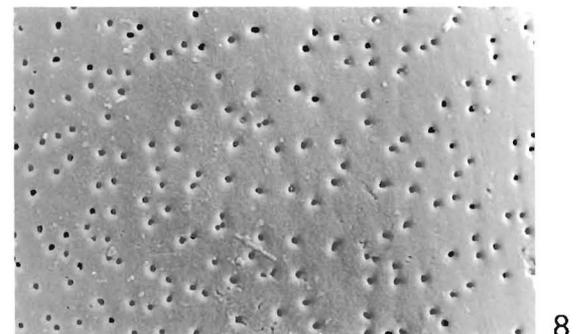
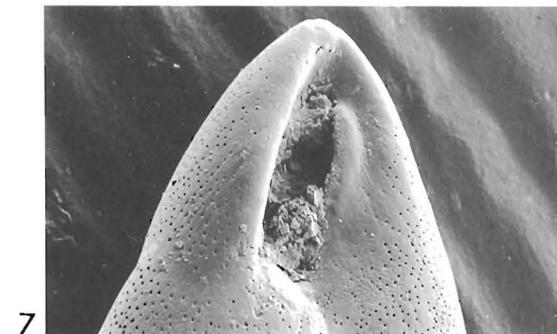
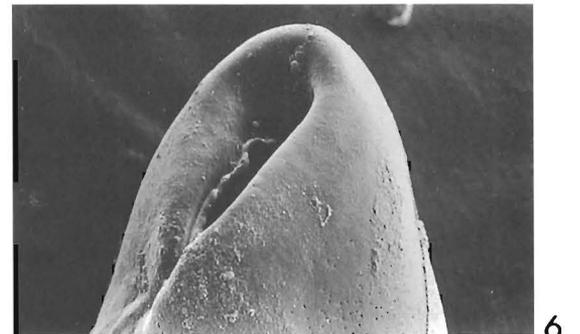
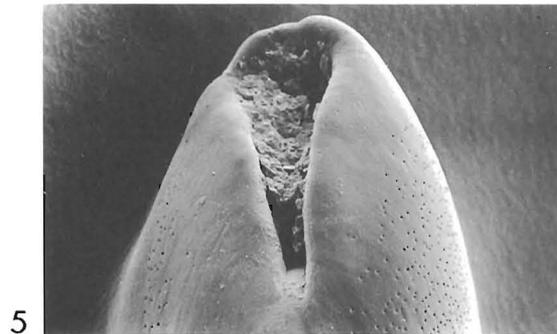
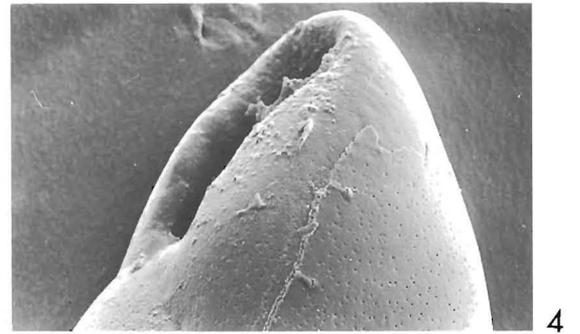
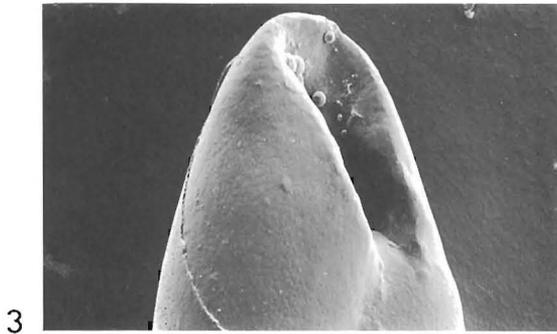
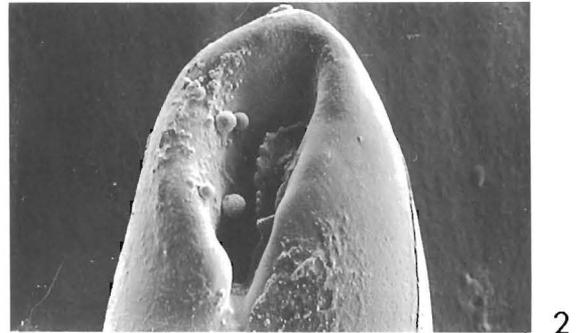
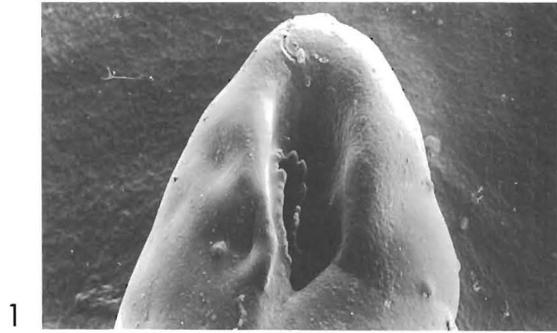
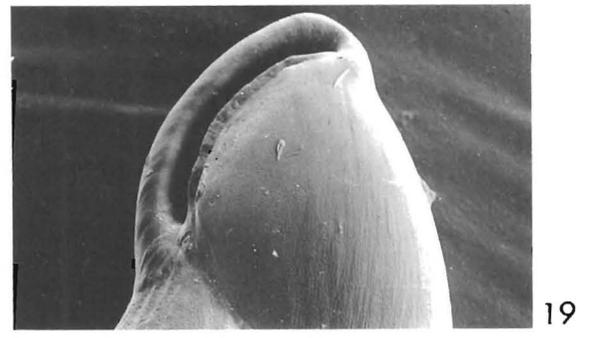
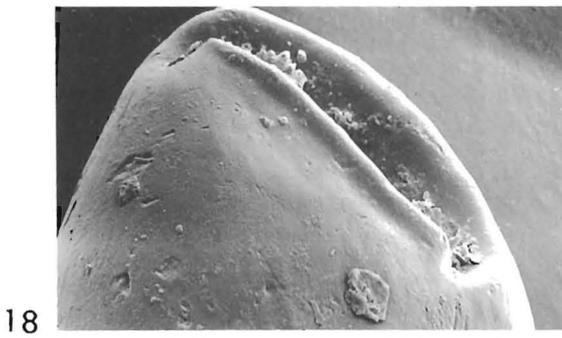
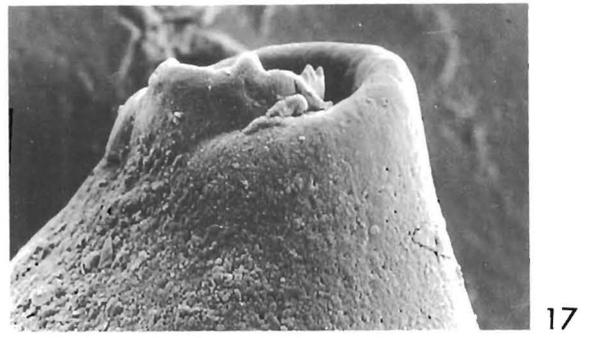
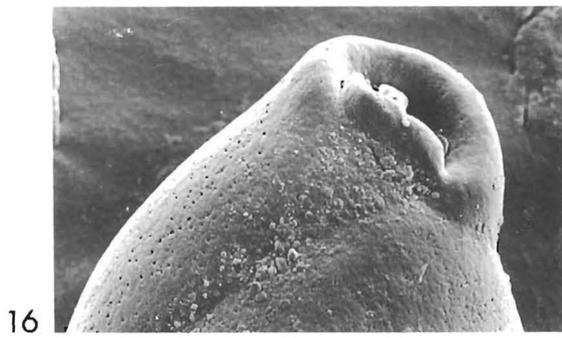


PLATE 3

Scanning electron microscope photographs. **1-7** *Stainforthia fusiformis* (Williamson) from recent and subrecent deposits of the Kattegat and Skagerrak (Scandinavia) (MGUH nos. 22126-22132), **1** × 140, **2** × 130, **3** × 170, **4** × 210, **5** × 120, **6** × 150, **7** × 130. **8-11** *Fursenkoina acuta* (d'Orbigny). **8-9** Specimens from Lower Pleistocene deposits from Rhodes (Greece) (MGUH nos. 22133-22134), **8** × 60, **9** × 50; **10-11** specimens from Middle Miocene (Badenian) deposits from the Baden-Soos quarry (south of Vienna, Austria) (MGUH nos. 22135-22136), **10** × 50, **11** × 70. **12-13** *Stainforthia concava* (Höglund) from recent deposits from the Skagerrak (Scandinavia) (MGUH nos. 22137-22138), × 90. **14** *Stainforthia loeblichii* (Feyling-Hanssen) from Saalian deposits from the Anholt II boring (Denmark) (MGUH no. 22139), × 90. **15** *Fursenkoina? skagerakensis* (Höglund), specimen from subrecent deposits from the Skagerrak (Scandinavia) (MGUH no. 22140), × 60. Apertural sections. **16-17** *Stainforthia fusiformis* (Williamson). **16** × 700 (MGUH no. 22126), **17** × 1,100 (MGUH no. 22130). **18** *Fursenkoina acuta* (d'Orbigny), × 390 (MGUH no. 22135). **19** *Fursenkoina? skagerakensis* (Höglund), × 220 (MGUH no. 22140).



ROLFINA ARNEI GEN. NOV. ET SP. NOV.—A STRATIGRAPHICALLY SIGNIFICANT FORAMINIFERA FROM THE OLIGOCENE/LOWER MIOCENE OF THE NORTH SEA BASIN

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ABSTRACT

Rolfina arnei gen. nov. et sp. nov. is a common benthic species in the Upper Oligocene/Lower Miocene of the North Sea region. The species has a regional biostratigraphical significance, but has hitherto been designated by open nomenclature as “*Rotalia*” sp. 1 or *Glabratella?* sp. A by authors working in the North

Sea basin. The genus *Rolfina* is hereby erected and the species *Rolfina arnei* is described and illustrated. The species seems to be restricted to the North Sea basin between latitudes of 55°N and 59°N in an outer neritic to upper bathyal paleoenvironment, probably at restricted oxygen levels.

INTRODUCTION

Previous research dealing with Tertiary deposits of the North Sea and the Danish onshore area revealed a stratigraphically important but hitherto unnamed rosalinid species (Dinesen, 1959; Ulleberg, 1971, 1987; King, 1983, 1989; Eidvin and others, 1993). The locations are, among others, shown in Figure 1. This species was placed in open nomenclature as “*Rotalia*” sp. 1 by Dinesen (1959), *Glabratella?* sp. by King (1983) and *Glabratella?* sp. A by King (1989). Both authors found the generic assignment problematic. The present study of the species revealed resemblance to several genera, but no genus covered all the characteristics of the species. In order to solve the problem of the generic assignment, 60 specimens were forwarded to Helen Tappan who kindly examined the material. She supported my view that these specimens did not belong to any established genus (written communication, 1992). This necessitated the establishment of a new genus, herein named *Rolfina*.

King (1983) suggested that “*Rotalia*” sp. 1 might be conspecific with *Glabratella?* sp. Arne Dinesen and Chris King most kindly placed some specimens of “*Rotalia*” sp. 1 and *Glabratella?* sp. A at my disposal and a comparison of these specimens clearly proved that they belong to the same species. The species is here

designated as *Rolfina arnei*. The purpose of the present paper is to describe this rather well known species and to document its stratigraphical and possible paleoecological range. The present classification follows that of Loeblich and Tappan (1988).

SYSTEMATICS

Order FORAMINIFERIDA Eichwald, 1830
Suborder ROTALIINA Delange and Hérouard,
1896

Superfamily DISCORBACEA Ehrenberg, 1838
Family ROSALINIDAE Reiss, 1963

Genus **ROLFINA** gen. nov.

Type Species. *Rolfina arnei* sp. nov.

Derivation of Name. Patronymic, in recognition of the major work of Rolf W. Feyling-Hanssen on Scandinavian foraminiferal stratigraphy.

Diagnosis. Test compact, trochospirally coiled, 2–3 whorls. The chambers are globular, increase gradually in size as added, 3–5 in number in the last whorl. The wall is perforate, hyaline, radial, calcitic, and the aperture is an umbilical-interiomarginal to strictly umbilical arc.

Description. Test free, trochospirally enrolled, with 2–3 whorls of 3–5 chambers in each whorl. Equatorial

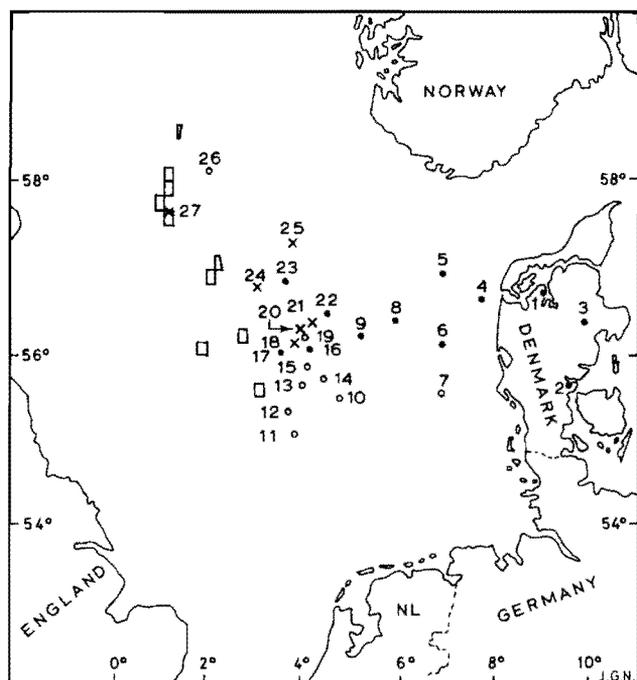


FIGURE 1. Map of the central North Sea area showing sites examined for *Rolfina arnei*. A black dot indicates that *R. arnei* is represented with percentages higher than 1% of the benthic fauna, a cross indicates that *R. arnei* is present, a ring indicates that *R. arnei* is not recorded. The following outcrops and wells are indicated (the maximum frequencies of *R. arnei* as percentages of the benthic fauna are indicated in brackets): 1, Mogenstrup cliff (20%); 2, Skansebakken (15%); 3, Sofienlund (8%); 4, C-1 (13%); 5, Inez-1 (5%); 6, R-1 (11%); 7, S-1; 8, Ibenholt-1 (12%); 9, L-1 (8%); 10, N-10; 11, A-18-1; 12, A-12-1; 13, B-1; 14, Bo-1; 15, W-1; 16, I-1 (5%); 17, P-1 (3%); 18, Q-1; 19, T-1; 20, Mona-1; 21, Lulu-1; 22, Elna-1 (2%); 23, 2/2-1 (1%); 24, 2/4-C-11; 25, 8/12-1; 26, 15/12-3; 27, 22/11-2. Squares indicate the UK blocks: 16/13; 16/26; 21/10; 22/1; 22/11; 23/27; 29/30; 30/1; 30/24 and 39/11 where presence of *R. arnei* is reported.

periphery lobate, axial periphery rounded. Spiral side strongly convex and rather coarsely perforated. Umbilical side ranges from concave to flat or slightly convex, finely perforate. Flaps reaching from the base of each chamber toward umbilicus are seen in specimens where the umbilicus is not obscured by coarse granulation. The test is calcitic (as shown by x-ray diffractometry) and optically radial. The sutures are depressed, gently curved and slightly oblique on the spiral side, nearly radial on the umbilical side. The aperture is an umbilical-interiomarginal to strictly umbilical arc, in some cases with a weakly developed lip.

Remarks. The new genus *Rolfina* shows most affinity to *Glaboratella* Dorreen (1948) or *Disconorbis* Sellier de Civrieux (1977). King (1983) tentatively proposed the genus *Glaboratella* for the species here described as *Rol-*

fina arnei. Later he stated that the generic assignment was uncertain (King, 1989), and that the species rather resembles a small globigerinid. *Rolfina* deviates from *Glaboratella* by the aperture being an arc and not a slit. It also lacks both radiate striae and pustules arranged in rows on the umbilical side.

Rolfina also resembles *Disconorbis* Sellier de Civrieux (1977). However, the aperture of *Rolfina* does not possess a prominent bordering lip, but has, if any, only a relatively weakly developed lip.

When Dinesen (1959) described the species "*Rotalia*" sp. 1, the quotation marks made it clear that he did not consider *Rotalia* Lamarck (1804) the right genus for the species. Dinesen suggested that the species should belong to the same genus as "*Rotalia*" *spini-gera*. The latter is now considered a *Pararotalia* Le Calvez, 1949 (Hottinger and others, 1991). However, *Rolfina* deviates from *Pararotalia* by the lack of an umbilical plug and of a carinate periphery.

The globose chambers of *Rolfina* resemble those of *Globorosalina* Quilty, 1981. However, *Globorosalina* has more chambers per whorl, and the aperture is a slit and not an arc.

Rolfina arnei sp. nov.

"*Rotalia*" sp. 1 DINESEN, 1959, p. 92–93, pl. IX, figs. 4–5.
Glaboratella? KING, 1983, p. 29, pl. 3, figs. 13–15.
Glaboratella? sp. A KING, 1989, p. 476, pl. 9.7, figs. 10–11.

Derivation of Name. Patronymic, in honor of Arne Dinesen, who first recognized this species.

Diagnosis. A species of *Rolfina* with 3–5 chambers in the last whorl, and an aperture which is an umbilical-interiomarginal to strictly umbilical arc.

Holotype. Specimen (MGUH no. 22142) from Mogenstrup Cliff. Deposited in the Department of Earth Sciences, University of Aarhus, Denmark.

Paratypes. Sixteen specimens (MGUH nos. 22143–22158) deposited in the Department of Earth Sciences, University of Aarhus, Denmark; two specimens (P nos. 52867–52868) deposited in Natural History Museum, London, England; two specimens (USNM nos. 477220–477221) deposited in the National Museum of Natural History, Smithsonian Institution, Washington, D.C., U.S.A.

Material. More than a thousand specimens were collected from the type locality. Additional tests from exploration wells in the North Sea were also studied. The material of Arne Dinesen from the Vejle Fjord was examined, and two specimens from the central North Sea were generously added by Chris King.

The holotype and the paratypes are all illustrated by

TABLE 1. The dimensions of type specimens of *Rolfina arnei*.

Locality	Specimen	Minimum diameter	Maximum diameter	Height	Illustrated here as
Mogenstrup	Holotype (MGUH 22142)	0.23 mm	0.24 mm	0.16 mm	Pl. 1, Figs. 1a-c
Mogenstrup	Paratype 1 (MGUH 22143)	0.30 mm	0.34 mm	0.23 mm	Pl. 1, Figs. 2a-b
Mogenstrup	Paratype 2 (MGUH 22144)	0.18 mm	0.21 mm	0.13 mm	Pl. 1, Figs. 3a-c
Mogenstrup	Paratype 3 (MGUH 22145)	0.23 mm	0.25 mm	0.19 mm	Pl. 1, Figs. 4a-c
Mogenstrup	Paratype 4 (MGUH 22146)	0.15 mm	0.16 mm	0.13 mm	Pl. 1, Figs. 5
Mogenstrup	Paratype 5 (MGUH 22147)	0.23 mm	0.28 mm	0.20 mm	Pl. 1, Figs. 6a-b
Mogenstrup	Paratype 6 (MGUH 22148)	0.23 mm	0.28 mm	0.19 mm	Pl. 1, Figs. 7a-b
Mogenstrup	Paratype 7 (MGUH 22149)	0.20 mm	0.23 mm	0.15 mm	Pl. 1, Figs. 8a-b
Mogenstrup	Paratype 8 (MGUH 22150)	0.15 mm	0.16 mm	0.11 mm	Pl. 1, Figs. 9
Mogenstrup	Paratype 9 (MGUH 22151)	0.13 mm	0.14 mm	0.13 mm	Pl. 1, Figs. 10
Mogenstrup	Paratype 10 (MGUH 22152)	0.19 mm	0.19 mm	0.13 mm	Pl. 1, Figs. 11a-b
Mogenstrup	Paratype 11 (MGUH 22153)	0.18 mm	0.20 mm	0.15 mm	Pl. 1, Figs. 12a-b
Mogenstrup	Paratype 12 (MGUH 22154)	0.15 mm	0.18 mm	0.13 mm	Pl. 1, Figs. 13
Elna-1	Paratype 13 (MGUH 22155)	0.20 mm	0.24 mm	0.18 mm	Pl. 1, Figs. 14
Elna-1	Paratype 14 (MGUH 22156)	0.24 mm	0.25 mm	0.20 mm	Pl. 1, Figs. 15
Ibenholt-1	Paratype 15 (MGUH 22157)	0.25 mm	0.26 mm	0.19 mm	Pl. 1, Figs. 16a-b
Ibenholt-1	Paratype 16 (MGUH 22158)	0.21 mm	0.24 mm	0.20 mm	Pl. 1, Figs. 17
Mogenstrup	Paratype 17 (P 52867)	0.18 mm	0.21 mm	0.15 mm	Pl. 1, Figs. 18
Mogenstrup	Paratype 18 (P 52868)	0.18 mm	0.20 mm	0.15 mm	Pl. 1, Figs. 19a-c
Mogenstrup	Paratype 19 (USNM 477220)	0.13 mm	0.15 mm	0.11 mm	Pl. 1, Figs. 20
Mogenstrup	Paratype 20 (USNM 477221)	0.14 mm	0.14 mm	0.11 mm	Pl. 1, Figs. 21a-b

light micrographs and additional specimens by scanning electron micrographs.

Type Locality. The cliff at Mogenstrup, on the eastern coast of Salling in North Jutland, Denmark (Upper Oligocene deposits), is selected as type locality, because of the high amount of *Rolfina arnei* in the faunal assemblage (Fig. 1).

Distribution. *Rolfina arnei* is so far only known from Upper Oligocene and lower Miocene deposits in the central and northern North Sea region including the Danish onshore localities (Fig. 1).

Description. Test compact, consisting of 2–3 trochospirally coiled whorls. Equatorial periphery lobate, axial periphery rounded. Spiral side strongly convex and rather coarsely perforated. Umbilical side ranges from concave to flat or slightly convex, finely perforated. The chambers are globular increasing gradually in size as added, 3–5 in number in the final whorl. All chambers are visible on the spiral side, only those of the last whorl are visible on the umbilical side. Umbilicus is often obscured by coarse granulation. Flaps reaching from the base of each chamber towards the umbilicus are seen in specimens where the umbilicus is not obscured by coarse granulation. The test is calcitic (ex-

amined by x-ray diffractometry), optically radial, often brown in color. The sutures are depressed, gently curved and slightly oblique on the spiral side, nearly radial on the umbilical side. The aperture is an umbilical-interiomarginal to strictly umbilical arc. There seems to be a variation from an areal to an umbilical-interiomarginal aperture. In young specimens the areal aperture is surrounded by a very low brim, while the umbilical-interiomarginal aperture in the mature specimens may have a weakly developed lip.

Dimensions. For holotype and paratypes see Table 1, Figure 2 and Plate 1, for 80 other specimens (average value in brackets): minimum diameter 0.13 mm–0.30 mm (0.20 mm), maximum diameter 0.13 mm–0.34 mm (0.22 mm), height 0.10 mm–0.30 mm (0.17 mm). The height variation is shown in Plate 2, Figs. 18–20.

VARIATION

The excellent preservation state and the abundance of specimens permit analysis of the variability in *Rolfina arnei*.

The number of chambers in the last whorl varies from 3 to 5, but most of the specimens have 4 chambers in the last whorl (Table 2).

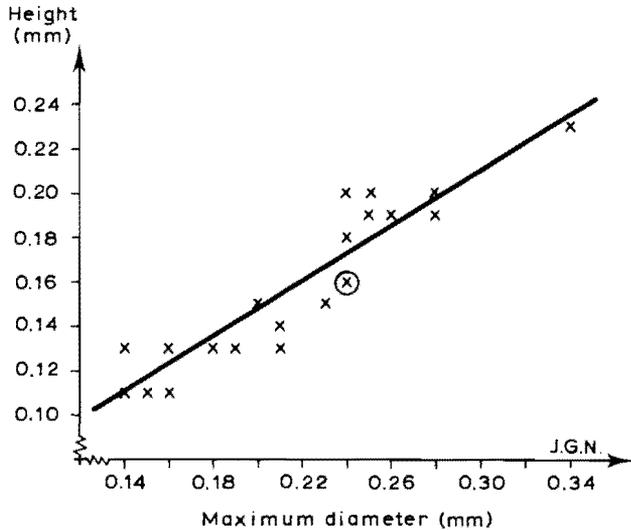


FIGURE 2. Diagram of the dimensions of type specimens of *Rolfina arnei*. The holotype is encircled.

The position of the primary aperture varies from umbilical-interiomarginal to strictly umbilical, but specimens with a secondary areal aperture are also observed (Pl. 2, Fig. 3). A septal aperture can be found between the last and the penultimate chamber (Pl. 2, Fig. 10).

The pores on the spiral side are sometimes projected on small knobs, making the pores resemble small volcanoes (Pl. 2, Figs. 24, 26). Some specimens tend to have the raised pores especially on the early chambers. This feature was also observed by King (1983, pl. 3, figs. 13–15). In the light microscope the raised pores appear as simple granules. The difference in pore size between the spiral and the umbilical side is not always distinct. In some of the specimens with small pores the pore size does not decrease towards the umbilicus.

Coiling density is not always equal. Some specimens are so closely coiled that the umbilicus is closed and the specimens become convex on the umbilical side, whereas others are very loosely coiled with an open umbilicus. Closely coiled specimens tend to be higher than more loosely coiled tests (Pl. 2, Figs. 18–20). There seems to be a slight preference in coiling direction to the sinistral (55% of 915 examined specimens, Table 2).

STRATIGRAPHY

Both this paper and previous studies show that *Rolfina arnei* is of stratigraphic significance in the Tertiary of the North Sea area.

TABLE 2. The coiling mode of 915 specimens of *Rolfina arnei*.

No. of chambers in last whorl	Sinistral		Dextral	
	No. of specimens	% of 915 specimens	No. of specimens	% of 915 specimens
3	25	2.7	13	1.4
4	464	50.7	370	40.4
5	23	2.5	20	2.2

The species was first recorded from the Brejning Clay of the Vejle Fjord Formation at Skansebakken (Fig. 1, Locality no. 2) by Dinesen (1959) as "*Rotalia*" sp. 1. He considered the Brejning Clay to be Late Oligocene in age.

A very rich mollusc fauna indicates the Chattian B substage (Schnetler and Beyer, 1990) for the acme of *Rolfina arnei* at the type locality at Mogenstrup (Fig. 1, Locality no. 1). Paleomagnetic measurements at the same locality suggest that the mollusc and foraminiferal fauna may belong to the polarity chronozones C7a and C8, which implies an age of about 27 Ma (Schnetler and Beyer, 1990).

In the North Sea zonation of King (1983, 1989) *Rolfina arnei* (as *Glabratella?* sp. A) is considered to be a key species for the Late Oligocene to Early Miocene (Zone NSB 8 and Zone NSB 9). In the cored Harre boring (Fig. 1, close to Locality no. 1) *Rolfina arnei* is found together with *Asterigerina guerichi* (Franke, 1912) according to King (written communication, 1993). Here it occurs in an interval usually referred to NP 24 of early Late Oligocene age (King, 1983). In the Norwegian well 2/2-1 (Fig. 1, Locality no. 23) the highest occurrence of *Rolfina arnei* is recorded from an interval referred to NN 1-2, Early Miocene, according to E. Thomsen (oral communication, 1992).

PALEOECOLOGY AND DISTRIBUTION

Most of the specimens examined in this study are from ditch cutting samples recovered from exploration wells. This precludes establishment of detailed distributional and faunal associations, but the preservation and recovery of this distinctive species is good, and a clear picture of the general foraminiferal assemblage and downhole succession has emerged. The faunal association of *Rolfina arnei* in the onshore profiles presents a reliable database to be compared with the offshore records.

The faunal association of *Rolfina arnei* indicates a neritic environment. The Mogenstrup Cliff yields a mollusc fauna indicative of a water depth of 100–200 m, in the outer neritic zone (Schnetler and Beyer, 1990). This environmental setting is further confirmed by the foraminifera. The faunal assemblage associated with *Rolfina arnei* is dominated by *Trifarina gracilis* (Reuss, 1851) and *T. tenuistriata* (Reuss, 1870), together constituting more than 50% of the fauna. Other faunal components include *Melonis affine* (Reuss, 1851), *Pullenia bulloides* (d'Orbigny, 1846), *Ehrenbergina pupa* (d'Orbigny, 1839), *E. serrata* Reuss, 1850, *Globocassidulina subglobosa* (Brady, 1881), and *Sphaeroidina bulloides* d'Orbigny, 1826. The benthic assemblage is rather diverse; the number of species ranging from 35 to 45. Approximately 10% of the foraminiferal fauna is planktic. This indicates an open outer shelf environment with a water depth of 100–200 m as suggested by the mollusc assemblages. Moving out into the North Sea the faunal composition changes. Where calcareous species are present, they are the same species as observed at Mogenstrup. However, agglutinated foraminifera tend to be the dominant faunal component here. King (1989) observed that *Rolfina arnei* (as *Glabratella?* sp. A) occurs associated with the so-called “*Rhabdammina*-biofacies.” This faunal association is commonly interpreted as having inhabited an environment where the water depth exceeded 200 m and the oxygen levels were probably lowered (King, written communication, 1993). However, in this environment, *Rolfina arnei* represents less than 2–3% (see Fig. 1) of the benthic fauna. The conclusion of all these observations must be that *Rolfina arnei* preferably inhabits the outer neritic zone but it can also survive in the upper bathyal environment probably under restricted oxygen conditions.

Rolfina arnei has so far only been recorded from the North Sea area, and mostly in hydrocarbon exploration wells. Its occurrence in Danish outcrops is so far the only onshore record of the species.

The occurrences of *Rolfina arnei* are shown in Figure 1 together with indications of its maximum frequency as percentages of the benthic fauna. The absence of this species from the southern North Sea in the Danish and Dutch sectors may reflect the fact that Upper Oligocene and Neogene deposits are only partially preserved (King, 1983; Vandenberghe and others, 1992; Michelsen and others, in prep.). So far, *Rolfina arnei* has not been observed north of 59°N (Eidvin, written communication, 1992; King, written communication, 1993). This is probably caused by unfavorable living conditions for the species north of 59°N.

CONCLUSIONS

Rolfina arnei gen. nov. et sp. nov. occurs in sediments of Late Oligocene to Early Miocene age in the North Sea region. It seems to be restricted to latitudes north of 55°N and south of 59°N. Its absence from the southern part of the North Sea might be ascribed partly to the absence of Upper Oligocene–Lower Miocene deposits here.

The faunal associations of *Rolfina arnei* indicate that the species preferably inhabited the outer neritic zone but it was also capable of living in upper bathyal environments, probably at restricted oxygen levels.

ACKNOWLEDGMENTS

Much work concerning this species was carried out by Dinesen (1959). Unfortunately his results were published in Danish, so much of the present description has been translated from his original manuscript. I wish to express my gratitude to Arne Dinesen, Danish Geological Survey (Copenhagen, Denmark), who placed his material at my disposal, and to Chris King, Paleoservices (Watford, England), who most kindly forwarded specimens for comparison and contributed to the distribution map. I am indebted to Helen Tappan (Los Angeles, California, U.S.A) for help with the generic assignment of the genus. Tor Eidvin, Oljedirektoratet (Stavanger, Norway), is acknowledged for information about the species distribution and Claus Heilmann-Clausen, University of Aarhus (Denmark), for providing the samples from Mogenstrup. Special thanks are extended to Marit-Solveig Seidenkrantz, Karen Luise Knudsen and David N. Penney, University of Aarhus, for critically reading the manuscript. I wish to thank Jytte Thomsen for doing the x-ray diffractometry, Jette Gissel-Nielsen for drafting the figures and Svend Meldgaard for preparing the photographs.

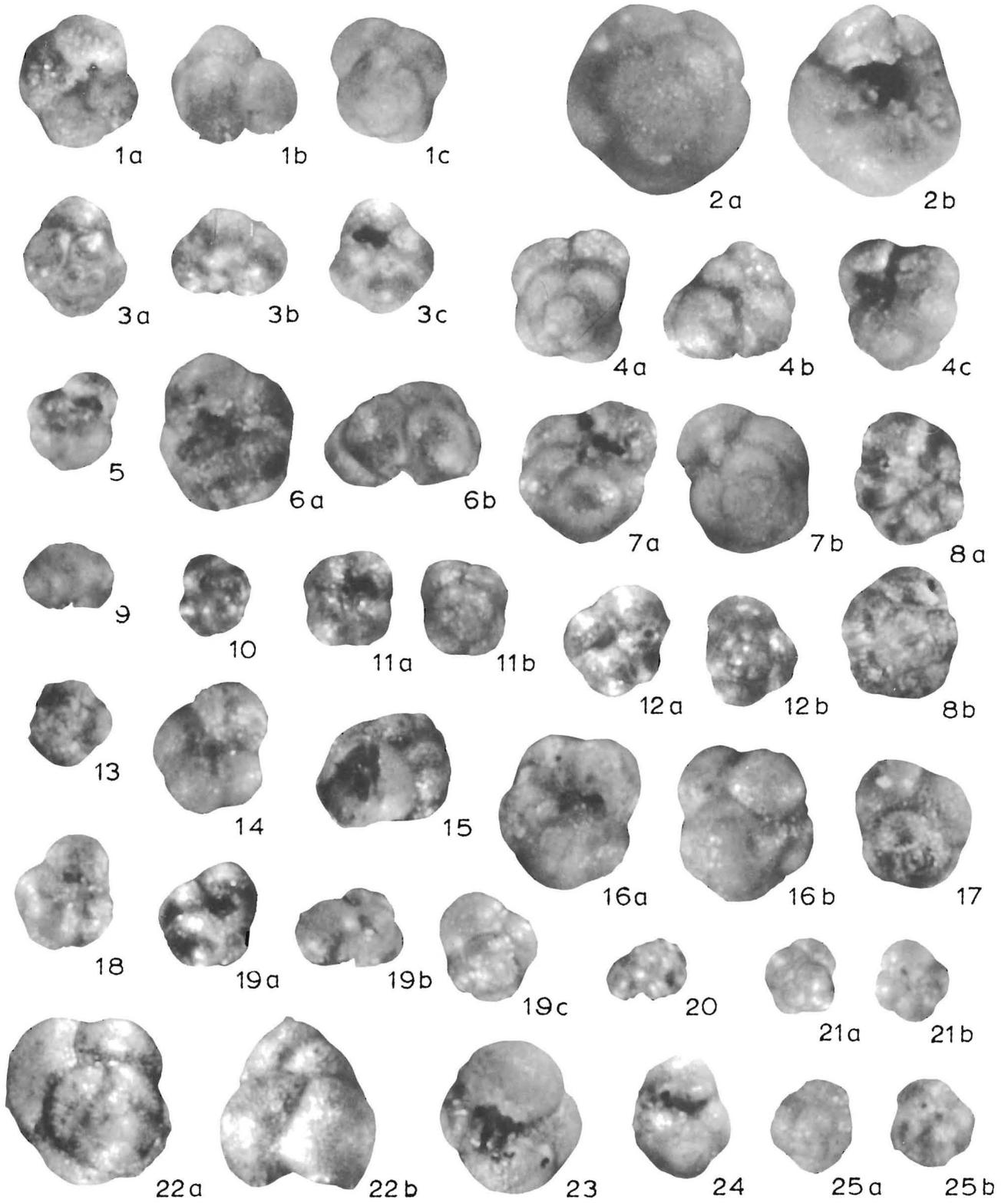
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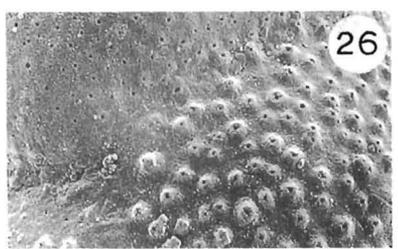
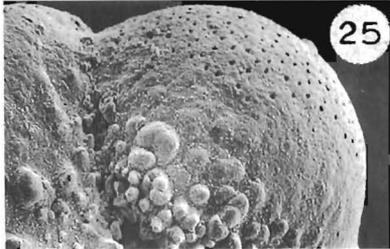
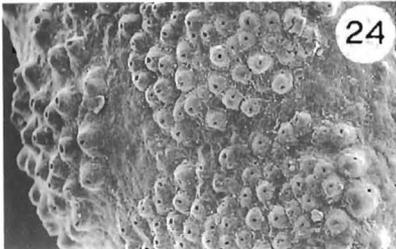
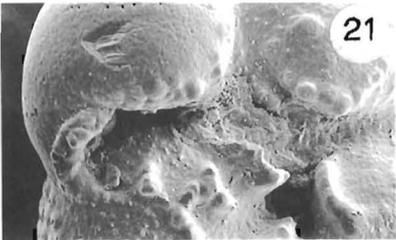
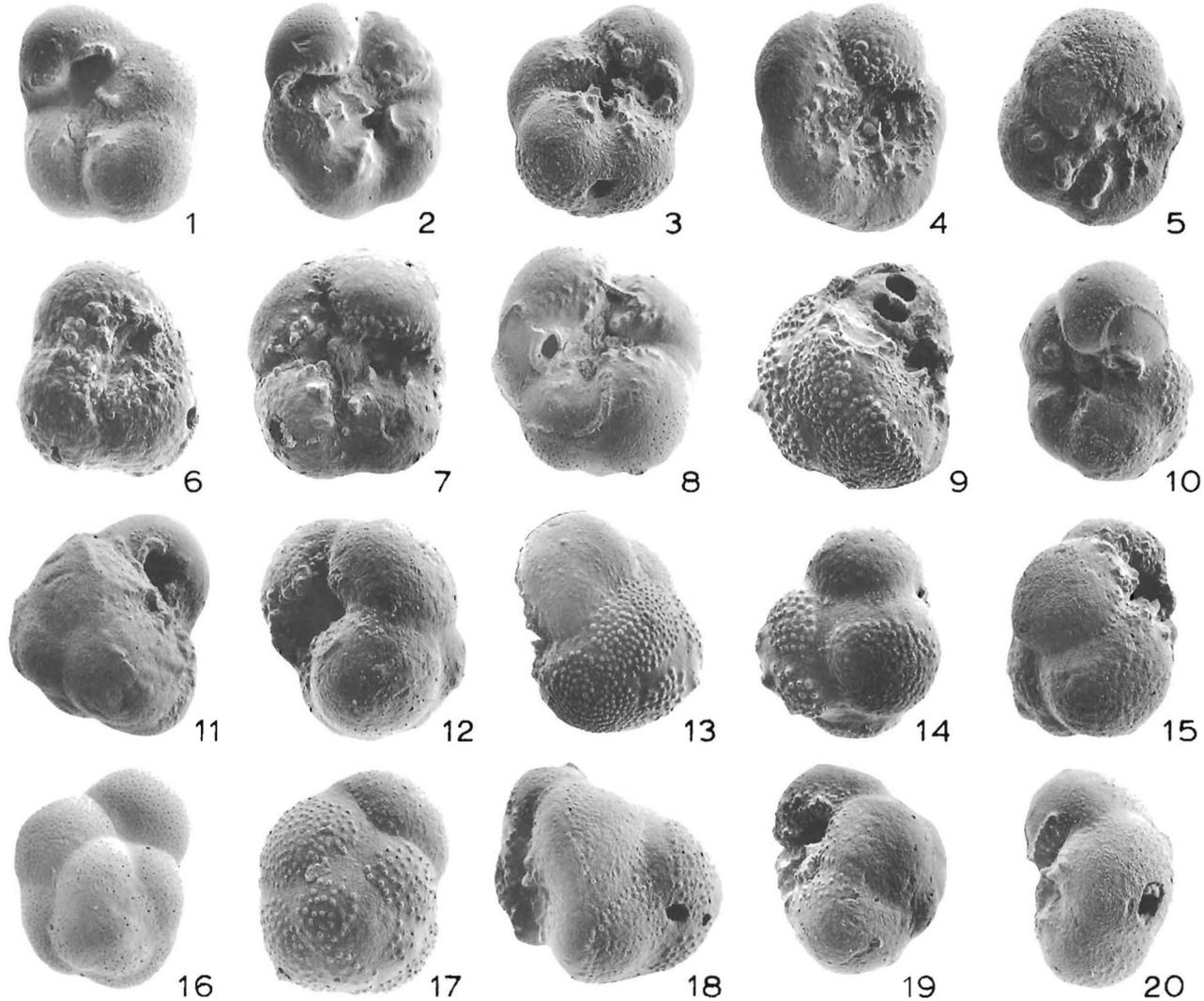
 PLATE I
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Rolfina arnei gen. nov. et sp. nov. in reflected light. All specimens $\times 105$. Note the size variation. **1** Holotype MGUH 22142; sinistral specimen with four chambers in the last whorl; *a* umbilical view; *b* side view; *c* spiral view. **2** Paratype 1 MGUH 22143; dextral specimen with five chambers in the last whorl; aperture with a narrow lip; *a* spiral view; *b* umbilical view. **3** Paratype 2 MGUH 22144; *a* spiral view; *b* side view; *c* umbilical view. **4** Paratype 3 MGUH 22145; *a* spiral view; *b* side view; *c* umbilical view. **5** Paratype 4 MGUH 22146; umbilical view. **6** Paratype 5 MGUH 22147; *a* umbilical view; *b* side view. **7** Paratype 6 MGUH 22148; *a* umbilical view; *b* spiral view. **8** Paratype 7 MGUH 22149; *a* umbilical view; *b* spiral view. **9** Paratype 8 MGUH 22150; side view. **10** Paratype 9 MGUH 22151; umbilical view. **11** Paratype 10 MGUH 22152; *a* umbilical view; *b* spiral view. **12** Paratype 11 MGUH 22153; *a* umbilical view; *b* spiral view. **13** Paratype 12 MGUH 22154; spiral view. **14** Paratype 13 MGUH 22155; umbilical view. **15** Paratype 14 MGUH 22156; side view into broken chamber. **16** Paratype 15 MGUH 22157; *a* umbilical view; *b* spiral view. **17** Paratype 16 MGUH 22158; spiral view. **18** Paratype 17 P 52867; umbilical view. **19** Paratype 18 P 52868; *a* umbilical view; *b* side view; *c* spiral view. **20** Paratype 19 USNM 477220; side view. **21** Paratype 20 USNM 477221; *a* spiral view; *b* umbilical view. **22** High specimen from the Norwegian well 2/2-1; *a* spiral view; *b* side view. **23** Umbilical side of a specimen from the Danish well Elna-1. **24** Umbilical side of a specimen from the Danish well Ibenholt-1. **25** Specimen collected by Chris King; *a* spiral view; *b* umbilical view.



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PLATE 2

Rolfina arnei gen. nov. et sp. nov., SEM photomicrographs. **1** Umbilical side of specimen from Mogenstrup $\times 155$. **2** Umbilical side of specimen from Mogenstrup $\times 140$. **3** Umbilical side of specimen from Mogenstrup $\times 165$. **4** Umbilical side of specimen from Mogenstrup $\times 120$. **5** Umbilical side of specimen from the Danish well Elna-1 $\times 150$. **6** Umbilical side of specimen from the Danish well Elna-1 $\times 160$. **7** Umbilical side of a specimen from the Danish well Ibenholt-1 $\times 100$. **8** Umbilical side of a specimen from Mogenstrup $\times 150$. **9** Side view of a specimen from Mogenstrup $\times 150$. **10** Oblique umbilical view of a specimen from Mogenstrup $\times 160$. **11** Side view of a specimen from Mogenstrup $\times 145$. **12** Oblique side view of a specimen from the Danish well Ibenholt-1 $\times 250$. **13** Side view of a specimen from Mogenstrup $\times 120$. **14** Side view of a specimen from the Danish well Ibenholt-1 $\times 120$. **15** Side view of a specimen from the Danish well Ibenholt-1 $\times 120$. **16** Spiral side of a specimen from Mogenstrup $\times 120$. **17** Spiral side of a specimen from Mogenstrup $\times 160$. **18** Side view of a specimen from Mogenstrup $\times 150$. **19** Side view of a specimen from the Danish well Ibenholt-1 $\times 135$. **20** Side view of a specimen from Mogenstrup $\times 160$. **21** Aperture of Figure 2 $\times 300$. **22** Internal foramen of Figure 8 $\times 750$. **23** Internal double foramen of Figure 9 $\times 600$. **24** Pores of Figure 9 $\times 450$. **25** Pores and umbilical ornamentation of Figure 4 $\times 350$. **26** Pores of Figure 13 $\times 450$.



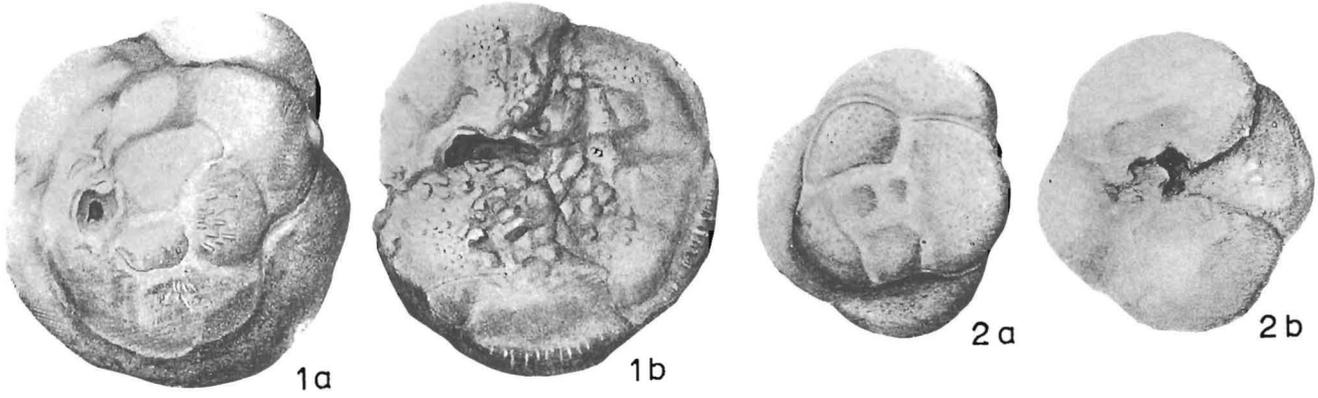


PLATE 3

Rolfina arnei gen. nov. et sp. nov., 1a-b, 2a-b Original drawings of "*Rotalia*" sp. 1 (from Dinesen 1959, pl. 9, figs. 4-5).

***ELPHIDIUM KARENÆ*, A NEW FORAMINIFERAL SPECIES FROM INTERGLACIAL SEDIMENTS IN ICELAND**

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ABSTRACT

A new species, *Elphidium karenæ*, has been recorded from pre-Weichselian interglacial (probably Eemian) sediments of southwest Iceland and from interglacial marine deposits belonging to the Breidavík Group (Ear-

ly Pleistocene) of north Iceland. The new species resembles *Elphidium advenum*, *Elphidium gerthi* and *Elphidium excavatum* but is not conspecific with these species.

INTRODUCTION

Foraminiferal research in Iceland and surrounding waters is restricted to relatively few studies. Recent faunas around Iceland were investigated by Terquem and Terquem (1886), Nørvang (1945), Adams and Frampton (1965), and Helgadóttir (1984). Late Pleistocene faunas in west and southwest Iceland were studied by Símonarson (1974), Helgadóttir (1984), and Ásbjörnsdóttir (in prep.), while Early Pleistocene and Neogene faunas from the Tjörnes Peninsula in north Iceland were recorded by Eiríksson and others (1992).

The sparseness of observations concerning Neogene and Quaternary foraminifera in Iceland can probably be explained by the fact that a distinctive fauna has hitherto been overlooked. This community contains a previously undescribed species, ranging in age from Early to Late Pleistocene. In this paper the species is described and named *Elphidium karenæ*.

SYSTEMATICS

Suborder ROTALIINA Derange and Hérouard,
1896

Family ELPHIDIIDAE Galloway, 1933

Subfamily ELPHIDIINAE Galloway, 1933

Genus *Elphidium* de Montfort, 1808

Elphidium karenæ n.sp.

Pl. 1, Figs. 11–25, Pl. 2, Figs. 1–9

Derivation of Name. Name given in honour of Dr. Karen Luise Knudsen, University of Aarhus, who was the first to record the species.

Diagnosis. A small species of *Elphidium* with subacute periphery, 9–12 narrow chambers in the final whorl, depressed sutures with 3–6 septal bridges covering about ¼ of the length of each chamber, and a translucent umbilical boss.

Description. Test small, planispiral, involute, biconvex and biumbonate with a subacute to acute periphery without any keel. Margin entire, but may become slightly lobulate in the final chambers. Umbilical region only slightly depressed and with a flat, central boss of clear shell material flush with the surface of the test. Wall translucent to semitranslucent, calcareous, hyaline, and optically granular. Chambers narrow, 9–12 (usually 11) in the final whorl, gradually increasing as added. Sutures slightly depressed, increasingly so towards the periphery, curved backwards, and with a single row of sutural pores and 3–6 sutural bridges (retral processes) covering about ¼ of the length of each chamber. Sutures usually closed before reaching umbilical region. Aperture and foramina consist of three round openings at the base of the final chamber.

Variation. The species shows relatively little variability, restricted mainly to the size of the umbilical boss. Some specimens may have a slightly more rounded periphery than usual for the species.

Dimensions. Holotype: greatest diameter: 300 µm, least diameter: 260 µm, thickness: 130 µm. Other spec-

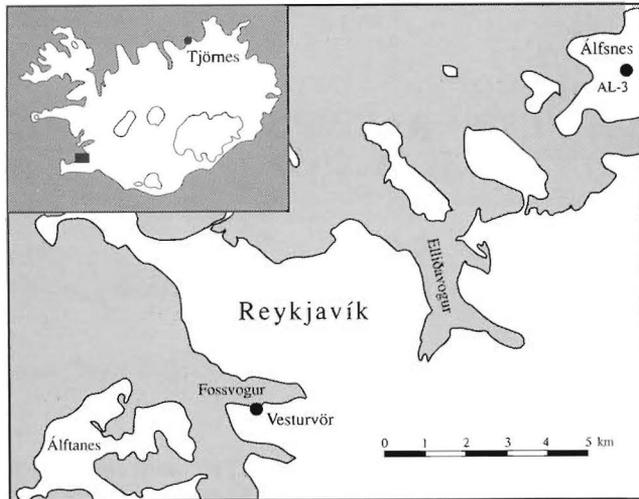


FIGURE 1. Map of Reykjavík, southwest Iceland, showing the positions of the boreholes at Vesturvör and Álfanes (AL-3).

imens (average value in brackets): greatest diameter: 200–400 μm (280 μm), least diameter: 150–340 μm (240 μm), thickness: 60–160 μm (110 μm).

Material. This is one of the dominant species (maximum about 4,000 specimens per 100 g sediment) in Upper Pleistocene deposits from Vesturvör and Álfanes, southwest Iceland, but only a few specimens have been found in Lower Pleistocene deposits at Tjörnes, north-east Iceland.

Type Locality and Type Level. Boring AL-3 from Álfanes, southwest Iceland. Late Pleistocene.

Holotype. Specimen (NI no. 746) from 46.0 m below surface in boring AL-3 from Álfanes. Deposited at the Museum of Natural History of Iceland, Reykjavík.

Paratypes. Eleven specimens (nos. 1–4, 6, 8–10, 12–14) from 46.0 m and three specimens (nos. 5, 7, 11) from 51.5 m below surface in boring AL-3 at Álfanes are selected as paratypes. These are deposited as follows: nos. 1–8 (NI nos. 747–754) at the Museum of Natural History in Iceland (Reykjavík, Iceland), nos. 9 and 10 (USNM nos. 477222–477223) in the Smithsonian Institution (Washington, D.C., U.S.A), nos. 11 and 12 (MGUH nos. 22159–22160) at the University of Aarhus (Århus, Denmark) and nos. 13 and 14 (nos. P52871–P52872) in the Natural History Museum (London, United Kingdom).

Affinities. *Elphidium karenæ* shows some affinity to *Elphidium advenum* (Cushman, 1922) but the latter species has a much more acute periphery, often with a distinct carina (Pl. 1, Figs. 6, 7). Furthermore, the sutures of *E. advenum* are generally slightly more depressed, especially in the central area (towards the um-

bilicus), its sutural bridges are somewhat longer and more distinct, and its umbilical area is more depressed preventing the central plug from becoming flush with the surface of the test.

Elphidium karenæ also shows affinity to *Elphidium gerthi* van Voorthuysen (1957), but this species generally has a more rounded periphery and shorter, less distinct sutural bridges (Pl. 1, Figs. 1–5). *E. gerthi* usually has more than three pores comprising the aperture and foramina.

Elphidium karenæ differs from *Elphidium excavatum* s.l. (Terquem, 1876) by its much thinner test and subacute to acute periphery. *E. excavatum* has a rounded periphery and usually fewer chambers and coarser pores than *E. karenæ* (Pl. 1, Figs. 8–10). The arctic form, *E. excavatum* forma *clavata* Cushman, 1930, may have a distinct umbilical boss, but this is either flush with the surface or even elevated, giving a biumbonate shape of the test (see Feyling-Hanssen, 1972). Furthermore, *E. excavatum* differs from *E. karenæ* by its optically radial wall structure.

Stratigraphy and Ecology. *Elphidium karenæ* occurs in Pleistocene deposits at three localities in Iceland. It is found in Lower Pleistocene, interglacial deposits belonging to the Breidavík Group on Tjörnes, north Iceland (Fig. 1) (Eiríksson and others, 1992), and it has been found in Upper Pleistocene deposits in borehole sections at Vesturvör and Álfanes, southwest Iceland (Fig. 1) The deposits are believed to be interglacial, probably Eemian in age (isotope stage 5e) (Ásbjörnsdóttir, in prep.).

Elphidium karenæ is characteristic for a rather restricted interval of the borings at Vesturvör and Álfanes, and its numbers seem to increase with increasing sand content compared to pure silt.

The species accounts for up to 30% of the total fauna and it is usually third in frequency after *Cibicides lobatulus* (Walker and Jacob) and *Elphidium excavatum*. The composition of the foraminiferal assemblages is believed to indicate a cold boreal environment in shallow to moderate water depths with nearly normal salinity. The occurrence of *E. karenæ* may be taken as a relatively warm water indicator in northern regions.

ACKNOWLEDGMENTS

Elphidium karenæ is named in honour of Karen Luise Knudsen (University of Aarhus = AU) in recognition of her contribution to Quaternary foraminiferal stratigraphy and in gratitude for her kind help and guidance.

I am grateful to Marit-Solveig Seidenkrantz (AU) for comparing the specimens with type material of *El-*

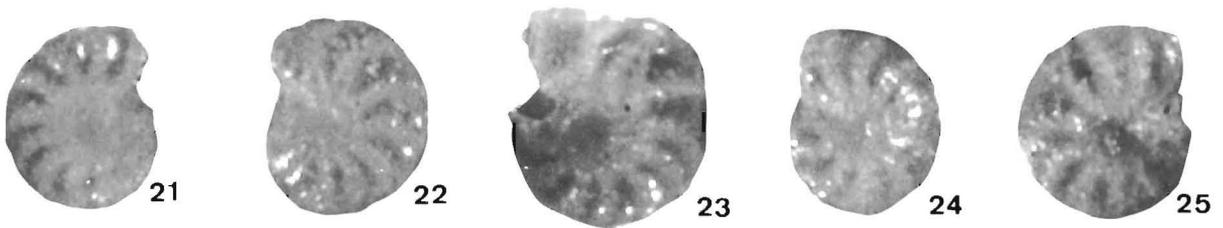
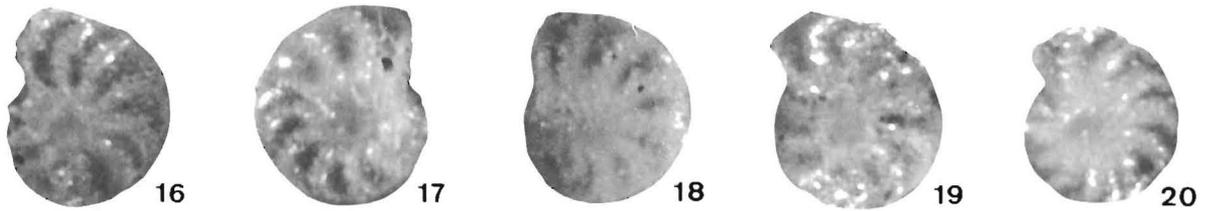
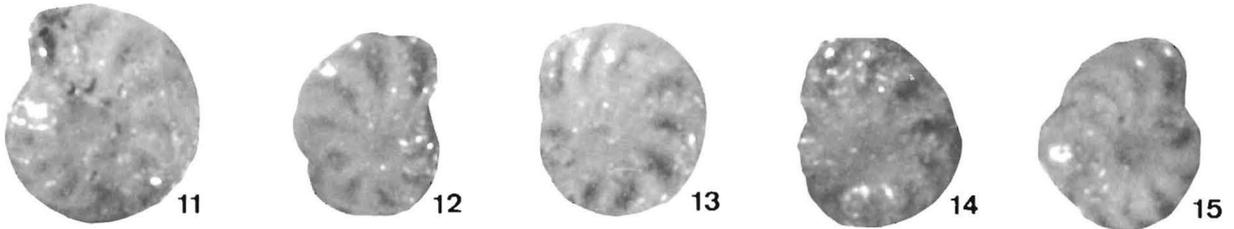
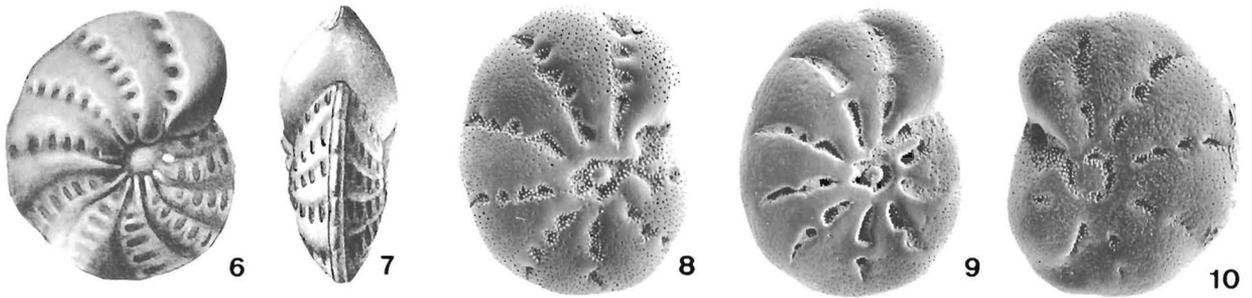
phidium advenum from the Smithsonian Institution (Washington, D.C.) and for assisting with the description of the new species. Thanks are also extended to Jón Eiríksson (Science Institute, University of Iceland) and David N. Penney (AU) for critically reading the manuscript, and to David N. Penney and Svend Meldgaard Christiansen (AU) for help with the scanning micrographs and photographs.

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PLATE 1

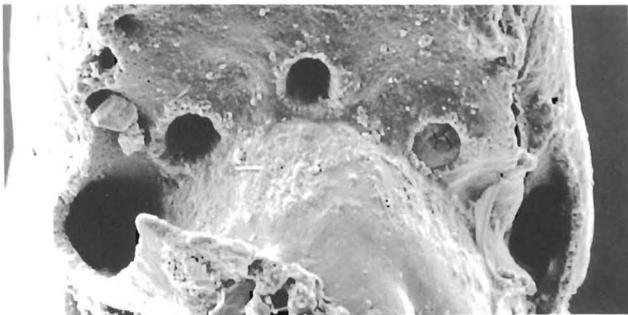
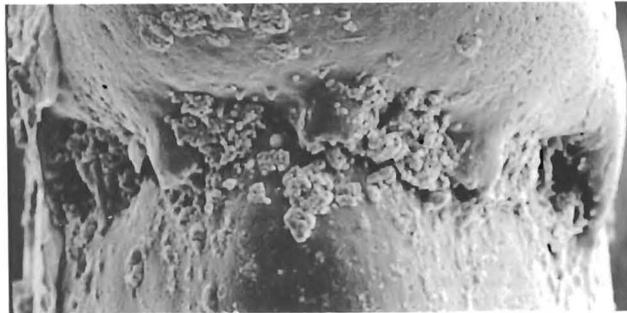
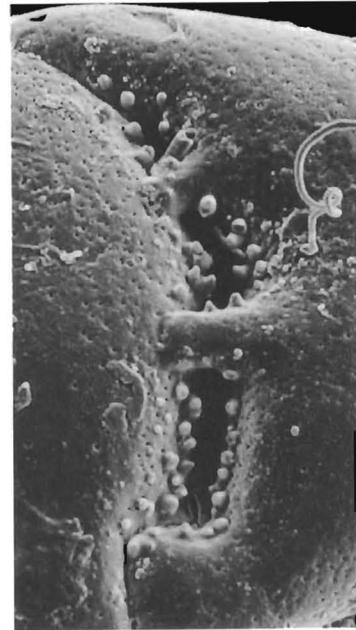
1-5 *Elphidium gerthi* van Voorthuysen (SEM). **1** from boring 328/226 at Amersfoort (Holland), depth 20.0–20.4 m, side view, ×130. **2** from boring 328/226 at Amersfoort (Holland), depth 20.0–20.4 m, side view, ×195. **3** from Recent deposits at Skagen (Denmark), front view, ×135. **4** from Recent deposits at Skagen (Denmark), side view, ×180. **5** from boring 328/226 at Amersfoort (Holland), depth 20.0–20.4 m, side view, ×120. **6-7** *Elphidium advenum* (Cushman), holotype, Cushman Coll. 3281a (from Buzas and others, 1985, drawings). **6** side view, ×85. **7** front view, ×85. **8-10** *Elphidium excavatum* (Terquem) (SEM). **8** from Eemian Interglacial deposits from the Anholt III boring (Denmark), side view, ×95. **9** from Upper Weichselian deposits from boring PC 10-1 (Kattegat), side view, ×95. **10** from Holocene deposits from boring PC 10-1 (Kattegat), side view, ×115. **11-25** *Elphidium karenæ* (light microphotographs) ×105, side views. **11** holotype (NI no. 746). **12-19** paratypes 1–8 (NI nos. 747–754). **20-21** paratypes 9–10 (USNM nos. 477222–477223). **22-23** paratypes 11–12 (MGUH nos. 22159–22160). **24-25** paratypes 13–14 (nos. P52871–P52872).



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PLATE 2

1-9 *Elphidium karenae* from Upper Pleistocene deposits at 46.0 and 51.5 m depth in the boring at Álfnes, southwest Iceland (SEM). **1** side view, ×990. **2** side view, ×900. **3** side view, ×810. **4** side view, ×750. **5** detail of the sutures and sutural bridges, ×3,900. **6** detail of the aperture, ×3,600. **7** front view, ×1,290. **8** detail of the foramina, ×3,000. **9** front view, ×1,050.



HIGH DIVERSITY AGGLUTINATED FORAMINIFERAL ASSEMBLAGES FROM THE NE ATLANTIC: DISSOLUTION EXPERIMENTS

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ABSTRACT

The occurrence of exclusively agglutinated assemblages in the fossil record has remained an enigma in terms of the environmental significance because the modern examples are confined either to the deep ocean or intertidal marshes. Two questions can be asked: are the fossil examples primary (and therefore not represented by modern analogues), or are they the dissolution residues of originally calcareous assemblages? In this paper we address the second question by making a comparison between original, mainly calcareous, modern assemblages and agglutinated assemblages experimentally produced from them. The samples studied were from the outer shelf, continental slope and abyssal

plain. All were dominated by calcareous taxa. Following dissolution by acetic acid, each yielded a diverse assemblage of agglutinated forms. The agglutinated taxa show distribution patterns that can be broadly correlated with water mass and substrate tranquility or disturbance. We conclude that many fossil agglutinated assemblages are the result of partial or total loss of the calcareous element through dissolution. However, differential loss or preservation of organically-cemented taxa during early diagenesis may further alter the taxonomic composition of recent assemblages, leading to a further difference between the modern fauna and the "flysch-type" fauna of the Palaeogene North Atlantic.

INTRODUCTION

Most modern benthic marine environments are inhabited by both calcareous and agglutinated foraminifera. The distribution of the calcareous and some agglutinated forms is limited to regions of nil or minimal carbonate dissolution whereas other agglutinated taxa are able to colonise areas of moderate to severe carbonate dissolution.

The wall structure of agglutinated foraminifera has been classified by Banner and others (1991) into three groups: organo-agglutinated, with an organic cement only; ferro-agglutinated, with additional ferric or other non-calcareous microgranular cements; calc-agglutinated, with additional calcareous cement. The organo- and ferro-agglutinated forms are present in modern environments ranging from intertidal marshes to the deepest parts of the oceans, whereas the calc-agglutinated forms occur only in normal marine environ-

ments such as shelf and bathyal seas and in slightly hypersaline shelf seas. Modern assemblages made up exclusively of organo- and ferro-agglutinated foraminifera are found only in those environments where carbonate dissolution is active, that is, below the calcite compensation depth in the oceans and on high intertidal marshes (see Murray, 1991 for summary).

Assemblages consisting entirely of organo- and ferro-agglutinated foraminifera (the "flysch-type" assemblage of some authors) also occur in the fossil record. Scott and others (1983) gave two possible origins for such assemblages: they may be primary or they may represent the residue of assemblages that originally included calcareous (porcelaneous or hyaline) species. If the former is the case, the only modern analogues are from intertidal marshes or the deep sea. If the latter is the case, then the range of environmental possibilities is very varied.

Previous studies of dissolution have concerned ei-

ther *in situ* syndepositional activity (Jarke, 1961; Murray, 1989) or experimental studies of the susceptibility of selected taxa (Murray and Wright, 1970; Corliss and Honjo, 1981; Grobe and Fütterer, 1981). The consequence of severe dissolution on original assemblages in which agglutinated tests formed only a minor component was shown to result in assemblages comprising juveniles and adults of mainly agglutinated species (Murray 1991, fig. 5.8, field 1-cc).

In this study our objective has been to test this hypothesis by experimentally producing residual agglutinated assemblages from a range of environments extending from the continental shelf to the abyssal plain; we report the preliminary results of a study of 21 samples.

WATER MASSES OF THE NORTH EAST ATLANTIC

In the following discussion, the use of the bathymetric terms bathyal (200–3,500 m) and abyssal (3,500–5,500 m) follows Edwards (1979; see Kennett, 1982). The oceanography of the continental margin of the NE Atlantic is summarised in a profile in Worthington (1976, fig. 18). The mid to upper bathyal zone from 20°N to 61°N is under the influence of Mediterranean Water (MW), a warm, saline water mass (temperature > 4°C, salinity > 35.0‰) flowing out of the Mediterranean. South of 20°N is South Atlantic Water with salinities of <35.0‰ and temperatures > 4°C (Fig. 1).

In the region of latitude 50°N at a depth > 1,600 m is another intermediate water mass, the Labrador Sea Water (LSW) of Worthington (1976) or North East Atlantic Deep Water (NEADW) of Lonsdale and Hollister (1979). It forms an upper layer of North Atlantic Deep Water (NADW). NEADW has a salinity of <34.4‰, temperature 3.2–3.9°C and high oxygen > 6 ml/l (Worthington, 1976; Lonsdale and Hollister, 1979). At a temperature of 3.2–3.7°C there is a marked front separating NEADW from MW at about 45°N (Harvey, 1982). Elsewhere, the lower bathyal zone is overlain by NADW having a salinity of 34.90–35.00‰, a temperature of <4.0°C and a dissolved oxygen content of 5.2–5.6 ml/l.

MATERIAL AND METHODS

The present study is based on benthic foraminiferal analysis of 21 sediment surface samples (mainly dry) from five separate areas in the NE Atlantic (Fig. 2). The samples cover a wide range in water depths from 160 to 4,660 m and are all from above the Calcite Compensation Depth (CCD) (Table 1). Ten samples

represent the NW European outer shelf and slope (area I), four samples are from the NE Atlantic ocean basin (area II), two are from a canyon off Portugal (area III), one is from the Azores (area IV) and, finally, four are from off NW Africa (area V).

Each sample was treated by two different preparation techniques in order to obtain 1) the total modern assemblage and 2) the residual, acid-resistant assemblage. The samples were first washed through a 63 µm sieve (240 mesh) and dried at 50°C. After picking the modern assemblages, the samples were treated with acetic acid (pH 3) for 4–6 hours and washed. If necessary, the procedure was repeated until all calcareous tests had been dissolved. Finally, the samples were dried at 50°C.

Most samples consisted of sandy mud with high abundance of planktonic foraminifera. To prevent loss of heavy, agglutinated forms, floatation was generally avoided. However, the sand content in samples 3209, 3216, 3224, 3230 and 3231 was so high compared to the abundance of benthic foraminifera that concentration by floatation (trichloroethylene) was the only reasonable method to use.

Nine of the agglutinated assemblages contained large numbers of test fragments from tubular or branching species. Most authors dealing with tubular tests regard each fragment as one specimen and base their calculations on this assumption. Consequently, the percentage of tubular or branching forms in a sample is strongly dependent on how roughly the samples are processed and on the relative abundance of robust and fragile species. Therefore, in the present study, we have decided to treat the tubes and the whole specimens separately, and base our calculations (percentages and Fisher alpha index) solely on tests that we know represent only one specimen. For comparative reasons we have also calculated percentages based on the total number of specimens including tube fragments.

One species, *Hormosinella guttifer*, in most cases, is represented by fragments of 1–3 chambers. The figured specimens of this species in Brady (1884) show that it may have up to 8 chambers. By assuming the average number of chambers to be 4, we have been able to make a rough estimate of how many specimens we have, simply by dividing by 4 the total number of chambers present in a sample.

The relative frequency of the non-tubular agglutinating genera in 16 of the 21 acid-resistant samples are treated in a Q-mode factor analysis using the program CABFAC (Imbrie and Kipp, 1971; Klován and Imbrie, 1971). Genera occurring with a maximum frequency of 1% or less of the acid-resistant assemblage

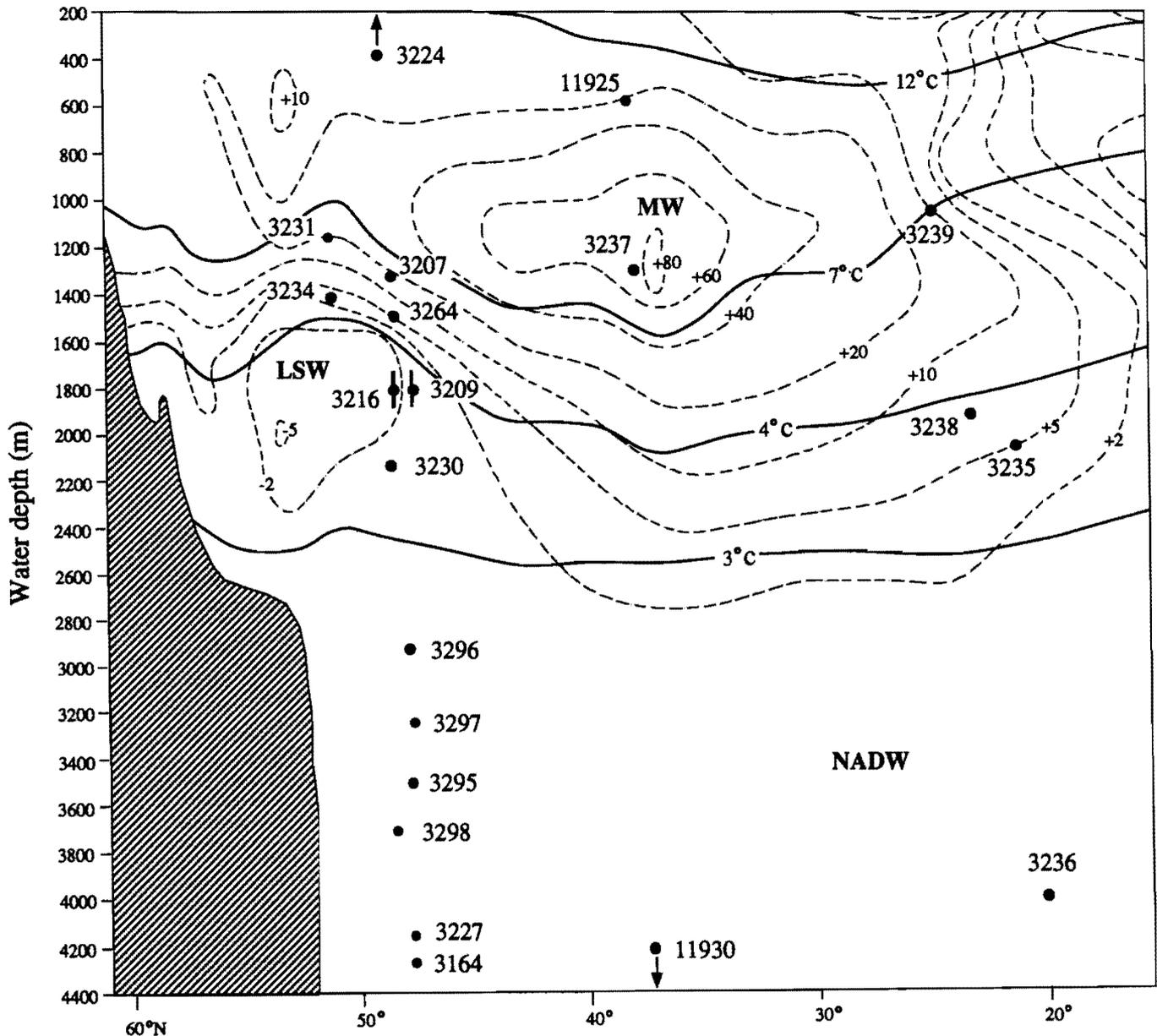


FIGURE 1. A north-south transect of the NE Atlantic Ocean (latitude-depth plot) to show the temperature and water masses (based on Worthington, 1976). The isohalines record deviations from a salinity of 35.00‰. The water masses are Mediterranean Water (MW), Labrador Sea Water (LSW) and North Atlantic Deep Water (NADW). The sample points have been projected into the plane of the section.

in any sample are removed from the data matrix, because of expected statistical insignificance. Samples 3239, 3227, 3207, and 3295 are excluded from the factor analysis because they contain <50 specimens. Sample 3224 is also excluded because the assemblage composition is so obviously different from the others that it only would have represented an additional factor.

All the percentage results have been rounded to the

nearest whole number. The agglutinated foraminifera have been subjectively divided into fine, medium and coarse textured as listed below. Fine textured: *Glomospira* spp., *Repmanina charoides*, *Buzasina ringens*, *Cribrostomoides jeffreysii*, *Haplophragmoides bradyi*, *Labrospira wiesneri*, *Ammobaculites* spp., some trochamminaceans, *Cystammina pauciloculata*, *Ammodiscus* spp. Medium grained: *Lagenammina* spp., *Psammosphaera* spp., *Adercotryma glomeratum*, *Cri-*

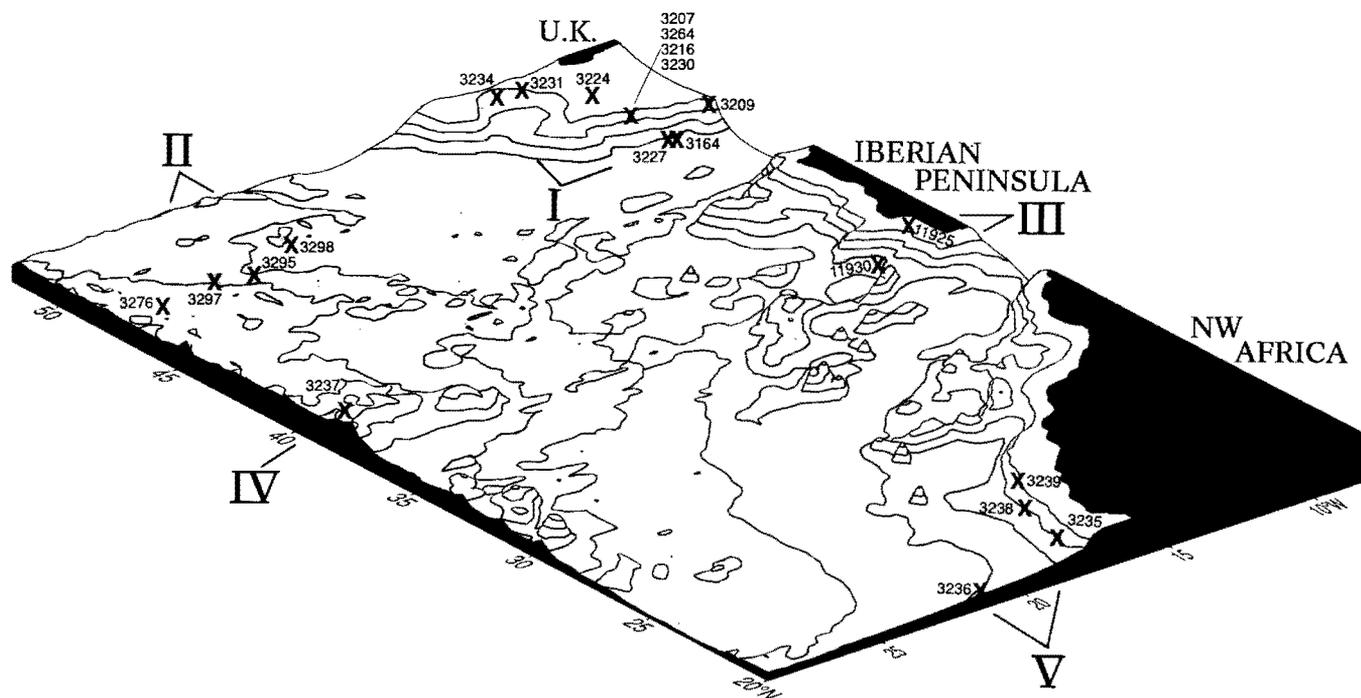


FIGURE 2. An isometric view of the NE Atlantic (contour interval 1 km) showing the sample points and the five geographic areas: I, shelf and slope off NW Europe; II, NE Atlantic ocean basin; III, off Portugal; IV, off the Azores; V, off NW Africa.

brostomoides kosterensis, *Haplophragmoides sphaeriloculus*, *Recurvoides* spp., ?*Eratidus foliaceus*, *Hormosinella guttifer*, *Karreriella apicularis*, *Liebusella goesi*, most *Reophax* spp., some tubes, some trochamminaceans. Coarse grained: *Psammosphaera fusca*, *Saccamina* spp., *Cribrostomoides nitidus*, *C. subglobosus*, *Tritaxis* sp., *Ammoscalaria tenuimargo*, *Era-*

tidus foliaceus and some *Reophax* spp. The maximum length or diameter, as appropriate, of each agglutinated test was measured with an ocular micrometer.

TOTAL ASSEMBLAGES

The results are summarized in Figure 3. A single sample from the shelf (sample 3224, depth 160 m) is dominated by *Eggerelloides scabrus* (43%). It is composed of 30% hyaline, 11% porcellaneous, 14% calc- and 44% organo- and ferro-agglutinated tests. All the other samples studied are from the slope, rise and abyssal plain (575–4,660 m). They have a high proportion of calcareous tests: 81–98% hyaline, 0–10% porcellaneous, 0–3% calc-agglutinated. Organo- and ferro-agglutinated tests make up 0–16% of the total. The calc-agglutinated taxa are *Eggerella bradyi*, *Karreriella bradyi*, *Sigmoilopsis schlumbergeri* and *Siphotextularia* spp. The organo- and ferro-agglutinated taxa are the same as those recorded in the acid-concentrated assemblages. Agglutinated tubes, representing several foraminiferal taxa, are generally rare, but are noteworthy in sample 3238 from off NW Africa (1,805–1,807 m).

The species diversity of the assemblages, measured by the α index of Fisher and others (1943), is very high

TABLE 1. Details of the samples.

Area	Sample	Latitude (°N)	Longitude (°W)	Depth (m)	Water masses	Gear
I	3224	49°36'	10°44'	160	MW	Dredge
	3231	51°21'	11°46'	1135	MW	Dredge
	3207	48°28'	10°20'	1330	MW	Dredge
	3234	51°34'	12°28'	1380	MW	Dredge
	3264	48°30'	10°20'	1450	MW	Dredge
	3209	47°49'	08°08'	1700-1900	MW	Dredge
	3216	48°29'	10°20'	1710-1920	LSW	Dredge
	3230	48°30'	10°23'	2150	NADW	Dredge
	3227	47°36'	09°44'	4150	NADW	Dredge
	3164	47°29'	09°33'	4250-4262	NADW	Dredge
II	3296	47°43'	25°26'	2928	NADW	Corer
	3297	47°28'	24°20'	3257	NADW	Corer
	3295	47°34'	27°26'	3569	NADW	Corer
	3298	48°22'	22°14'	3678	NADW	Corer
III	11925	38°16'	08°58'	575	MW	Corer
	11930	38°07'	10°12'	4660	NADW	Corer
IV	3237	38°39'	28°24'	1248	MW	Sledge
V	3239	24°02'	16°59'	1020	MW	Sledge
	3238	22°49'	17°42'	1806	MW	Sledge
	3235	20°56'	18°09'	2007	MW	Sledge
	3236	20°07'	21°25'	3850	NADW	Sledge

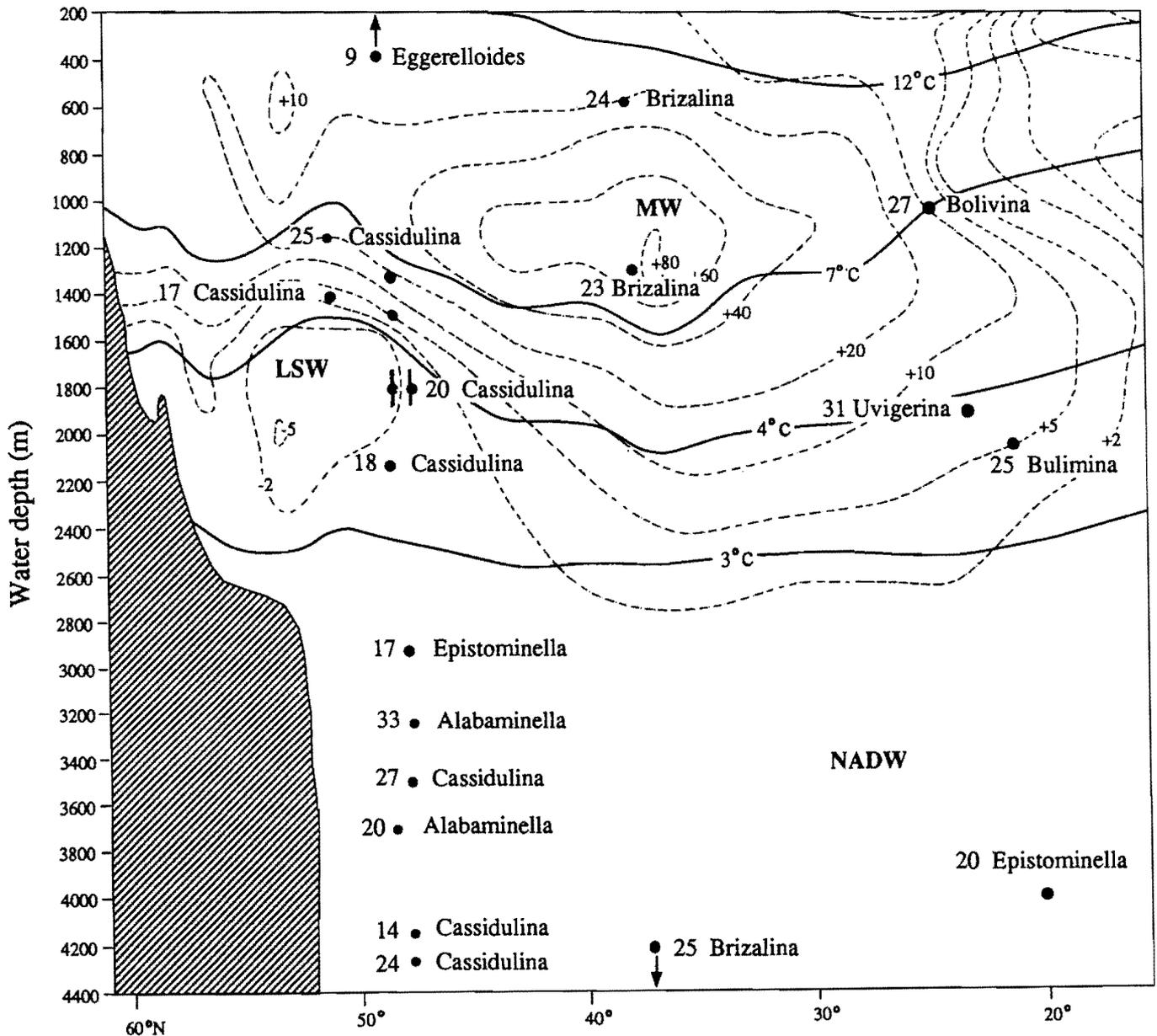


FIGURE 3. Depth-latitude plot of the diversity (Fisher α values as numbers) and dominant genera of total assemblage.

and ranges from α 9 in the shelf sample and from α 14 to 33, but generally ≥ 20 , on the slope and abyssal plain (Fig. 3).

The dominant genera are *Brizalina* in the core of the Mediterranean Water (area IV), *Cassidulina* in MW, LSW and NADW (areas I and II), *Bolivina*, *Uvigerina* and *Bulimina* in MW close to its southern limit and beneath the area of upwelling off NW Africa (area V), and *Epistominella* and *Alabaminella* in NADW (areas II and V).

ACID-TREATED ASSEMBLAGES

After acid treatment, most samples contained abundant, highly diverse agglutinated assemblages. Five small samples contained between 40 and 100 specimens. The data are presented in Table 2 and summarized in Figure 4.

The Trochamminacea is one of the most abundant and diverse superfamilies in the acid-treated assemblages and represents $\geq 15\%$ of the assemblages in 18

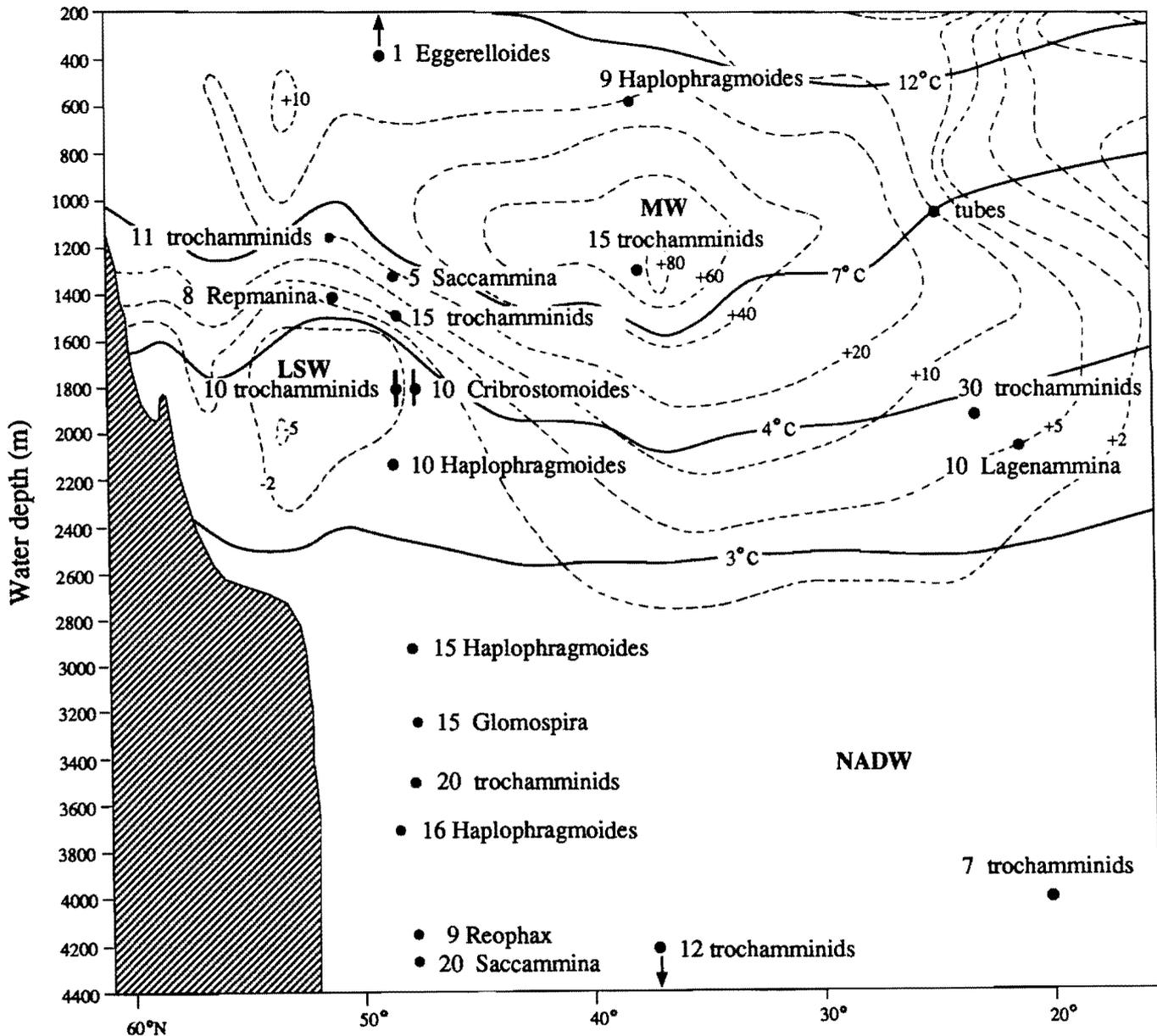


FIGURE 4. Depth-latitude plot of the diversity (Fisher α values as numbers) and dominant genera of the acid-treated agglutinated assemblages.

samples. The distribution and taxonomy of these forms in the North East Atlantic are poorly known, and only a few of them can be identified. The total number of species is roughly 150, including at least 15 trochamminaceans, representing a total of approximately 60 genera.

The assemblages from the NE Atlantic shelf to the abyssal plain (area I) are influenced by MW, LSW and NADW. The shelf sample is strongly dominated by *Eggerelloides scabrus* (96%) and the species diversity

is low ($\alpha = 1$). The deeper samples from this area have α -values ranging between 8 and 20 (Fig. 4). There is no obvious trend concerning dominant genera, but trochamminaceans represent $\geq 30\%$ in all but 3 samples and show a maximum abundance of 59% at 1,450 m. The most frequently occurring genera are *Cribrostomoides* (<1–39%), *Lagenammina* (0–29%), *Psammosphaera* (0–14%), and *Adercotryma* (0–13%). Additionally, *Repmanina* (23%) is dominant in the transition between MW and LSW and *Haplophragmoides* is

AGGLUTINATED ASSEMBLAGES FROM DISSOLUTION EXPERIMENTS

TABLE 2. Census data for the acid-treated agglutinated assemblages (percentages rounded to the nearest whole number).

Morpho- group	Area Sample	I										II			III		IV		V				
		3209	3227*	3164	3224	3231	3207*	3234	3264	3216	3230	3296	3297	3295*	3298	11925	11930	3237	3239*	3238	3235	3236	
	Water depth (m)	1700-1900	4150	4250-62	160	1135	1330	1380	1450	1710-1920	2150	2928	3257	3569	3678	575	4660	1248	1020	1806	2007	3850	
B1	Lagenammina	13	29	4	160	4	2	1	2	1	2	1	1	2	10	7	2	3	12	1	34	10	
	Psammospira		12	14			34	12	11	13		12	3	7	10	7	2	3	12	1	5	5	
	Saccammina			1					1			1	2	2					1	12	19	2	
	Technitella																						
	Thurammina			0					0					0									
B2	Textularina sp			0																			
	Ammodiscus			0					1	1	1	2	3	5	1	1							
	Arenoturrispifilina																						
	Glomospira		2	3		2	7	23	3	3	1	1	4	10	1	3			6				
	Repmanina								0	5	10	0	2	2	3	3	7	4					
B3	Adercoityma	2	7	13		11																	
	Buzasina	0	10	2		1																	
	Cribrostomoides	39	26	12	0	7	2	13	2	8	2	11	8	2	7	6	3	15	29	6	1	0	
	Cyclammina	1																					
	Cystammina			2		2	7	7	3			4	10		10			6	12	6		3	
	?Cystammina																						
	?Cystammina																						
	Evolutinella																						
	Globotrochamminopsis																						
	?Haplophragmoides			0										2									0
B4	?Haplophragmoides	0		4		10		1	1	6	48	26	10	22	14	28	1	1	6	4	1	1	
	Haplophragmoides																						
	Labrospra	1	2	2		2		3	1	8		5	0			2		4	6	6	1	1	
	Paratrochammina					2			1														
	Recurvoides	4						2			3	6	5			5	1					5	
	Trochamminids indet.	18				39	39	14	14	30	25	5	12	10	6	17	32	7	6	3	13	29	
	Ammolagena								1			1	0										
	?Cribrothionina																						
	Hemisphaerammina																						
	Placopsilina																						
C1	Tolypammina											2											
	Tritaxis					3		9	41														
	Trochamminella					1																	
	Textularina sp																						
	Amobaculites							2	3	3		1	1	2	5							2	
	Ammoscalaria			1	3			3				2			5				3	3	2	2	
	Eggerella		2	0				2	0													1	
	Eggerelloides																						
	?Eggerelloides																						
	Eratidus			4						3		12	6			1	6						1
C2	Glaphyrammina																						
	Hormosina			0																			
	Hormosinella	0		1					2	6	2	6	2	5	1	6	2	19	4			2	
	?Karreriella							1															
	Karrerullina			4				6		1			1	2								9	
D	Liebusella																						
	Nodelium																						
	Nodulina																						
	Reophax	5	5	9	1			2	1	12													
	Spiroplectammina					2				3													
B-D	Textularia	2				2			1	1													
	Verneuilinoidea	2		0		1			0	2	1												
	Millammina/Sigmoilina		5																				
	Deuterammina																						
	trochamminids indet.	13		1		4			2	5	3	4	2	3	5	16	10	12	21	1		2	
A	No. of specimens	242	42	225	290	94	41	258	209	171	106	228	248	41	87	151	195	227	17	72	172	270	
	No. of species	37	13	52	5	26	12	29	40	33	23	38	45	21	27	23	28	42	11	36	32	30	
	No. of tube fragments	3	3	17	1	0	43	42	55	10	0	18	9	10	1	98	5	75	122	50	54	84	

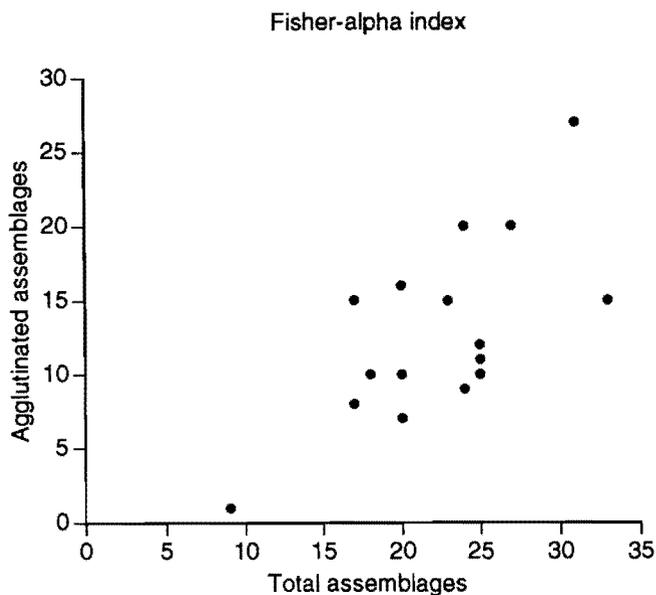


FIGURE 5. Scattergram of diversity (Fisher α values) of the original and residual agglutinated assemblages of each sample.

dominant (48%) in the upper part of NADW. Tube fragments only occur frequently (42–55 fragments) in three samples close to the lower boundary of MW between 1,330 and 1,450 m, whereas the samples influenced by NADW generally contain fewer than 5 fragments.

The four samples from the NE Atlantic ocean basin (area II) are all under the influence of NADW, and span a depth range between 2,928 and 3,678 m. All assemblages are very diverse ($\alpha = 13$ –16) and they show a relatively high degree of similarity. Trochamminaceans make up 13–27% of the assemblages. Other important faunal elements are *Haplophragmoides sphaeriloculus* (9–26%), *Cribr stomoides* (2–11%), *Eratidus* (0–12%), *Psammosphaera* (3–12%), *Glomospira* (2–17%), and *Cystammina* (4–11%). The number of tube fragments is generally low (<10, but 18 at 2,928 m).

Sample 3237 from 1,248 m in the core of MW off the Azores (area IV) is also very diverse ($\alpha = 15$), but in contrast to the samples from the ocean basin, this sample has a high content of tube fragments (75). Trochamminaceans make up 34% of this assemblage in which *Hormosinella guttifer* is the most frequently occurring species (19%). Other important forms are *Cribr stomoides* and *Cystammina*.

The two samples from the slope (575 m) and abyssal plain (4,660 m) off Portugal (area III) are influenced by MW and NADW respectively. The species diversity is high in both ($\alpha = 7$ –9). Whereas the slope assemblage

is dominated by *Haplophragmoides bradyi* (28%) with *Liebusella goesi* and trochamminaceans as important elements, the abyssal plain assemblage is dominated by trochamminaceans (52%) with *Lagenammina*, *Adercotryma* and *Eratidus* as important genera. Tube fragments are far more common in the shallow MW assemblage (98 fragments) than in the deeper NADW assemblage (5 fragments).

Finally, the four assemblages from off North West Africa (area V) also show high species diversity ($\alpha = 9$ –25), and maximum diversity occurs in the two samples from the lower area influenced by MW at 1,806–2,007 m water depth. These southern samples show the highest frequency of tube fragments (50–122), which is the dominant faunal component in the shallowest sample (997–1,037 m). The other assemblages are dominated by trochamminaceans (15–36%), *Lagenammina* (2–39%), *Adercotryma* (1–16%), *Reophax* (5–10%), and *Saccammina/Psammosphaera* (0–24%).

DISCUSSION

Our main objective was to determine whether residual agglutinated assemblages could be derived from original mainly calcareous assemblages. We selected samples from the continental shelf to abyssal depths, but all from above the CCD and all have yielded good agglutinated assemblages. This confirms that post-mortem dissolution is a potential method of producing such assemblages in the fossil record. A second objective was to learn more of the distribution of agglutinated taxa. In previous studies of the NE Atlantic (Weston, 1984; Weston and Murray, 1984) the agglutinated component received little attention because it was so small. However, Gooday has focussed on the taxonomy and biology of deep sea agglutinated forms (see Gooday, 1990 for a review).

In this study we have shown that the residual agglutinated assemblages are diverse both in terms of species and genera. Of course, the original calcareous assemblages were even more diverse. Figure 5 shows the relationships between the two assemblages from each sample. There is not a direct correlation between the species diversity of the original and the residual assemblages but nevertheless there is a broad trend.

The acid treatment of material led to the destruction of calc-agglutinated foraminifera such as *Textularia sagittula*, *Eggerella bradyi*, *Karrerella bradyi*, *Sigmoilopsis schlumbergeri* and *Siphotextularia* spp. Fossil agglutinated assemblages lacking such forms are most likely dissolution residues. On the other hand, Weston (1984) showed that *Eggerella bradyi* is found at depths

below the CCD and under these circumstances the amount of primary calcareous cement is reduced.

Neither the calcareous nor the residual agglutinated assemblages show clear patterns of distribution with regard to water mass or depth, perhaps because only a few samples are spread over a wide geographic area and depth range. Also the continental slope area between 47°N and 51°N is dissected by submarine canyons which create much local environmental variability. Weston (1985) found no evidence of depth zonation in the benthic assemblages. She attributed the distribution patterns to variability of sediment type, the energy of the environment and bottom water characteristics.

The factor analysis, however, has shown that some weak, general trends can be recognized. In addition to the unique sample 3224 on the NW European outer shelf (area I), five factor assemblages were recognized, accounting for 85% of the variance contained in the data matrix. The most important faunal components of the five factor assemblages are: Trochamminaceans (factor 1), *Haplophragmoides* (factor 2), *Tritaxis* (factor 3), *Cribrastomoides* (factor 4) and *Lagenammina* (factor 5). Other important faunal elements are underlined in Table 3. Factor 1 characterizes the abyssal samples near the continental margins of western Europe and NW Africa (areas I and V), whereas factor 2 is typically represented in samples from the NE Atlantic ocean basin (area II, Fig. 6). These are all beneath NADW.

The samples influenced by Mediterranean Water and those in transitional areas between NADW, MW and LSW show much more complex compositional patterns. This is partly due to the geographic and bathymetric spread, but it may also indicate that differences in microenvironmental conditions play a more important role for the species composition than has earlier been realized. It is illustrated by the strongly variable faunal composition of four samples (3207, 3264, 3216, 3230) from a very limited area (part of area I, Lat. 48.28–48.30°N, Long. 10.20–10.23°W, water depth 1,330–2,150 m, Fig. 2) on the NW European continental slope. The area is transitional as NADW, MW and LSW meet here. The four acid-resistant, residual samples consist of clean sand indicating relatively comparable hydrodynamic conditions. Nevertheless, the abundance and species composition of agglutinated forms show large variations and only one sample (3264) has common agglutinated foraminifera relative to the detrital sand grains. Tube fragments are dominant in 3207 with common subglobose trochamminids and *Saccammina*. In 3264 *Tritaxis* predominate with

TABLE 3. Varimax factor score matrix with important faunal elements in each factor underlined.

VARIMAX FACTOR SCORE MATRIX					
VAR.	1	2	3	4	5
ADERCOTRYMA	<u>.336</u>	-.001	-.064	.042	-.089
AMMOSCALARIA	-.042	.052	.013	.088	.023
TEXTULARIA	.016	-.009	.022	.000	.007
HAPLOPHRAGMOIDES	.050	<u>.850</u>	-.122	-.321	-.036
REOPHAX	<u>.200</u>	-.065	-.062	<u>.145</u>	.042
AMMODISCUS	-.046	.085	.021	.017	.028
EGGERELLOIDES	.012	-.003	-.004	.001	-.009
AMMOLAGENA	.005	.006	.018	-.005	-.007
LAGENAMMINA	.034	-.064	-.072	.011	<u>.831</u>
GLOMOSPIRA	-.176	<u>.302</u>	.106	.128	-.101
SPIROPLECTAMMINA	.012	<u>.029</u>	.003	.024	.002
VERNEUILLOIDES	.020	-.007	-.010	.047	-.027
LIEBUSELLA	.061	.067	-.025	-.069	-.045
SACCAMMINA	-.062	.021	-.014	-.011	<u>.433</u>
TRITAXIS	-.027	-.082	<u>.805</u>	-.217	-.053
RECURVOIDES	.006	.069	-.007	.011	.064
TROCHAMMINIDS	<u>.852</u>	.118	<u>.217</u>	.106	.097
CRIBROSTOMOIDES	-.077	<u>.137</u>	.009	<u>.742</u>	-.025
REPMANINA	-.131	<u>.045</u>	<u>.349</u>	<u>.151</u>	.010
CYSTAMMINA	-.109	<u>.158</u>	<u>.115</u>	<u>.228</u>	.004
PARATROCHAMMINA	.033	.003	-.053	<u>.183</u>	-.077
TOLYPAMMINA	-.010	.018	-.004	.004	.003
AMMOBACULITES	-.045	.044	.096	.017	.024
ERATIDUS	-.054	<u>.146</u>	.024	.043	.042
HORMOSINELLA	.060	.067	-.103	<u>.274</u>	-.170
LABROSPIRA	-.087	-.024	.011	.085	-.064
?CYSTAMMINA	.062	-.018	-.021	.004	-.042
PLACOPSELINA	.010	-.003	-.005	.000	.004
?EGGERELLOIDES	.030	-.011	-.004	-.009	.000
NODELLUM	.014	.001	-.005	-.003	-.010
NODULINA	.017	-.006	-.013	-.004	.059
PSAMMOSPHAERA	-.083	<u>.216</u>	<u>.309</u>	<u>.167</u>	.110
ARENOTURRISPIRILLINA	-.004	.001	-.001	-.002	.026
CYCLAMMINA	-.022	.009	.044	.029	.038
GLAPHYRAMMINA	-.017	.002	-.006	-.011	.118
KARRERULINA	.012	-.008	.077	.064	.034
TROCHAMMINELLA	.007	-.007	-.017	.052	-.030
DEUTERAMMINA	-.076	.096	.013	.062	.035
BUZASINA	.017	.005	.000	.005	.000
?HAPLOPHRAGMOIDES	.006	-.002	.000	.000	.002
?KARRERIELLA	-.006	-.001	.015	.008	.000
?CRITHIONINA	-.009	.011	.002	.005	.004
OTHER GENERA	-.046	.080	-.004	.023	.039

subglobose trochamminids and *Psammosphaera* as important faunal elements (factor 3). In 3216 subglobose trochamminids are dominant with common *Lagenammina* and *Reophax* (factor 1), whereas *Haplophragmoides* is the most important genus (48%) in 3230 with subglobose trochamminids and *Adercotryma* as important elements (factor 2). This example illustrates that strongly different assemblages may be found even within a limited and apparently uniform area in terms of hydrodynamics.

The following general trends indicate, however, a reasonable, but at the moment unknown, explanation for the differences in the agglutinated assemblage composition. The frequency of astrorhizids decreases from 74 to 6% with increasing water depth. Interesting trends concern test composition and size of the non-tubular forms: a pronounced, gradual increase (2–87%) in relative abundance of fine grained, small (63–150 μm) specimens with increasing water depth, partly at the expense of large (>400 μm), coarse grained forms which decrease from 20 to 2%. The most striking environ-

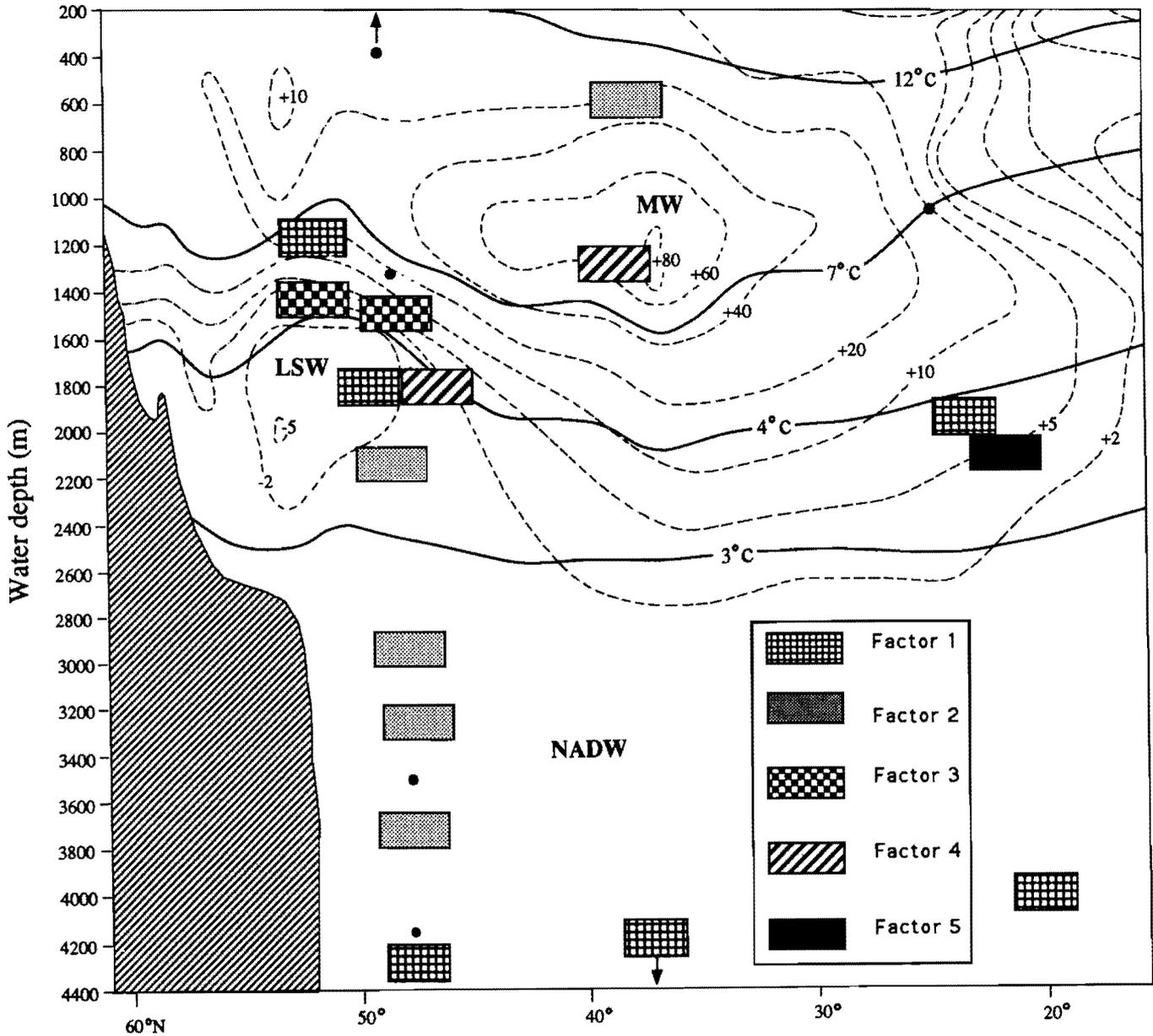


FIGURE 6. Depth-latitude plot of the major varimax factor for each agglutinated assemblage.

mental difference (except water depth) between these samples is that they represent a hydrographic transitional area, but this can hardly explain differences in the test composition.

Our present lack in knowledge in this field is also commented on by Schafer and others (1983) who concluded that "Inspection of the parameters that define individual factors controlling generic distributions on the (Newfoundland) slope indicates that the response of the genera is complex."

RELATIONSHIPS TO THE HYDRODYNAMIC ENVIRONMENT

The role of disturbance in controlling the characteristics of modern agglutinated assemblages has been investigated by Kaminski (1985) and Kaminski and Schroder (1987). Tranquil areas such as the Nares abyssal plain and the upper continental rise off Nova Scotia are dominated by epifaunal suspension feeders with branching, fragile tests and contain a large pro-

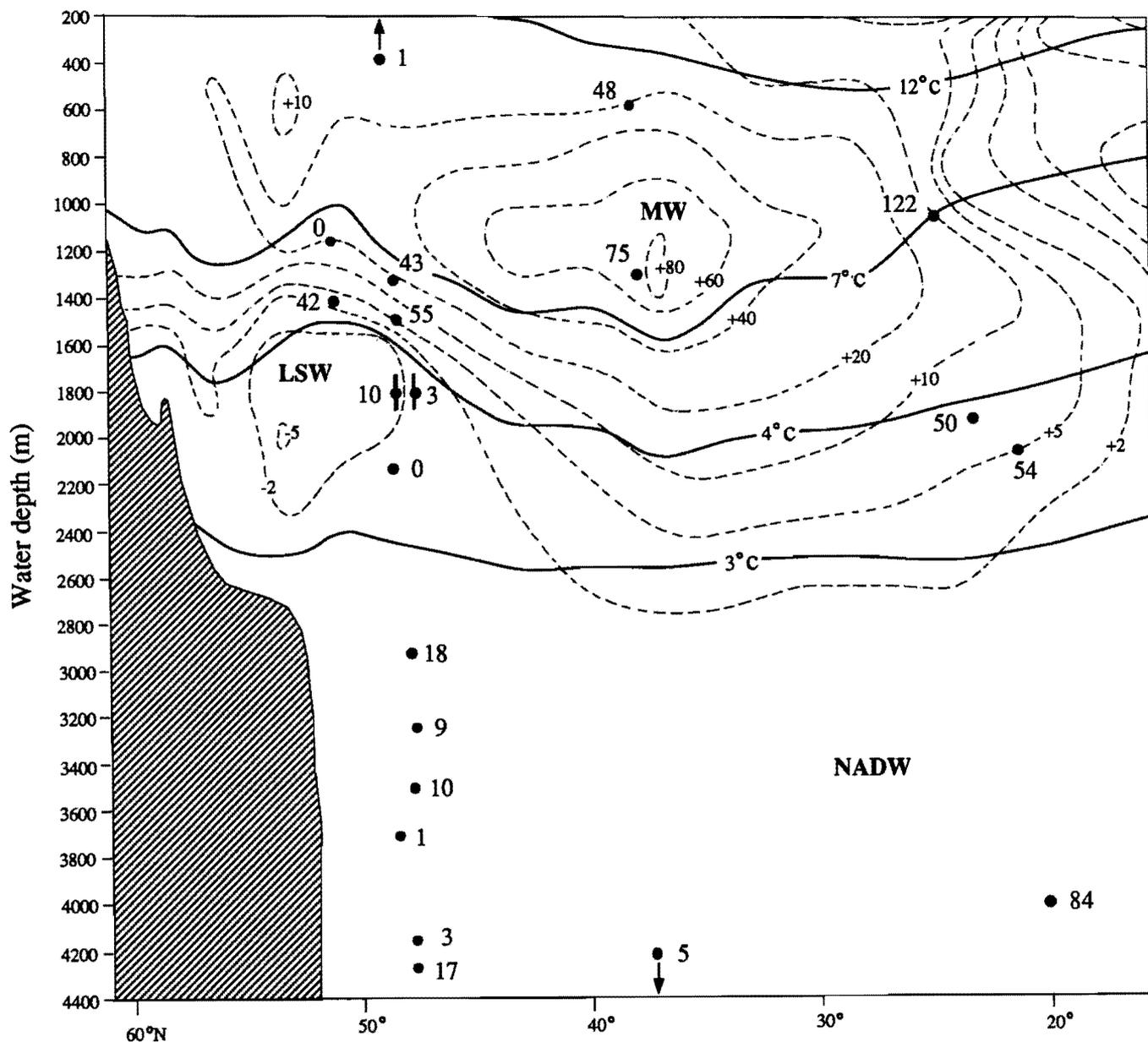


FIGURE 7. Depth-latitude plot of the number of tube fragments in agglutinated assemblages.

portion of finely agglutinated forms. Common genera are *Adercotryma*, *Reophax* and *Nodellum*. On the other hand, areas disturbed by currents have diverse assemblages with frequent occurrences of species which utilize coarse grained detrital particles. The fauna from 2,500–4,000 m off Nova Scotia is dominated by robust, non-branching, epifaunal astrorhizids together with lituolids and trochamminids. At greater depths in the HEBBLE area, which experiences periodic “benthic storms,” there is branching *Rhizammina* and abundant infaunal *Reophax*.

In the present study, tube fragments show a maximum frequency on the continental slope and rise (area I) and are sparse in samples from the NE Atlantic ocean basin (area II). The most frequent occurrences are off NW Africa (area V) where they make up 24–88% of the total residual agglutinated assemblages, and in samples influenced by MW (areas III and IV, Fig. 7). The maximum frequency of tube fragments in the samples off NW Africa may partly be related to nutrient-rich conditions due to upwelling. A relatively high productivity is also indicated by increased fecal pellet

TABLE 4. Data on the quartz content of the sand fraction in the original sediment. For the agglutinated assemblages, the dominant test texture is given together with the proportions of morphogroups B-D 63-150 μm or >400 μm in length or diameter. The test texture is subjectively divided into fine (F), medium (M) and coarse (C). * indicates a small sample (19 specimens). N.D. = no data.

Area	Sample	Depth (m)	Sediment		Agglutinated assemblages (-tubes)	
			% quartz in sand fraction	Dominant test texture	Specimens (B-D) 63 - 150 μm (%)	Specimens (B-D) > 400 μm (%)
I	3224	160	94	C-M-F	0	20
	3231	1135	99	MF	68	2
	3207	1330	N.D.	C-M-F	2	20
	3234	1380	1	F-M-C	33	8
	3264	1450	N.D.	C-F-M	48	8
	3209	1700-1900	N.D.	F-M-C	28	2
	3218	1710-1920	N.D.	F-M-C	39	6
	3230	2150	99	F-M	87	2
	3227	4150	54	C-M-F	2	52
	3164	4260-4262	60	C-M-F	22	18
II	3296	2928	19	M-C-F	28	7
	3297	3257	2	F-M-(C)	48	2
	3295	3569	54	M-C-F	41	10
	3298	3678	63	F-M-C	47	2
	3298	3678	63	F-M-C	47	2
III	11925	575	67	M-C-F	59	14
	11930	4660	26	M-F-C	68	1
IV	3237	1248	79	M-C-F	37	13
	3239	1020	< 1	M-C-F	24*	24*
V	3238	1806	5	M-F-(C)	32	15
	3235	2007	7	M-C-F	5	20
	3236	3850	< 1	MF	35	9

concentrations. The agglutinated tubes in the three samples between 1,800 and 3,850 m water depth off NW Africa are mainly fragments of the suspension feeding, branching astrophorids *Rhizammina algaeformis* and *Saccorhiza ramosa*. Common agglutinated genera are *Adercotryma*, *Reophax*, and delicate, micaceous lagenamminids, and the non-tubular forms are strongly dominated by individuals having medium to fine grained detrital particles. A tubular form such as *Saccorhiza*, being a sessile suspension feeder, relies upon the sedimentation of organic matter or the lateral advection of organic particles. Suspension-feeding organisms are often associated with gentle current activity. The sand fractions of the sediments in these samples are strongly dominated by planktonic foraminifera, and radiolarians (except the shallowest sample) and sponge spicules (also filter feeders) are common. These environments off NW Africa are considered to be relatively tranquil and fit Kaminski and Schroder's (1987) model remarkably well. The MW is present as a gentle eastern boundary current which brings water and suspended particles from the south. In summary, the findings are in agreement with Gooday's (1990) data from the NE Atlantic. He stated that "these distribution patterns may be controlled by food input rather than, or in addition to, hydrographic conditions."

Other investigations from the NW African slope, beneath a region of upwelling and high productivity, have also revealed that tubular agglutinated foraminifera form >5% of the total assemblage at 1,000-4,000 m. The dissolved oxygen in the bottom water

ranges from 3 to >5 ml/l and the organic carbon content of the sediment is from <0.5 to >3.0% (Lutze, 1980; Lutze and Coulbourn, 1984).

All samples (except 3234) from the NW European slope show a high content of quartz grains. The shelf sample (3224) consists primarily of well sorted, medium to coarse sand and represents an area exposed to bottom currents. This is reflected by the strong dominance of robust, coarse grained specimens of *Eggerelloides scabrus* which, with its infaunal mode of life, is sheltered in the hydrodynamically unstable (disturbed) environment. At the HEBBLE site, where substrate disturbance by benthic storms may affect the upper few centimetres of the surface layer, infaunal taxa such as *Reophax* and *Psammosphaera* were the dominant faunal elements (Kaminski, 1985).

The residual samples from the NW European slope consist of relatively clean, fine to medium grained quartz sand except samples 3209, 3234 and 3164 which have common radiolarians. Additionally, 3234, and to a lesser extent 3209, contain common organic detritus and sponge spicules. Mica flakes are abundant in 3209. The latter three may represent somewhat more tranquil environments than the former. Another characteristic feature is that the frequency of specimens is significantly lower (relative to the sand content) in the former (except 3264) than in the more tranquil 3164 and 3234, indicating either a higher productivity and/or a reduced sedimentation rate in the more tranquil areas. Tube fragments are generally sparse on the NW European continental slope but those which are present generally represent relatively robust, unbranched astrophorids, in accordance with Kaminski and Schroder's (1987) "disturbed environment" model. However, test texture exhibits no clear pattern. Coarse grained forms represented by both infaunal and epifaunal taxa (*Cribrostomoides subglobosus*, *Psammosphaera*, *Tritaxis*, *Saccamina*, and *Reophax*) are dominant in four samples (one of them from the more tranquil areas) ranging from 1,330 to 4,260 m water depth, while fine to medium grained forms, typically represented by subglobose trochamminaceans, *Haplophragmoides*, *Adercotryma*, *Repmanina*, *Lagenamina*, and *Cribrostomoides jeffreysii*, dominate in the remaining 5 samples (Table 2). Consequently, despite the fact that the areas on the NW European continental slope are more or less disturbed and contain substantial amounts of fine to medium sand, the grain size composition of the agglutinated tests are unaffected; the assemblages may be dominated by coarse grained forms or, as in 3230, exclusively by fine to medium grained forms regardless of sediment grain size (Table 4).

Of special interest concerning the relationship between sediment and test composition is sample 3209, with abundant mica in the quartz dominated, acid treated residue. The assemblage composition is unique in the present study with a strong dominance of *C. jeffreysii* (38%). Common forms are subglobose trochamminids (16%), *Lagenammina* (13%), and scale- and watchglass-like trochamminaceans (8%). *Cribrostomoides jeffreysii* is usually reported from shelf areas of less than 350 m water depth (Höglund, 1947; Vilks, 1969; Murray, 1971; Haward and Haynes, 1976), while sample 3209 is from 1,700–1,900 m. The tests of the present specimens differ from what is commonly reported in being transparent to white, rather than greyish yellow to rich brown (Höglund, 1947; Murray, 1971) and their surfaces are shiny and smooth. The test wall is extremely thin and may be constructed primarily of tiny mica flakes. The same may be the case for some of the scale- and watchglass-like trochamminaceans. Kaminski has observed watchglass-shaped trochamminaceans adhering to *Rhabdammina* tubes in material from off California (written communication, 1993). The tests of all the lagenamminids are very delicate and made of mica flakes. Such lagenamminids also occur frequently in samples 3235, 3236, and 11930 where mica is abundant in the sediments. Among other taxa in the latter samples, some *Reophax* spp. and *Rhizammina algaeformis* (only 3235) include mica in their tests.

COMMENTS ON "FLYSCH-TYPE" ASSEMBLAGES

In a review of fossil "flysch-type" agglutinated assemblages, that is the so-called *Rhabdammina* fauna which is known from flysch sequences and from the Labrador and North Seas, Gradstein and Berggren (1981, p. 212) wrote: "This type of assemblage has been interpreted as being indicative of (very) deep water, of lagoons or brackish realms or has been essentially related to potential hydrocarbon source rocks. No major category of foraminifers has seen such divergent (paleo) bathymetric and intriguingly complex (paleo) environmental interpretations as agglutinated dominant assemblages."

Gradstein and Berggren (1981) distinguished two types of assemblages. Type A from the Pacific and Atlantic Ocean basins resembles that found in the Alpine-Carpathian basins and in the Labrador shelf and North Sea basins. This type was also recognised by Miller and others (1982) from paleodepths of 2,500–4,500 m except in the Norwegian-Greenland Sea. It is

characterised by coarse-grained, generally larger tests of simple tubular (*Bathysiphon*, *Ammodiscus*, *Lituotuba*) and uniserial forms (*Reophax*, *Hormosina*) with some *Spiroplectammina*, *Textularia*, *Gaudryina*, *Dorothia*, *Trochammina*, *Recurvoides*, *Trochamminoides*, *Cribrostomoides*, *Haplophragmoides* and *Cyclammina*.

Type B assemblage is less common. It has been recorded from Indo-Pacific and Atlantic Cretaceous sediments with a paleodepth >4,000 m. It is composed of generally 63–150 μm , thin, smooth walled Lituoliidae, Trochamminidae and Textulariidae (Gradstein and Berggren, 1981; Miller and others, 1982).

In the Eocene to lower Miocene of the Norwegian Sea, Kaminski and others (1990) have distinguished 5 agglutinated assemblages which appear in stratigraphic sequence. All seem to be dominated by tubular taxa with varying numbers of more complex forms. These assemblages are probably equivalent to Gradstein and Berggren's (1981) type A. Similarly, the Paleogene "*Rhabdammina*" faunas of the North Sea are also type A (Gradstein and Berggren, 1981; Charnock and Jones, 1990).

In many respects the four closely spaced samples from the NW European continental slope (area I, 3207, 3264, 3216, 3230) may represent a transitional series from a type A to a type B assemblage. Other possible examples of type B assemblages are samples 3231 (area I), 3297 (area II), 3298 and 11930 (area III), all consisting of >47% small (63–150 μm), generally smooth forms. They range in water depth from 1,135 to 4,660 m.

Some taxa in the acid-treated assemblages are extremely fragile and would probably not survive fossilization. These include species of *Lagenammina*, *Psammospaera*, *Nodulina*, *Nodellum*, remaneicids and some tubes. Indeed, the typical flysch-type faunas contain very few trochamminaceans and *Lagenammina*. This is the main difference between acid-treated assemblages and preserved Paleogene assemblages from the North Atlantic region. In addition, differential preservation or loss of organo- and ferro-agglutinated taxa during early diagenesis may alter the taxonomic composition of the recent assemblages, further enhancing differences between the modern fauna and the flysch-type fauna.

COMMENTS ON MORPHOGROUPS

Foraminifera occupy infaunal, epifaunal and elevated epifaunal microhabitats (Kitazato, 1981, 1984; Matsushita and Kitazato, 1990; Corliss, 1991), but the

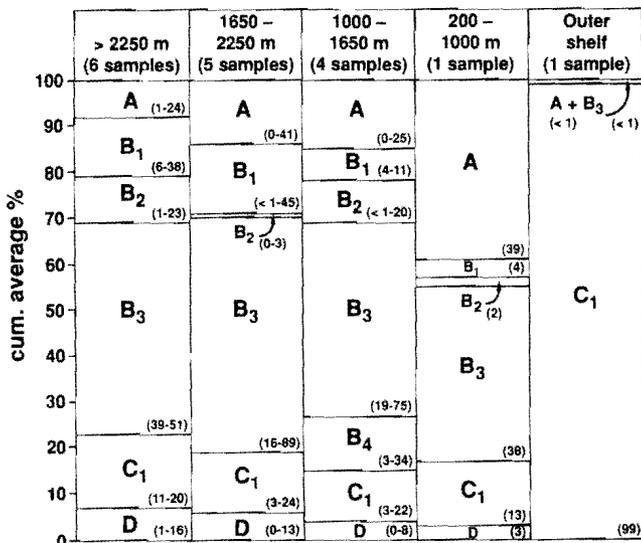


FIGURE 8. Depth distribution of agglutinated morphogroups (following the scheme of Jones and Charnock, 1985). Numbers in brackets refer to the compositional range in each morphogroup.

degree to which the microhabitat preference is related to test form and feeding strategy is uncertain. Several attempts have been made to try to relate morphology and life position or environment and one of the most applicable and comprehensive approaches concerning agglutinated forms is that of Jones and Charnock (1985). They described four main morphogroups and eight subgroups whose present distributions are considered to be related to an appropriate food supply. Recently, Nagy (1992) has modified their scheme to apply it to Jurassic examples.

Morphogroup A includes primarily suspension-feeding, primitive, tubular or branching forms. Group B includes surface-dwelling herbivore, detritivore and omnivore forms such as globular saccamminids, coiled ammodiscids, lenticular, planispiral litiolids, some globular trochoid forms, and, probably, all attached genera. Group C includes sediment-dwelling herbivores and detritivores and comprises primarily elongated forms. The last, group D, includes herbivores represented by low trochospiral forms. Based on Recent data from the NE Atlantic and the West European seaboard, Jones and Charnock found the distribution of the morphogroups to largely follow bathymetrically defined fields. Group A is dominant at depths exceeding 1,000 m, groups B and C are most abundant in shelf and upper bathyal environments, whereas group D is present primarily in high-energy, marginal marine environments.

In the acid-resistant assemblages from middle bathyal

to abyssal depths, group A is subordinate compared to group B, which predominates (Fig. 8) and, consequently, these results differ significantly from the findings of Jones and Charnock (1985). This discrepancy is probably partly due to methodical differences in that we have considered the size fraction ($> 63 \mu\text{m}$) which includes smaller tests than in most studies dealing with deep sea foraminifera (where the sieve size is commonly > 125 or $> 150 \mu\text{m}$). In the majority of samples analysed for the present study, small specimens ($63\text{--}150 \mu\text{m}$) make up more than 30% of the acid resistant assemblages (Table 4). They are predominantly small, spherical and flask or drop-shaped astrophorids, concavo-convex, low conical, high conical and subglobose trochamminids (*sensu* Brönnimann and Whittaker, 1988a, b), ammodiscids and some litiolids and they all belong to morphogroup B. Another important factor is the geographic and bathymetric spread of the samples (and the environmental variability this involves). This introduces the classical problem that arises when trying to relate general distributional patterns to water depth, clearly illustrated by the wide range in relative abundance of the different morphogroups (Fig. 8). Group A is much more common in the nutrient-rich, relatively tranquil environments off NW Africa (area V) than at corresponding depths in the more disturbed areas on the NW European continental slope (area I).

CONCLUSIONS

The primary aim of this research was to determine whether assemblages of organo- and ferro-agglutinated foraminifera could be derived from calcareous-dominated parent assemblages. We have shown that by gentle treatment with acid this is indeed the case for modern sediment samples from the NE Atlantic. The acid-residual assemblages are abundant in individuals and high in species diversity. Approximately 60 genera and 150 species of agglutinated foraminifera have been recovered. These include tubular, unilocular, biserial, triserial, planispiral, trochospiral and streptospiral forms.

Other studies have related the effects of disturbance (e.g., currents or benthic storms) or tranquility (lack of disturbance) to the composition of agglutinated assemblages, but the results of our study are less conclusive. Tubular forms were found to be widely distributed. The texture of the test bears no relation to the grain size of the sediment. For example, fine grained tests frequently occur in coarse sands.

The assemblages described here are similar to the

“flysch-type” assemblages known from the fossil record but they contain some fragile taxa which are unlikely to survive fossilization.

The morphotype classification of Jones and Charnock (1985) does not hold true for our study area. Instead of their group A being dominant on the slope, our results show a dominance of group B.

We conclude from our experiments that postmortem concentration of agglutinated foraminifera, through the partial or total loss of calcareous taxa by dissolution, is a likely origin of some agglutinated assemblages in the fossil record.

Dissolution residual agglutinated assemblages contain useful paleoecological data. Our results show that high diversity original (mainly calcareous) assemblages yield high diversity agglutinated assemblages. We are now extending our studies to a broader range of environments to establish in more detail the distribution of agglutinated foraminifera and to determine those ecological controls which are significant. Once such a data base has been established for the modern faunas, the paleoecological interpretation of the fossil examples will be much improved.

ACKNOWLEDGMENTS

We acknowledge a grant from the Norwegian Research Council for Science and Humanities (NAVF) to Elisabeth Alve to spend 4 months working at Southampton. We would like to thank the British Museum (Natural History) and Janice Weston for supplying some of the samples and John Whittaker, Andrew Gooday and Michael Kaminski for discussions on taxonomy. We are grateful to Barbara Cressey and Tim Khan for help with SEM preparation and Barry Marsh for photography. Joan Bernhard, Michael Kaminski and John Whittaker offered helpful comments on the draft manuscript. The reviewer (Jere Lipps) also suggested worthwhile editorial improvements.

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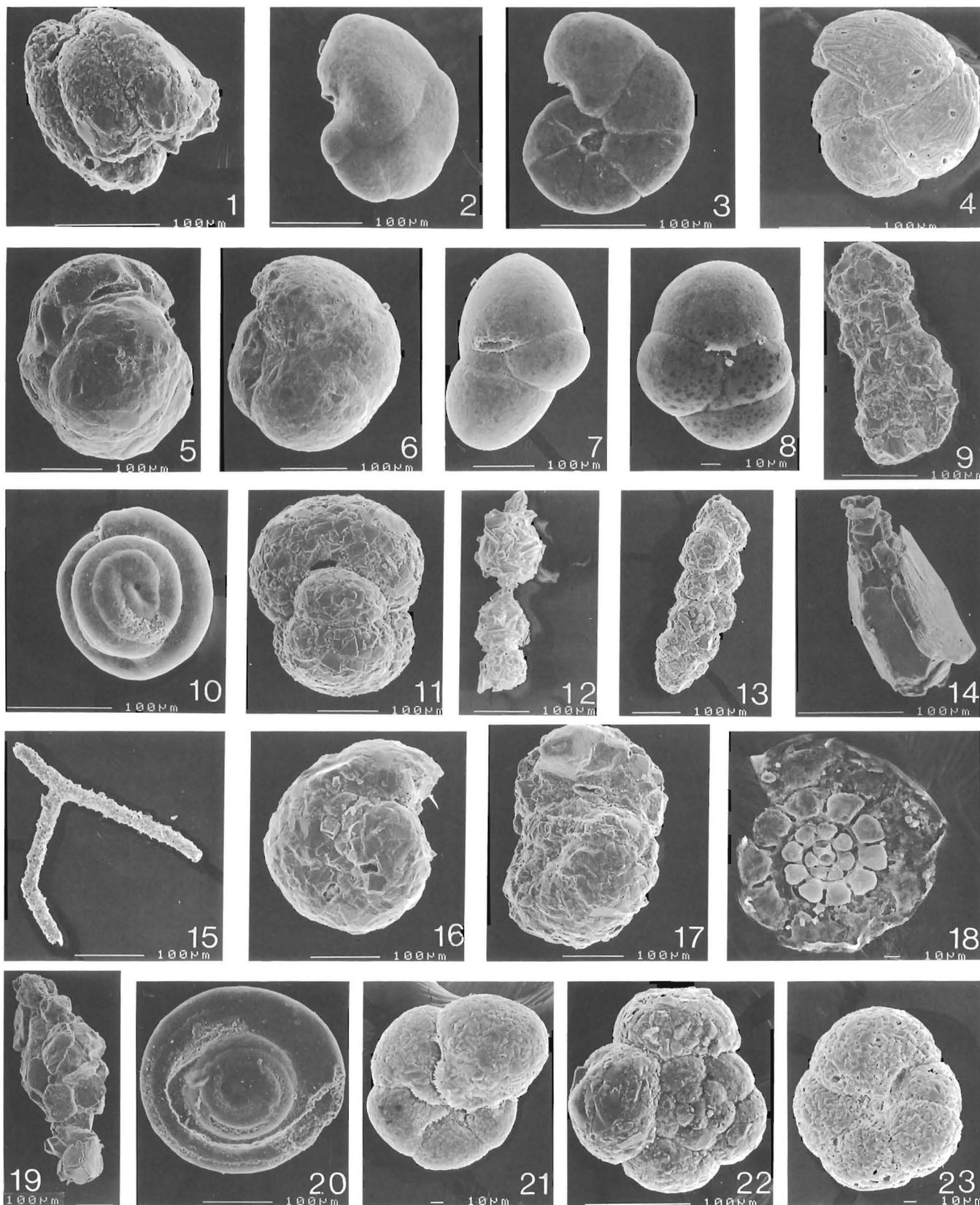
APPENDIX 1. Faunal reference list

- Adercotryma glomeratum* (Brady) = *Lituola glomerata* Brady, 1878
- Ammobaculites exiguus* Cushman and Brönnimann, 1948
- Ammodiscus planorbis* Höglund, 1947
- Ammolagena clavata* (Jones and Parker) = *Trochammina irregularis* (d'Orbigny) var. *clavata* Jones and Parker, 1860
- Ammoscalaria pseudospiralis* (Williamson) = *Proteonina pseudospiralis* Williamson, 1858
- Ammoscalaria tenuimargo* (Brady) = *Haplophragmium tenuimargo* Brady, 1884
- Arenoturrispirillina catinus* (Höglund) = *Ammodiscus catinatus* Höglund, 1947
- Buzasina galeata* (Brady) = *Trochammina galeata* Brady, 1881
- Buzasina ringens* (Brady) = *Trochammina ringens* Brady, 1879
- Cribrostomoides jeffreysii* (Williamson) = *Nonionina jeffreysii* Williamson, 1858
- Cribrostomoides kosterensis* (Höglund) = *Labrospira kosterensis* Höglund, 1947
- Cribrostomoides nitidus* (Goës) = *Haplophragmium nitidum* Goës, 1896
- Cribrostomoides subglobosus* (Sars) = *Lituola subglobosa* Sars, 1868
- Cystammina pauciloculata* Brady, 1884
- Eggerelloides scabrus* (Williamson) = *Bulimina scabra* Williamson, 1858
- Eratidus foliaceus* (Brady) = *Haplophragmium foliaceum* Brady, 1881
- Glyphyrammina americana* (Cushman) = *Ammobaculites americanus* Cushman, 1910
- Globotrochamminopsis bellingshausenii* Brönnimann and Whittaker, 1988
- Glomospira gordialis* (Jones and Parker) = *Trochammina squamata* var. *gordialis* Jones and Parker, 1860
- Haplophragmoides bradyi* (Robertson) = *Trochammina bradyi* Robertson, 1891
- Haplophragmoides sphaeriloculus* Cushman, 1910
- Hormosinella distans* (Brady) = *Reophax distans* Brady, 1881
- Hormosinella guttifer* (Brady) = *Lituola (Reophax) guttifer* Brady, 1881

- Karrerulina apicularis* (Cushman) = *Gaudryina apicularis* Cushman, 1911
Labrospira crassimargo (Norman) = *Haplophragmium crassimargo* Norman, 1892
Labrospira scitula (Brady) = *Haplophragmium scitulum* Brady, 1881
Labrospira wiesneri Parr, 1950
Lagenammina atlantica (Cushman) = *Proteonina atlantica* Cushman, 1944
Lagenammina micacea (Cushman) = *Proteonina micacea* Cushman, 1918
Lagenammina tubulata (Rhumbler) = *Saccamina tubulata* Rhumbler, 1931
Liebusella goesi Höglund, 1947
Nodellum membranaceum (Brady) = *Reophax membranaceum* Brady, 1913
Nodulina dentaliniformis (Brady) = *Reophax dentaliniformis* Brady, 1884
Paratrochammina (*Paratrochammina*) *tricamerata* (Earland) = *Trochammina tricarinata* Earland, 1934
Placopsilina confusa Cushman, 1920
Psammosphaera fusca Schultze, 1875
Psammatodendron arborescens Norman, 1881
Recurvoides laevigatus Höglund, 1947
Recurvoides trochamminiforme Höglund, 1947
Reophax bilocularis Flint, 1899
Reophax nodulosus Goës, 1894
Reophax pilulifer Brady, 1884
Reophax scorpiurus Montfort, 1808
Repmantina charoides (Jones and Parker) = *Trochammina squamata* Jones and Parker var. *charoides* Jones and Parker, 1860
Saccamina sphaerica Sars, 1871
Spiroplectammina biformis (Parker and Jones) = *Textularia agglutinans* d'Orbigny var. *biformis* Parker and Jones, 1865
Technitella legumen Norman, 1878
Thurammina papillata Brady, 1879
Trochamminella siphonifera Cushman, 1943

PLATE I

1 *Adercotryma glomeratum* (Brady), sample 3297. **2** *Buzasina ringens* (Brady), sample 3297. **3** *Cribrostomoides jeffreysii* (Williamson), sample 3209. **4** *Cribrostomoides* sp., sample 3237. **5, 6** *Cribrostomoides subglobosus* (Sars), sample 3297. **7** *Cystammina pauciloculata* Brady, sample 3236. **8** *Cystammina?* sp., sample 3297. **9** *Eratidus foliaceus* (Brady), sample 3296. **10** *Glomospira gordialis* (Jones and Parker), sample 3297. **11** *Haplophragmoides sphaeriloculus* Cushman, sample 3234. **12** *Hormosinella distans* (Brady), sample 3237. **13** *Karrerulina apicularis* (Cushman), sample 3236. **14** *Lagenammima micacea* Cushman, sample 3209. **15** *Psammatodendron arborescens* Norman, sample 3237. **16, 17** *Recurvoides trochamminiformis* Höglund, sample 3234. **18** Remaneicid, sample 3209. **19** *Reophax scorpiurus* Montfort, sample 3209. **20** *Repmanina charoides* (Jones and Parker), sample 3234. **21-23** Trochamminids; **21, 22** *Portatrochammina* sp., sample 3236, **23** *Trochammina* sp., sample 3237.



RECENT BENTHIC FORAMINIFERAL DISTRIBUTION IN THE KATTEGAT AND THE SKAGERRAK, SCANDINAVIA

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ABSTRACT

This paper presents data on the distribution of recent benthic foraminifera (total faunas) in the Kattegat-Skagerrak area (Scandinavia) based on a compilation and interpretation of new and previously published data. A Q-mode factor analysis based on the 22 most important species in 177 samples identified five major assemblages. These were the *Elphidium excavatum*, *Eggerelloides scabrus*, *Bulimina marginata*, *Cassidulina laevigata* and *Bolivina skagerrakensis* assem-

blages. The first three assemblages were found within areas of significant hydrographic variability whereas the last two assemblages inhabited areas of stable hydrography in the deeper parts of the Skagerrak. A number of other species were common in the area. Among these, the distributional patterns of *Cibicides lobatulus*, *Stainforthia fusiformis* and *Nonionellina labradorica* are described.

INTRODUCTION

Benthic foraminiferal faunas respond to environmental factors of which the hydrography, water-mass properties and sediment characteristics are the most important. The purpose of this study is to extend our knowledge of the recent distribution of foraminiferal assemblages and selected species in the Kattegat-Skagerrak region. New data from the Skagerrak and Kattegat and a compilation of previous studies allow us to construct distribution maps of benthic foraminifera that reveal the present-day oceanography and environmental conditions. In addition, this information can also be used to provide a modern analogue for paleoceanographic and paleoclimatic reconstructions.

Recent benthic foraminifera in the Kattegat-Skagerrak area have previously been investigated by Höglund (1947), Olsson (1974, 1976), van Weering and Qvale (1983), Qvale and van Weering (1985), Kuijpers and others (1989), Cedhagen (1991), Bergsten and oth-

ers (1992), Moodley (1992), Troelstra (1992), Seidenkrantz (1992, 1993) and Conradsen (1993), while adjacent areas have been studied by Jarke (1961) (the North Sea), Risdal (1964) (the Oslo Fjord), Thiede and others (1981) (the Oslo Fjord) and Lutze (1965) (the Baltic). Holocene stratigraphies have been studied by Lange (1956), Kihle (1971), Jørgensen and others (1981), Fält (1982), Nagy and Qvale (1985), Knudsen and Nordberg (1987), Nordberg and Bergsten (1988), Nordberg (1989, 1991) and Christiansen and others (1993).

THE STUDY AREA

THE CURRENT SYSTEM IN THE NORTH SEA REGION

The outflow of low salinity water from the Baltic Sea plays an important role for the major circulation system of the North Sea. The Kattegat-Skagerrak forms the connection between the epicontinental Baltic and North Seas. A large volume of low salinity water is drained through the Kattegat and the Skagerrak on its way to the North Sea and the Norwegian Sea, resulting

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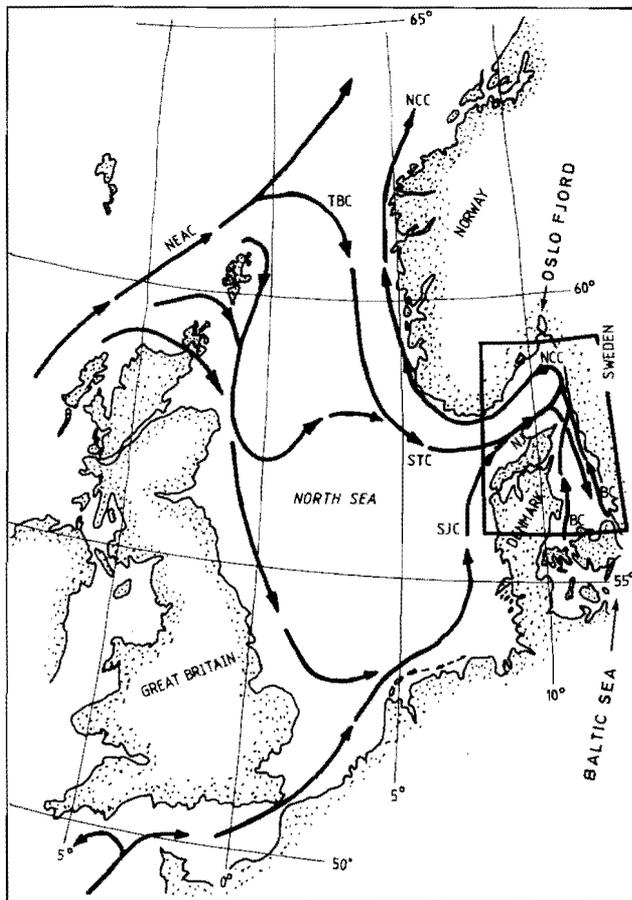


FIGURE 1. Present current system of the North Sea, Skagerrak and Kattegat area. Data compiled from Dooley (1974), Svansson (1965, 1975), Lee (1980) and Furnes and others (1986). NEAC, North East Atlantic Current; TBC, Tampen Bank Current; STC, Southern Trench Current; SJC, Southern Jutland Current; NJC, North Jutland Current; NCC, Norwegian Coastal Current; BC, Baltic Current. Redrawn from Nordberg (1991).

in a reverse flow of saline water from the North Sea and the North Atlantic. These features are considered a major driving force for the prevailing cyclonic circulation system of the North Sea (Saetre and Mork, 1981).

The Kattegat is relatively shallow, with a maximum depth of slightly more than 100 m and a mean depth of 26 m. The Skagerrak is considerably deeper, with a mean depth of 218 m, and a maximum depth of more than 700 m. The hydrography of the Kattegat is marked by a stable two-layer stratification, with a pronounced halocline at 10–20 m water depth, formed by the outflowing low salinity water (8–12‰) from the Baltic Sea in the south and the inflowing saline Skagerrak water (30–35‰) to the north. The latter is composed of North Atlantic water, North Sea water, and recirculated Skag-

errak water (Svansson, 1965, 1975, 1984; Lee, 1980; Aure and Saetre, 1981; Furnes and others, 1986; Rodhe, 1987). Deep-water salinity is nearly consistent from north to south in the Kattegat whereas surface water becomes substantially diluted toward the south. The deep-water in the Skagerrak, occurring below approximately 200 m, is dominated by oceanic water with salinities generally exceeding 35‰.

The current system in the Skagerrak-Kattegat area is dominated by outflowing Baltic water and by large-scale atmospheric and oceanic circulation patterns (Stigebrandt, 1983). The tidal range is very small, approximately 20 cm, and has little influence on the current system. The prevailing current system in the North Sea, Skagerrak and Kattegat is illustrated in Figure 1. The Southern Jutland Current (SJC), as distinguished here, flows along the Danish west coast and is part of the cyclonic circulation of the North Sea. The SJC continues on to form part of the North Jutland Current (NJC) which flows into the Skagerrak-Kattegat. The NJC is dominated by the Southern Trench Current (STC, named herein) which supplies large quantities of North Atlantic water flowing along the southern rim of the Norwegian Trench. The intermittently outflowing hyposaline water from the Baltic Sea forms the Baltic Current (BC) which, together with the NJC, makes up the Norwegian Coastal Current (NCC). This current flows out of the Skagerrak along the Norwegian coast (Nordberg, 1991).

SEDIMENT DISTRIBUTION

The sediment distribution of the Skagerrak has been investigated by van Weering (1981), Fält (1982), van Weering and Qvale (1983), Salge and Wong (1988) and Olausson (1975), who also included the Kattegat. The Skagerrak is the main area of accumulation for fine grained material derived from the North Sea and the Kattegat. Part of this accumulation area extends into the large shallow Kattegat area east of the northernmost part of Denmark (Flodén, 1973; Rodhe, 1973; Fält, 1982).

In the Skagerrak the fine sediments are generally found in the deeper areas while coarser sediments are found in shallow areas. Along the Danish Skagerrak coast, however, sandy sediments dominate down to approximately 200 m. Above 200 m, erosion and non-deposition prevail as a result of the current system (Fig. 1). In the Kattegat, sands predominate in the shallow, western part while clays and silts are mainly found in the eastern, deeper part (Olausson, 1975). Generally, the accumulation rates are much higher in the Skag-



FIGURE 2. Bathymetry and location of sample stations. Bold circles are stations included in the Q-mode factor analysis. Open circles in the Skagerrak are stations of Qvale and van Weering (1985). Crosses in the northern Kattegat are stations of Kuijpers and others (1989).

errak and the northernmost Kattegat than in the remaining Kattegat.

MATERIAL AND METHODS

One-hundred and seventy-seven surface samples have been treated quantitatively in this study (Fig. 2; Appendix 1). These samples were collected using different equipment: grab sampler, multi core, box core, gravity core, piston core and vibro core. Generally, standard techniques were applied for laboratory treatment (e.g., Feyling-Hanssen and others, 1971) but differences occur concerning the analyzed size fraction where both the 0.1–1.0 mm and the 0.125–1.0 mm fractions have been used. The surface samples of this study vary in thickness between 1 and ca. 10 cm. Some of the present data have been published by Høltedahl (1986), Nordberg and Bergsten (1988), Nordberg (1989), Conradsen (1993) and Seidenkrantz (1993). This material was supplemented with unpublished data of Bøe (1978) and the present authors. In total, 64 new samples have been used in the study. The distributional maps of species and assemblages (Figs. 2–4) also

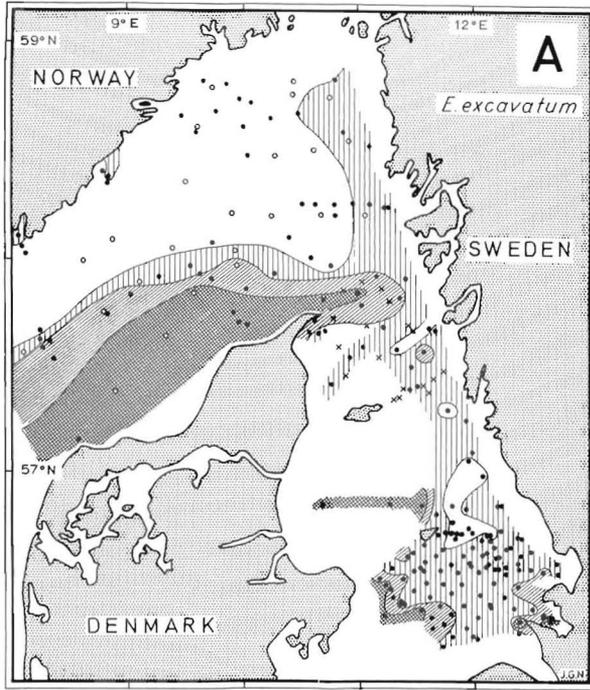
TABLE 1. Varimax factor score matrix, based on 177 samples.

	factor 1	factor 2	factor 3	factor 4
<i>Bulimina marginata</i> (d'Orbigny)	<u>0.937</u>	-0.131	0.066	0.004
<i>Cassidulina laevigata</i> d'Orbigny	-0.055	0.068	<u>0.793</u>	-0.051
<i>Cibicides lobatulus</i> (Walker & Jacob)	-0.031	0.145	0.156	0.012
<i>Elphidium albiumbilicatum</i> (Weiss)	0.011	0.080	0.010	0.089
<i>Elphidium excavatum</i> (Terquem)	0.129	<u>0.928</u>	-0.041	0.040
<i>Globobulimina turgida</i> (Bailey)	-0.026	-0.042	<u>0.268</u>	0.030
<i>Hyalinea balthica</i> (Schroeter)	0.057	-0.044	<u>0.313</u>	0.008
<i>Asterigerinata mamilla</i> (Williamson)	-0.002	0.020	-0.002	-0.009
<i>Nonionella turgida</i> (Williamson)	0.073	0.017	-0.004	0.000
<i>Quinqueloculina seminulum</i> (Linné)	-0.004	0.049	0.003	0.001
<i>Textularia bocki</i> Höglund	0.018	0.076	0.091	-0.027
<i>Uvigerina peregrina</i> Cushman	0.001	-0.001	0.100	-0.008
<i>Stainforthia fusiformis</i> (Williamson)	0.022	0.198	0.103	0.074
<i>Elphidium williamsoni</i> Haynes	-0.002	0.021	-0.005	-0.008
<i>Reophax fusiformis</i> (Williamson)	-0.005	0.004	0.021	0.040
<i>Elphidium magellanicum</i> Heron Allen & Earland	-0.012	0.142	-0.005	0.039
<i>Reophax subfusiformis</i> Earland	0.003	0.005	0.034	0.004
<i>Eggerelloides scabrus</i> (Williamson)	-0.016	-0.065	0.008	<u>0.981</u>
<i>Ammonia beccarii</i> (Hofker)	0.060	0.086	-0.023	0.108
<i>Nonionella labradorica</i> (Dawson)	<u>0.295</u>	-0.003	-0.052	-0.008
<i>Melonis barleeanus</i> (Williamson)	-0.011	-0.050	<u>0.275</u>	0.026
<i>Bolivina skagerrakensis</i> Qvale & Nigam	-0.012	-0.064	<u>0.247</u>	0.042

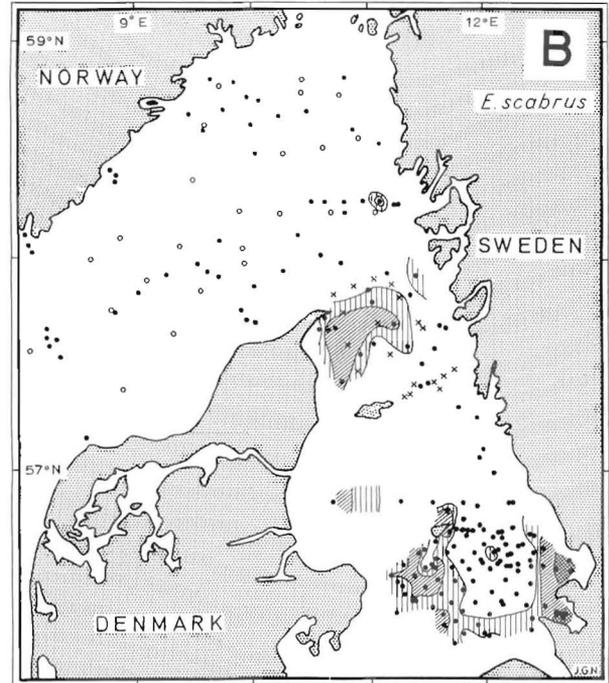
include the data of Kuijpers and others (1989) from the northern Kattegat (no data on *Bolivina skagerrakensis*, *Elphidium excavatum* and *Cibicides lobatulus*) and of Qvale and van Weering (1985) from the Skagerrak (no data on *Eggerelloides scabrus*, *C. lobatulus*, *Stainforthia fusiformis* and *Nonionella labradorica*).

The data were treated in a factor analysis using the program CABFAC (three samples, containing less than 100 specimens, were omitted) (Imbrie and Kipp, 1971; Klován and Imbrie, 1971). Twenty-two species with frequencies of at least 15% in one or more sample were included in the analysis (*Haynesina germanica* (Ehrenberg) and a trochamminacean species, which were common in only one sample (Skagen 27 and BC 08, respectively) were omitted). This treatment identified four factors, explaining 82% of the variance of the data. The varimax factor score matrix is shown in Table 1 and the varimax factor component matrix in Appendix 2. Some samples were dominated by locally abundant species, and these are indicated separately in Figure 6.

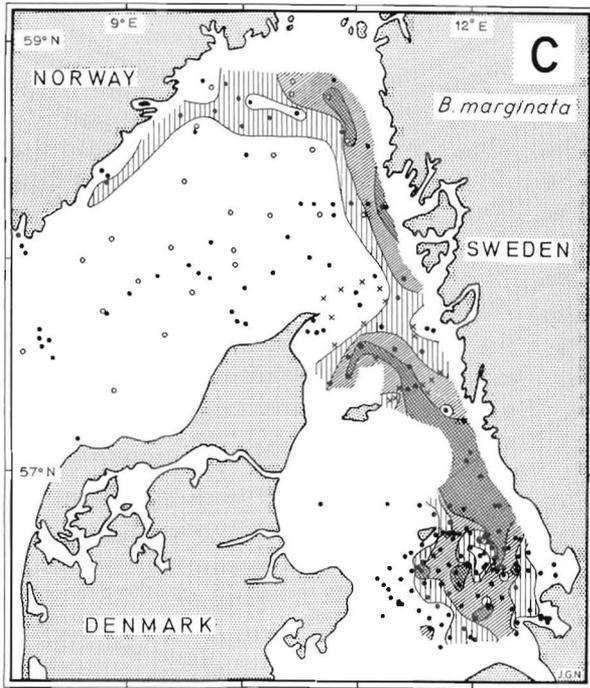
The validity of living, dead and total (living + dead) assemblages in recent investigations has been discussed extensively (e.g., Scott and Medioli, 1980; Murray, 1982, 1991; Conradsen, 1993). However, inter-



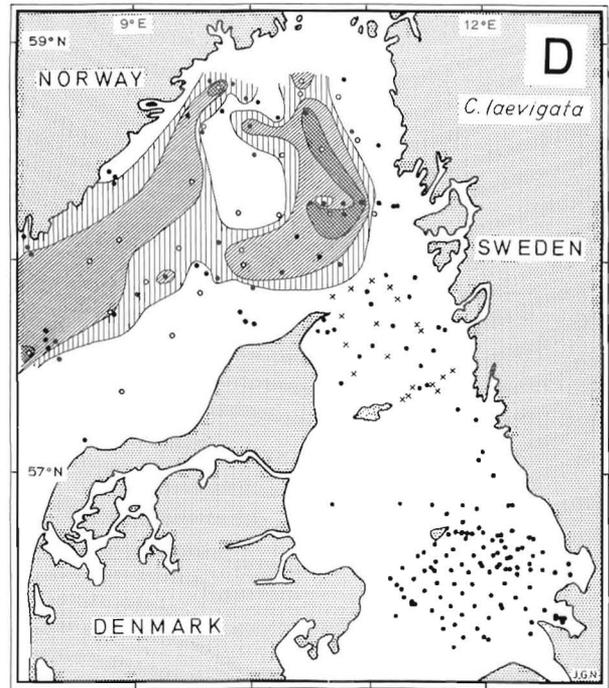
10 - 25% 25 - 40% > 40%



10 - 20% 20 - 50% > 50%

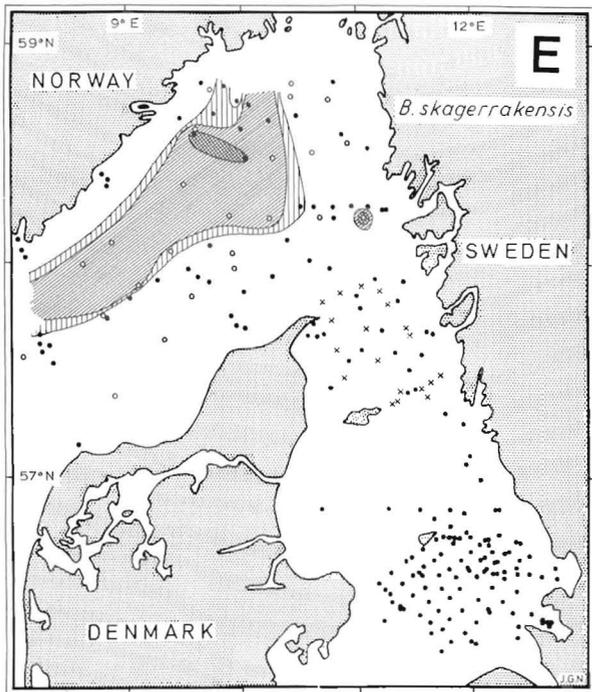


10 - 25% 25 - 40% > 40%

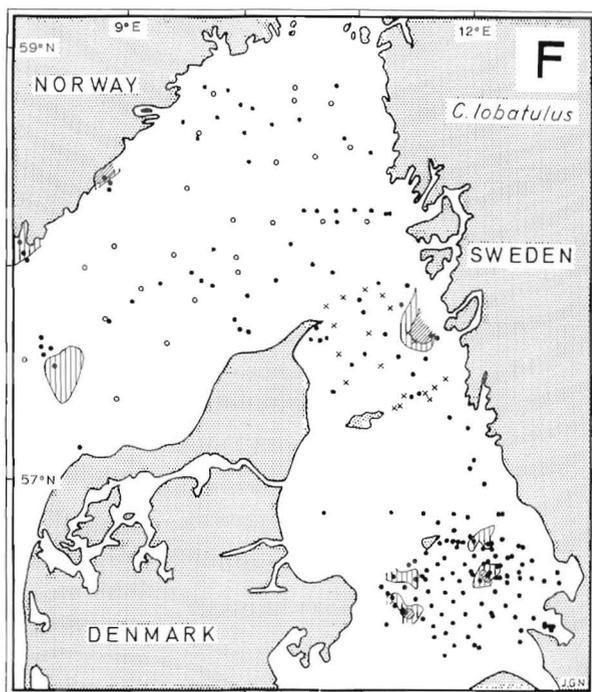


10 - 20% 20 - 35% > 35%

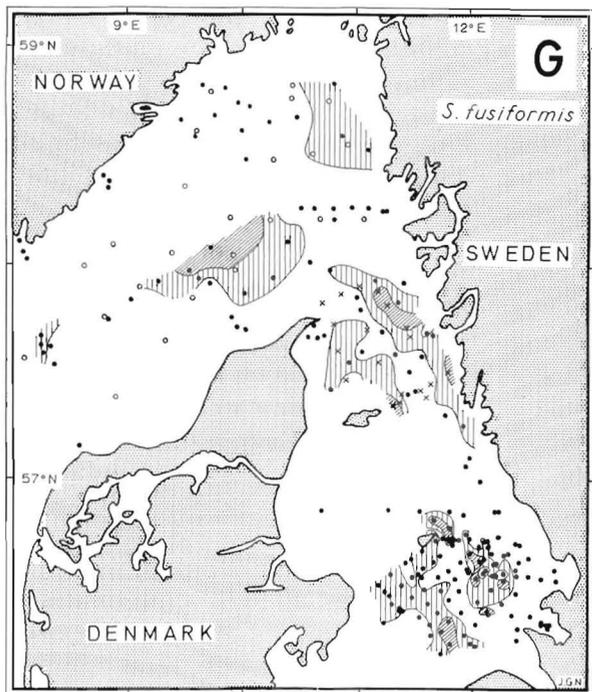
FIGURE 3. Distribution of selected benthic foraminiferal species in the Kattegat-Skagerrak area. A = *Elphidium excavatum*, B = *Eggerelloides scabrus*, C = *Bulimina marginata*, D = *Cassidulina laevigata*, E = *Bolivina skagerrakensis*, F = *Cibicides lobatulus*, G = *Stainforthia fusiformis*, H = *Nonionellina labradorica*.



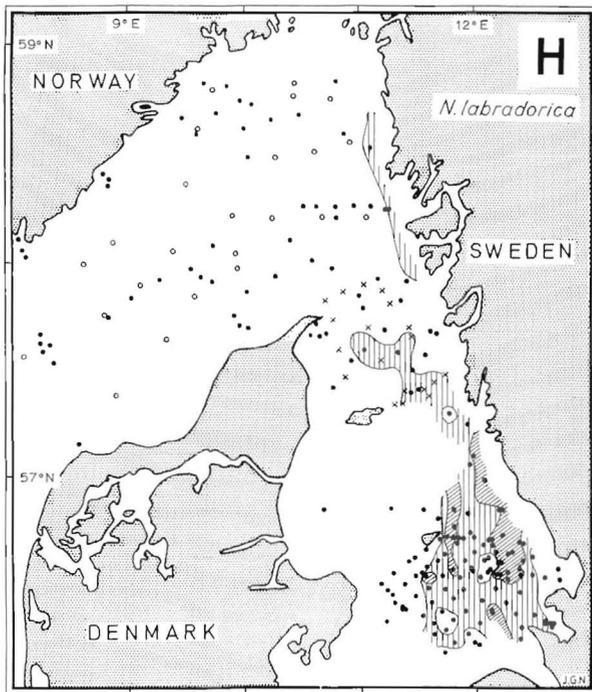
10-25% 25-50% > 50%



10-30% > 30%



5-15% > 15%



5-15% > 15%

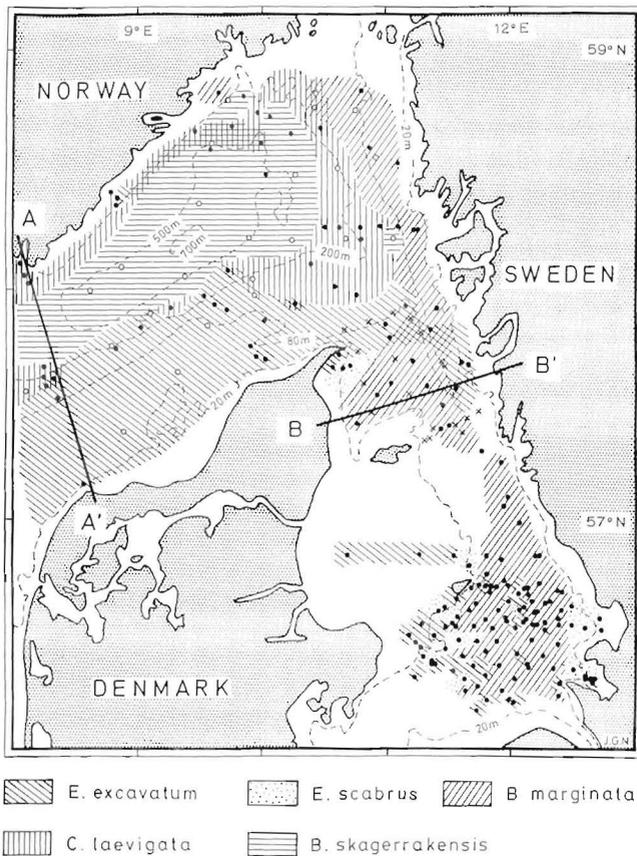


FIGURE 4. Distribution of recent benthic foraminiferal assemblages in the Kattegat-Skagerrak area.

pretations had to be based on total faunas, because most samples in the present study were unstained.

FORAMINIFERAL DISTRIBUTION

DISTRIBUTION OF ASSEMBLAGES

In this study five foraminiferal assemblages were established for the Kattegat-Skagerrak. The data matrix was reduced to four variables by factor analysis and these factors defined foraminiferal assemblages that were named after the characteristic species, *Elphidium excavatum*, *Eggerelloides scabrus*, *Bulimina marginata* and *Cassidulina laevigata*, respectively. A fifth assemblage characterized by *Bolivina skagerrakensis* was established in the central, deep Skagerrak. Our material contained only five data points from this area, but by using additional information from van Weering and Qvale (1983) and Qvale and van Weering (1985), who defined a *B. skagerrakensis* assemblage in this area, this assemblage became distinct. The geographical distribution and abundances of characteristic species are

shown in Figure 3 while the distribution of the five assemblages is shown in Figure 4. The bathymetric distribution of assemblages and hydrographic features in two transects are shown in Figure 5. Boundaries between assemblages were not sharp.

The Elphidium excavatum Assemblage. This assemblage was characterized by *E. excavatum* (21–75%) only, which is known to be an extremely tolerant, eurytopic species. In this study, the *E. excavatum* assemblage was found in two areas. In the Kattegat it was found in the marginal, shallow areas (12–30 m plus a single sample at 59 m) at a depth interval characterized by large seasonal and annual variations in salinity (20–35‰), temperature (0–16°C, occasionally below freezing point down to 40 m in the southern Kattegat) and current flow (Svansson, 1975, 1993 oral communication). These variations are both wind-induced and caused by water exchange between the Skagerrak-Kattegat and the Baltic. In the Skagerrak the assemblage was restricted to the shallow parts north and north-east of Denmark, but extended as far down as 200 m. This part of the Skagerrak is strongly influenced by inflowing North Sea water (Fig. 1) and experiences large seasonal and annual hydrographic variations (salinity 25–35.2‰, temperature 0–16°C), especially in the uppermost 50 m (Rodhe, 1987; SMHI-data base, SHARK Oceanographic Laboratory, Gothenburg). Even though erosion and non-deposition prevail in this area, Qvale and van Weering (1985) regarded *E. excavatum* as preserved *in situ* based on the well-preserved shells. Both areas of *E. excavatum* are characterized by sandy-silty substrates (van Weering, 1981; Olausson, 1975).

The Eggerelloides scabrus Assemblage. A second assemblage that occurred in areas with significant variability in salinity, temperature and current flow was the *E. scabrus* assemblage, which was found only in the Kattegat at depths of 14–35 m. This depth interval is similar to but slightly deeper than the *E. excavatum* assemblage in the Kattegat (Conradsen, 1993). *Eggerelloides scabrus* (15–81%) only characterizes the assemblage. In the northern Kattegat, the assemblage is associated with salinities of 25–35‰ and temperatures of 0–16°C (never below freezing point). In the southeastern Kattegat (salinities 20–35‰, temperatures 0–16°C, occasionally below freezing point down to 40 m) the assemblage was characteristic for water depths close to and below the halocline in hydrographic frontal areas where the saline bottom water is relatively thin and where oxygen deficiency occurs (Svansson, 1975, 1993 oral communication; Rosenberg, 1985; Rydberg, 1987; SMHI-data base). In this environment there is a sub-

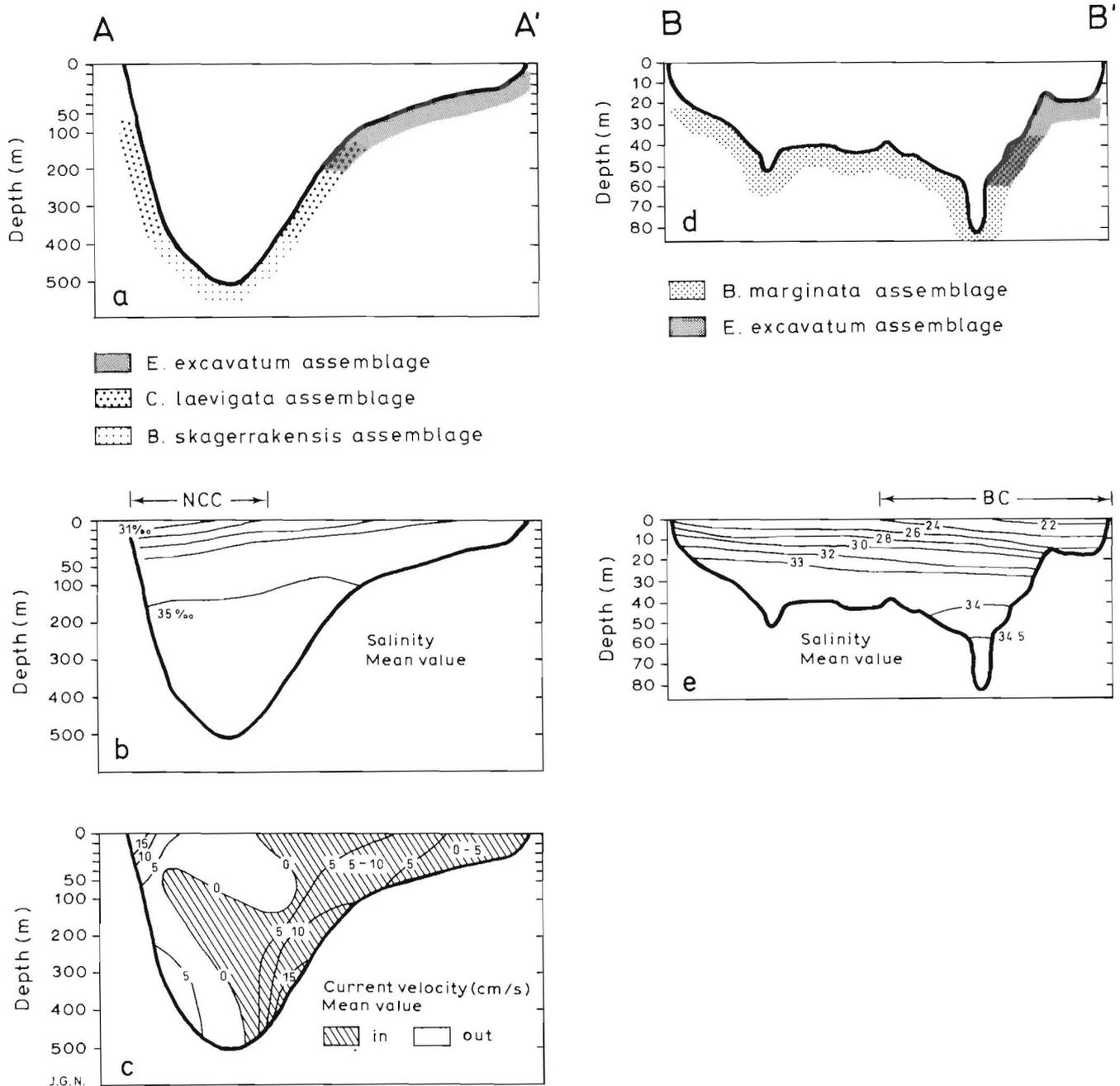


FIGURE 5. Foraminiferal assemblages and selected hydrographic features of the two transects A-A' and B-B' (Fig. 4). Sections b and c are redrawn from Rodhe (1987) and section e is redrawn from Svansson (1984). NCC = Norwegian Coastal Current, BC = Baltic Current. Note the difference in horizontal scale for the two transects. The extension of the *E. excavatum* assemblage below 30 m in section d is caused by a single sample and is not typical for the Kattegat.

stantial influx of organic-rich, sand-sized to fine grained sediments that are transported as continuous blankets or as flocks along the sea-floor (Floderus, 1989) until they settle, permanently or temporarily. The *E. scabrus* assemblage was associated with a sandy-silty substrate. In the Baltic, Lutze (1965) found *E. scabrus* connected

to inflowing water through the Danish Belts. It is also common in Scandinavian fjords along the Skagerrak coast (Höglund, 1947; Risdal, 1964).

The Bulimina marginata Assemblage. This assemblage was characterized by *B. marginata* (15–60%) and *N. labradorica* (1–29%) (Table 1). It was found in the

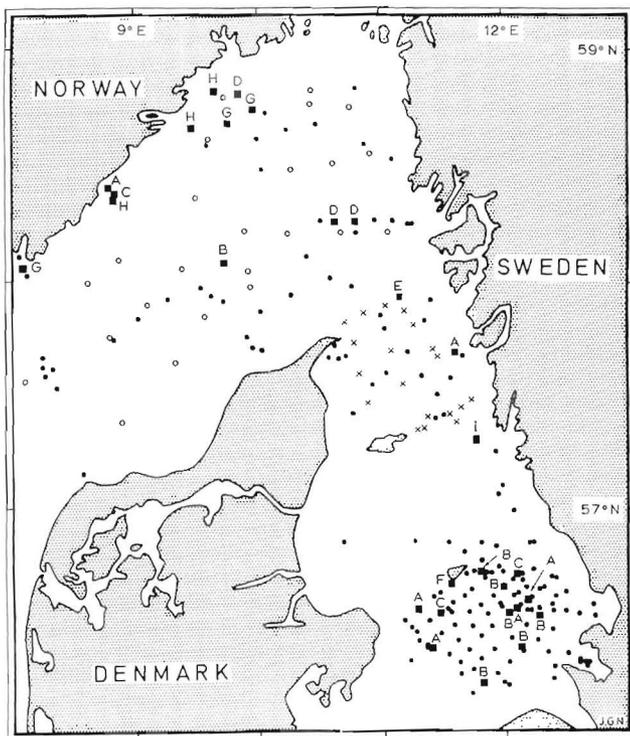


FIGURE 6. Map of study area indicating locally dominant species. A = *Cibicides lobatulus*, B = *Stainforthia fusiformis*, C = *Textularia bocki*, D = *Globobulimina turgida*, E = *Elphidium magellanicum*, F = *Elphidium williamsoni* (Haynes), G = *Melonis barleeanus*, H = *Hyalinea balthica*, I = a trochamminacean species.

deeper parts of the Kattegat below the halocline and along the Swedish coast of the Skagerrak (25–97 m). These areas display substantial variability and seasonal fluctuations in salinity (30–35‰), temperature (0–16°C) and current flows, which are indirectly associated with the Baltic Current (Fig. 1). In the Kattegat the assemblage occurred where the saline bottom water forms a thicker and more consistent layer. In this area the assemblage was associated with fine grained, organic-rich sediments (Kuijpers and others, 1989; Conradsen, 1993). In the Skagerrak the assemblage occurred at similar water depths and substrates. *B. marginata* has previously been recorded as tolerant of low oxygen levels in organic-rich sediments (e.g., Risdal, 1963). The species is also common in the adjacent Scandinavian fjords (Höglund, 1947; Risdal, 1964; Thiede and others, 1981).

The *E. excavatum*, *E. scabrus*, and *B. marginata* assemblages occurred in different areas and within different water depths but they all seem to tolerate substantial variability in salinity, temperature, and variable current flows. The two remaining assemblages both

occurred in the Skagerrak in deeper areas where bottom conditions are more stable.

The Cassidulina laevigata Assemblage. In addition to *C. laevigata* (8–55%), this assemblage was characterized by *Globobulimina turgida* (0–47%), *Hyalinea balthica* (0–46%), *Melonis barleeanus* (0–27%) and *B. skagerrakensis* (0–11%). It was found on sandy to fine grained sediments in areas bordering the deepest parts of the Skagerrak, at 80–300 m, an interval which is characterized by stable salinities around 35‰, seasonal variations in temperature (4.5–9°C) and rather high current velocities (Ljøen and Svansson, 1972; Ljøen, 1981; Rodhe, 1987; SMHI-data base). Hence the assemblage inhabits a fairly broad transitional zone below the variable surface waters and above the very stable Skagerrak deep-water.

The Bolivina skagerrakensis Assemblage. Important accessory species of this assemblage were *C. laevigata* (3–18%), *H. balthica* (3–12%), *M. barleeanus* (7–30%) and *G. turgida* (1–21%). The assemblage occupied the deepest part of the Skagerrak below ca. 300 m. Here, salinities exceed 35‰ and temperatures lie between 3° and 7°C throughout the year. This water mass is characterized by oceanic water and is not much affected by seasonal variations (Ljøen and Svansson, 1972; Svansson, 1975). The area is characterized by fine grained substrate. *B. skagerrakensis* is also common in the deep parts of the outer Oslo Fjord (Risdal, 1964; Thiede and others, 1981) where conditions are stable, and it does not appear to be very common outside the Skagerrak area (Qvale and Nigam, 1985).

When comparing the five assemblages of this study with previously established assemblages in the area, it can be seen that they generally correspond. However, van Weering and Qvale (1983) also defined an assemblage characterized by *M. barleeanus*, *G. turgida* and *H. balthica* in the Skagerrak, Conradsen (1993) defined a *S. fusiformis*, a *C. lobatulus* and a *T. bocki* assemblage in the southern Kattegat, and Seidenkrantz (1993) defined a *C. lobatulus* assemblage off the Norwegian Skagerrak coast and an assemblage characterized by a trochamminacean species in the Kattegat. In our study, focusing on the main foraminiferal assemblages, these minor assemblages are included in the five major assemblages of the area. Samples dominated by one of these species, indicating local minor assemblages, are shown in Figure 6.

Murray (1991) recognized five corresponding assemblages in his compilation of foraminiferal associations on the European seaboard (our *E. excavatum* includes *E. clavatum* and *E. excavatum* of Murray). In general, Murray's interpretation on the relation between these

assemblages and oceanography, substrate and water depths fits well with the present results, even though his amount of data from the study area was much less. However, Murray (1991) reported a different lower temperature limit of the *B. marginata* association than that found in the present study (5.5°C compared to 0°C in the Skagerrak-Kattegat). In addition, Murray's interpretation of salinity limits for the *B. skagerrakensis* assemblage does not agree with the present study.

DISTRIBUTION OF SELECTED SPECIES

Three additional species, *C. lobatulus*, *S. fusiformis* and *N. labradorica*, were selected for a more detailed description. They were all generally frequent, *C. lobatulus* and *S. fusiformis* are furthermore characteristic of minor assemblages while *N. labradorica* is stratigraphically important in the area (Nordberg and Bergsten, 1988; Nordberg, 1991; Christiansen and others, 1993). Other species in the Kattegat-Skagerrak which were abundant in more than just one sample include *G. turgida*, *M. barleeanus*, *H. balthica*, *T. bocki* and *Elphidium magellanicum* (see Fig. 6, Table 1 and description of assemblages).

Shallow, marginal areas with coarse grained sediments displayed high frequencies of *C. lobatulus* (Fig. 3F). As previously recorded, *C. lobatulus* was connected to high energy environments (e.g., Murray, 1971, 1979, 1991). Its patchy distribution can be interpreted as a response to local conditions and substrate.

Stainforthia fusiformis had also a rather patchy distribution in the Kattegat-Skagerrak region (Fig. 3G). Alve (1990) documented almost monospecific faunas of *S. fusiformis* in nearly anoxic fjord environments where organic-rich, oxygen consuming substrates characterize the sea-floor. In the Kattegat-Skagerrak this species prefers salinities exceeding ca. 30‰, which is consistent with the salinities of the oxygen depleted fjords described by Alve (1990) and Murray (1991) for the North Sea. Its distribution in the southern Skagerrak, in agreement with the findings of Collison (1980) and Conradsen (1993), suggests attachment to the high concentrations of very fine sand in this area (van Weering, 1981).

Highest frequencies of *N. labradorica* in the study area were found in the *B. marginata* assemblage (i.e., fine grained, organic rich sediments and salinities of 30–35‰). Nordberg (1989, 1991) interpreted the distribution of *N. labradorica* in the Kattegat-Skagerrak and along the Norwegian coast as dependent on continuous cooling in relatively shallow areas due to low winter temperatures and outflowing cold water from

the Baltic Sea, rivers and Norwegian Fjords during the spring. Cedhagen (1991) recorded *N. labradorica* only below 20 m in the Skagerrak and Kattegat, with highest frequencies at 30–50 m.

CONCLUSIONS

The compilation of new and previously published data on the distribution of the total foraminiferal assemblages showed that five assemblages dominated the Kattegat-Skagerrak area. These were the *Elphidium excavatum*, the *Eggerelloides scabrus*, the *Bulimina marginata*, the *Cassidulina laevigata*, and the *Bolivina skagerrakensis* assemblages. All assemblages could be related to hydrographic and sedimentological properties.

The *E. excavatum* and *E. scabrus* assemblages were characteristic of depths down to 30–35 m in the Kattegat, and the former down to a depth of approximately 200 m off the Danish Skagerrak coast. They both occurred in areas of substantial variability in temperature, salinity and current flow on sandy-silty substrates.

The *B. marginata* assemblage was found down to the deepest parts of the Kattegat, approximately 100 m, and to about the same depth off the Swedish Skagerrak coast. In these areas there are clear seasonal variations in hydrographic variables and the substrates are mostly fine grained and organic-rich.

The other two assemblages, characterized by *C. laevigata* and *B. skagerrakensis*, both occurred in the Skagerrak in areas of relatively stable bottom-water conditions. Here, the *C. laevigata* assemblage occurred in a transitional zone between approximately 100 and 300 m, between unstable, mixed upper waters and stable Skagerrak deep-water of oceanic origin. The *B. skagerrakensis* assemblage dominated the Skagerrak area below approximately 300 m.

The different assemblages of the Kattegat and the Skagerrak are clearly related to various oceanographic conditions. Through knowledge of the present foraminiferal distribution, oceanography and sediment distribution, this study offers great potential for the improvement of stratigraphic interpretations including paleoceanographical and paleoclimatological reconstructions.

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APPENDIX 1. Station names, geographic coordinates and water depths of 180 samples which provided original data for quantitative analysis.

Sample name	Latitude (°N)	Longitude (°E)	Waterdepth (m)				
2	56°29.67'	11°10.19'	18	8525	56°50.31'	11°32.95'	17
3	56°32.65'	11°16.99'	16	8526	56°51.19'	11°15.90'	13
4	56°35.44'	11°23.18'	22	8527	56°31.77'	11°33.40'	30
5	56°36.69'	11°26.05'	14	8531	56°20.75'	12°30.01'	25
6	56°39.27'	11°33.58'	18	8532	56°21.70'	12°20.00'	30
7	56°42.30'	11°40.82'	21	8534	56°22.90'	12°07.47'	30
8	56°42.82'	11°44.81'	40	8538	56°15.79'	11°37.05'	27
9	56°42.79'	11°47.47'	34	8541	56°14.00'	12°22.20'	24
10	56°42.78'	11°50.83'	40	8542	56°33.10'	11°57.38'	31
11	56°42.78'	11°57.37'	38	8543	56°32.40'	12°10.82'	46
12	56°43.02'	11°59.33'	32	8545	56°41.23'	12°07.90'	43
13	56°43.72'	11°56.79'	34	8546	56°50.75'	11°48.50'	45
15	56°45.64'	11°49.70'	50	8547	57°41.05'	11°36.50'	25
16	56°48.08'	11°40.45'	24	8602	57°40.19'	11°39.44'	26
17	56°41.24'	11°50.39'	38	8902	56°32.46'	12°11.14'	c. 42
18	56°38.21'	11°43.41'	36	8903	56°50.56'	12°12.70'	c. 35
19	56°37.08'	11°40.47'	31	9001	57°34.01'	11°33.03'	59
20	56°34.59'	11°34.99'	27	9005	58°14.92'	11°13.82'	51
21	56°32.67'	11°30.51'	27	9006	58°14.86'	11°12.11'	55
22	56°31.85'	11°28.54'	22	9007	58°15.15'	11°05.08'	82
23	56°29.44'	11°23.09'	20	9008	58°15.12'	10°56.54'	129
24	56°26.57'	11°16.41'	19	9009	58°15.08'	10°47.45'	184
25	56°27.75'	11°14.54'	17	9010	58°15.04'	10°37.41'	252
26	56°24.50'	11°18.80'	19	9011	58°15.33'	10°30.28'	300
27	56°19.25'	11°14.35'	20	9013	58°40.55'	10°28.23'	150
28	56°22.55'	11°21.92'	35	BC KB	57°25.38'	11°29.38'	67
29	56°22.77'	11°22.36'	19	BC 08	57°18.02'	11°44.37'	60
30	56°23.21'	11°21.79'	33	BC 09	57°15.16'	11°56.16'	46
31	56°25.65'	11°29.12'	23	BC 10	57°07.04'	11°58.66'	56
32	56°28.19'	11°35.27'	25	BC 11	57°03.07'	11°54.44'	49
33	56°31.00'	11°41.87'	30	BC 13	57°34.40'	11°19.67'	49
34	56°33.26'	11°47.72'	32	BC 15	57°30.50'	11°27.36'	50
35	56°36.33'	11°54.68'	29	BC 18	57°25.68'	10°45.52'	29
36	56°38.46'	11°58.81'	28	BC 19	57°32.31'	10°56.70'	33
37	56°40.58'	12°04.65'	42	BC 20	57°36.39'	11°02.06'	31
39	56°41.29'	12°06.64'	29	BC 22	57°39.81'	11°13.41'	40
40	56°43.62'	12°12.52'	39	BC 35	57°58.14'	10°45.03'	180
41	56°40.26'	12°09.14'	43	BC 48	57°49.62'	11°21.02'	66
42	56°38.75'	12°09.99'	45	BC 51	57°50.51'	10°62.30'	93
43	56°36.88'	12°05.34'	23	BC 53	57°51.99'	10°01.00'	62
44	56°36.43'	12°04.27'	23	BC 55	57°55.04'	09°41.01'	98
45	56°33.74'	11°57.59'	30	BC 56	57°57.51'	10°15.03'	80
46	56°30.93'	11°50.79'	31	BC 58	58°06.01'	10°25.10'	160
47	56°27.70'	11°43.80'	26	BC 59	57°46.75'	11°01.20'	41
48	56°24.60'	11°36.40'	26	BC 70	57°55.25'	11°24.34'	45
49	56°20.33'	11°31.35'	17	BC 80	56°33.09'	12°12.49'	53
50	56°18.18'	11°38.41'	30	BC 82	56°50.03'	12°03.67'	44
51	56°21.90'	11°41.70'	24	BC 83	56°59.53'	12°04.38'	45
52	56°25.20'	11°48.30'	29	BC 85	57°57.40'	11°09.00'	c. 75
53	56°27.99'	11°53.73'	32	BC 87	58°31.80'	11°06.30'	63
54	56°31.44'	12°01.65'	27	BC 89	58°35.75'	10°52.02'	78
56	56°32.97'	12°05.97'	20	BC 96	58°49.98'	10°47.95'	97
57	56°33.25'	12°07.01'	16	BC 100	56°17.33'	12°20.16'	27
58	56°35.32'	12°10.90'	38	BC 104	57°46.07'	08°48.47'	192
59	56°35.75'	12°11.74'	58	BC 107	57°36.85'	08°20.03'	182
60	56°38.22'	12°16.48'	38	BC 111	57°51.05'	09°00.42'	237
61	56°38.59'	12°18.15'	36	BC 112	57°53.90'	09°13.91'	219
62	56°41.54'	12°24.83'	25	BC 113	58°03.85'	09°42.79'	311
63	56°37.75'	12°29.50'	25	BC 115	58°01.00'	10°36.01'	159
64	56°36.20'	12°23.67'	30	GC 11	57°40.17'	09°56.22'	30
65	56°33.45'	12°22.60'	34	GC 14	57°41.55'	09°53.85'	46
66	56°30.75'	12°16.00'	29	GC 18	57°44.65'	09°50.07'	44
67	56°26.80'	12°21.80'	28	GC 22	57°55.37'	09°33.77'	129
68	56°24.16'	12°15.50'	32	GC 30	57°58.97'	09°27.87'	238
69	56°28.05'	12°09.60'	32	GC 39	58°22.32'	08°50.05'	89
70	56°24.90'	12°01.60'	30	GC 40	58°22.87'	08°49.13'	63
71	56°22.10'	11°54.90'	30	GC 42	58°24.25'	08°47.13'	85
72	56°19.35'	11°48.40'	20	GC 48	58°02.45'	08°06.13'	190
73	56°16.14'	11°44.63'	12	GC 52	58°04.63'	08°04.57'	c. 200
74	56°13.13'	11°59.58'	24	GC 56	58°04.93'	08°04.03'	220
75	56°12.70'	12°01.50'	24	GC 59	57°39.48'	08°18.53'	c. 200
76	56°21.27'	12°08.77'	34	GC 60	57°37.93'	08°19.43'	199
77	56°18.45'	12°02.10'	30	GC 61	57°35.67'	08°20.73'	167
78	56°15.57'	11°55.35'	27	GC 62	57°30.32'	08°23.65'	90
79	56°12.75'	11°48.70'	24	GC 71	57°08.67'	08°36.37'	23
80	56°09.88'	11°42.82'	24	PC 3-1	57°23.85'	11°25.70'	c. 65
8301	56°18.85'	12°39.09'	21	PC 10-1	58°12.01'	10°48.46'	185
8402	56°20.10'	12°29.38'	20	Skagen 7	57°42.87'	10°37.01'	14
8411	56°18.62'	12°35.95'	20	Skagen 22	57°40.10'	10°42.40'	24
8413	56°18.80'	12°35.00'	22	Skagen 27	57°40.10'	10°34.49'	13
8414	56°17.59'	12°39.00'	17	Skagen 31	57°39.34'	10°39.58'	20
8501	56°50.77'	10°40.40'	12	SK 1	58°39'	10°13'	272
8503	56°50.40'	12°12.00'	61	SK 2	58°42'	10°03'	290
8508	56°41.50'	12°21.40'	30	SK 3	58°44'	09°58'	221
8510	56°32.58'	12°22.20'	35	SK 4	58°48'	09°51'	313
8521	56°31.60'	12°43.05'	19	SK 5	58°49'	09°39'	114
8522	56°31.88'	12°35.40'	22	SK 6	58°41'	09°46'	380
8523	56°32.10'	12°29.55'	26	SK 7	58°37'	10°00'	552
8524	56°33.88'	12°42.60'	21	SK 8	58°29'	10°02'	554
				SK 9	58°35'	09°36'	533
				SK 10	58°40'	09°28'	272

RECENT BENTHIC FORAMINIFERA IN THE KATTEGAT-SKAGERRAK

APPENDIX 2. Varimax factor component matrix for 177 samples treated in the factor analysis.

Sample name	comm.	factor 1	factor 2	factor 3	factor 4						
02	0.975	0.130	0.829	-0.006	0.520	8531	0.961	0.514	0.480	0.035	0.682
03	0.406	0.029	0.414	0.125	0.467	8532	0.772	0.805	0.278	0.064	0.204
04	0.984	0.135	0.597	0.005	0.780	8534	0.562	0.500	0.532	0.135	0.106
05	0.751	0.147	0.588	0.042	0.619	8538	0.979	0.769	0.143	0.040	0.605
06	0.493	0.143	0.678	-0.001	0.115	8541	0.969	0.854	0.371	0.078	0.310
07	0.936	0.050	0.294	0.020	0.920	8542	0.951	0.952	0.167	0.116	0.057
08	0.991	0.982	0.144	0.051	0.063	8543	0.982	0.985	0.083	0.061	0.045
09	0.310	0.332	0.392	0.088	0.195	8545	0.989	0.984	0.076	0.080	0.090
10	0.950	0.943	0.096	0.139	0.181	8546	0.975	0.982	-0.070	0.065	0.047
11	0.987	0.962	0.050	0.115	0.213	8547	0.115	0.089	0.262	0.170	0.095
12	0.754	0.740	0.267	0.280	0.238	8602	0.802	0.156	0.678	0.001	0.564
13	0.948	0.949	0.190	0.097	0.047	8902	0.986	0.983	0.069	0.104	0.063
16	0.922	0.050	0.354	0.032	0.890	8903	0.981	0.979	0.140	0.055	0.032
17	0.984	0.980	0.010	0.098	0.122	9001	0.927	0.525	0.791	0.116	0.113
18	0.985	0.959	0.150	0.060	0.195	9005	0.969	0.976	0.074	0.079	0.067
19	0.946	0.874	0.237	0.087	0.343	9006	0.913	0.930	0.158	0.125	0.086
20	0.926	0.544	0.260	0.064	0.747	9007	0.935	0.677	0.230	0.148	0.634
21	0.942	0.942	0.217	0.077	0.039	9008	0.826	0.395	0.186	0.797	-0.009
22	0.148	0.075	0.267	0.155	0.215	9009	0.380	-0.028	0.021	0.615	0.010
23	0.977	0.148	0.694	0.015	0.687	9010	0.465	-0.043	-0.039	0.673	0.095
24	0.785	0.150	0.813	0.092	0.305	9011	0.878	0.153	0.017	0.924	-0.021
25	0.943	0.159	0.907	-0.013	0.309	9013	0.839	0.055	0.283	0.860	0.127
26	0.982	0.130	0.847	0.019	0.498	BC KB	0.958	0.916	0.233	0.217	0.136
27	0.952	0.166	0.878	-0.013	0.392	BC 08	0.001	0.002	0.015	0.034	0.007
28	0.823	0.474	0.452	0.109	0.619	BC 09	0.991	0.961	0.216	0.113	0.097
29	0.376	0.073	0.553	0.124	0.222	BC 10	0.981	0.971	0.173	0.080	0.047
30	0.816	0.488	0.237	0.121	0.712	BC 11	0.954	0.968	0.056	0.110	0.109
31	0.941	0.212	0.502	0.036	0.802	BC 13	0.931	0.875	-0.089	0.240	0.316
32	0.962	0.436	0.354	0.043	0.803	BC 15	0.934	0.919	0.217	0.107	0.175
33	0.982	0.906	0.253	0.038	0.311	BC 18	0.956	0.717	0.245	0.102	0.610
34	0.965	0.956	0.211	0.027	0.073	BC 19	0.948	0.778	0.247	0.106	0.520
35	0.877	0.694	0.585	0.055	0.224	BC 20	0.978	0.966	0.153	0.130	0.064
36	0.566	0.313	0.605	0.240	0.208	BC 22	0.944	0.627	0.450	0.059	0.587
37	0.972	0.971	0.126	0.073	0.086	BC 35	0.735	-0.014	0.092	0.853	-0.004
39	0.183	0.101	0.356	0.200	0.082	BC 48	0.963	0.526	0.787	0.100	0.239
40	0.996	0.989	0.109	0.067	0.024	BC 51	0.921	0.153	0.913	0.045	0.250
41	0.984	0.975	0.142	0.092	0.071	BC 53	0.955	0.279	0.915	0.160	0.119
42	0.800	0.815	0.361	0.052	0.060	BC 55	0.932	0.191	0.857	-0.005	0.400
43	0.741	0.111	0.806	0.073	0.271	BC 56	0.853	0.359	0.613	0.589	0.049
44	0.784	0.125	0.641	0.105	0.589	BC 58	0.463	0.015	0.175	0.657	0.013
45	0.974	0.866	0.441	0.097	0.140	BC 59	0.932	0.162	0.798	-0.022	0.518
46	0.985	0.968	0.195	0.081	0.053	BC 70	0.959	0.735	0.398	0.089	0.502
47	0.852	0.534	0.396	0.058	0.638	BC 80	0.882	0.909	0.105	0.132	0.164
48	0.933	0.626	0.615	0.035	0.402	BC 82	0.989	0.980	0.103	0.114	0.074
49	0.836	0.147	0.885	-0.036	0.173	BC 83	0.994	0.990	0.016	0.107	0.039
50	0.967	0.535	0.239	0.032	0.789	BC 85	0.443	0.073	0.657	0.009	0.069
51	0.954	0.118	0.797	0.004	0.551	BC 87	0.943	0.903	0.198	0.224	0.197
52	0.976	0.847	0.350	0.052	0.366	BC 89	0.825	0.581	0.577	0.231	0.318
53	0.989	0.959	0.181	0.056	0.181	BC 96	0.633	0.651	0.312	0.324	0.083
54	0.314	0.170	0.500	0.163	0.095	BC 100	0.901	0.297	0.828	-0.026	0.355
56	0.181	0.021	0.399	0.142	0.036	BC 104	0.877	0.140	0.851	0.363	0.039
58	0.324	0.373	0.307	0.287	0.093	BC 107	0.890	0.138	0.710	0.606	0.000
59	0.957	0.959	0.155	0.112	0.022	BC 111	0.913	0.173	0.713	0.612	0.022
60	0.976	0.943	0.266	0.079	0.093	BC 112	0.884	0.134	0.881	0.292	0.072
61	0.957	0.934	0.268	0.090	0.067	BC 113	0.531	0.037	0.469	0.554	0.055
62	0.985	0.766	0.408	0.041	0.479	BC 115	0.859	0.090	0.169	0.906	-0.008
63	0.976	0.227	0.243	0.016	0.930	GC 11	0.857	0.138	0.913	-0.011	0.069
64	0.807	0.696	0.531	0.010	0.200	GC 14	0.917	0.135	0.945	-0.037	0.070
65	0.978	0.922	0.324	0.077	0.129	GC 18	0.916	0.143	0.939	-0.037	0.109
66	0.134	0.171	0.310	0.054	0.077	GC 22	0.957	0.194	0.900	0.265	0.196
67	0.972	0.750	0.614	0.092	0.153	GC 30	0.923	0.119	0.869	0.391	0.031
68	0.990	0.872	0.453	0.057	0.143	GC 39	0.587	0.373	0.150	0.652	-0.003
69	0.965	0.880	0.417	0.104	0.077	GC 40	0.512	0.331	0.544	0.327	0.010
70	0.968	0.605	0.721	0.027	0.285	GC 42	0.283	0.034	0.275	0.455	0.006
71	0.962	0.934	0.283	0.087	0.043	GC 48	0.824	0.157	0.078	0.890	-0.020
72	0.845	0.174	0.855	0.061	0.282	GC 52	0.576	0.096	0.044	0.751	0.015
74	0.929	0.305	0.764	0.098	0.493	GC 56	0.832	0.151	0.346	0.822	0.113
75	0.960	0.342	0.604	0.061	0.689	GC 59	0.773	0.115	0.397	0.776	0.016
76	0.955	0.958	0.173	0.039	0.075	GC 60	0.882	0.113	0.602	0.712	0.006
77	0.990	0.967	0.099	0.103	0.187	GC 61	0.913	0.286	0.766	0.492	0.041
78	0.971	0.684	0.411	0.082	0.573	GC 62	0.729	0.247	0.799	0.171	0.038
79	0.591	0.477	0.592	0.057	0.097	GC 71	0.798	0.121	0.884	-0.037	0.040
80	0.935	0.322	0.721	0.066	0.554	PC 3-1	0.959	0.942	0.177	0.188	0.067
8301	0.973	0.187	0.114	0.009	0.962	PC 10-1	0.822	0.029	0.068	0.903	-0.036
8402	0.976	0.047	0.154	-0.003	0.975	Skagen 7	0.867	0.134	0.911	-0.042	0.130
8411	0.968	0.234	0.253	0.002	0.921	Skagen 2	0.841	0.158	0.140	0.007	0.892
8413	0.946	0.303	0.407	0.004	0.830	Skagen 27	0.915	0.126	0.912	-0.036	0.259
8414	0.903	0.114	0.811	-0.033	0.482	Skagen 31	0.922	0.114	0.172	0.012	0.938
8501	0.895	0.125	0.839	-0.039	0.416	SK 1	0.417	0.350	-0.080	0.529	0.093
8503	0.933	0.922	0.223	0.181	0.030	SK 2	0.342	0.127	-0.099	0.559	0.059
8508	0.944	0.851	0.250	0.104	0.383	SK 3	0.532	0.376	0.110	0.615	0.015
8510	0.987	0.985	0.100	0.080	0.034	SK 4	0.625	0.285	-0.064	0.730	0.087
8521	0.970	0.004	0.030	0.004	0.984	SK 5	0.711	0.556	0.102	0.626	-0.001
8522	0.943	0.084	0.445	-0.006	0.859	SK 6	0.550	0.331	-0.103	0.652	0.070
8523	0.965	0.471	0.415	0.014	0.756	SK 7	0.713	0.193	-0.037	0.821	0.009
8524	0.966	0.101	0.167	0.003	0.963	SK 8	0.223	0.041	-0.010	0.468	0.047
8525	0.906	0.115	0.933	-0.018	0.147	SK 9	0.185	0.060	-0.076	0.413	0.073
8526	0.901	0.174	0.931	-0.032	0.057	SK 10	0.469	0.247	-0.044	0.638	-0.012
8527	0.967	0.950	-0.028	0.062	0.245						
						VARIANCE	34.319	23.334	9.586	14.469	
						CUM. VAR	34.319	57.653	67.240	81.709	

APPENDIX 3. Percentage frequencies for 42 species with frequencies of at least 5% in one or more samples for 104 of the samples. Data for samples 2-80 are given in Conradsen (1993).

	<i>Astronotus gallowayi</i>	<i>Bulimina marginata</i>	<i>Cassidulina laevigata</i>	<i>Cassidulina reniforme</i>	<i>Cibicides lobatulus</i>	<i>Elphidium albuhibitacum</i>	<i>Elphidium excavatum</i>	<i>Elphidium incertum</i>	<i>Gavelinopsis praegeri</i>	<i>Globobulimina turgida</i>	<i>Hyalinea ballhica</i>	<i>Ammonia pseudospiralis</i>	<i>Asterigerinata mamilla</i>	<i>Nonionella turgida</i>	<i>Pullenia bulloides</i>
8301	0.000	8.380	0.290	0.000	0.290	2.310	10.980	0.290	0.000	0.000	0.870	0.000	0.000	0.580	0.000
8402	0.000	1.580	0.000	0.000	0.000	2.370	15.190	0.200	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8411	0.000	9.800	0.410	0.000	0.000	4.490	19.180	0.200	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8413	0.000	10.320	1.000	0.000	0.000	3.440	25.790	0.290	0.000	0.000	0.140	0.000	0.000	0.430	0.000
8414	0.000	0.000	0.000	0.000	0.000	8.640	52.780	5.250	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8501	0.000	0.000	0.000	0.000	0.000	1.730	56.710	2.160	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8503	0.000	36.620	1.620	0.000	6.820	1.800	14.360	0.000	0.000	0.360	11.850	0.000	0.000	0.180	0.000
8508	0.000	31.870	3.770	0.000	0.000	0.840	16.560	0.210	0.000	0.000	3.350	0.000	0.000	0.000	0.000
8510	0.000	52.350	1.660	0.000	0.280	1.110	12.740	0.280	0.000	0.000	3.050	0.000	0.000	0.000	0.000
8521	0.000	0.390	0.000	0.000	0.000	1.950	7.990	0.970	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8522	0.000	1.560	0.440	0.000	0.220	2.000	31.330	0.670	0.000	0.000	0.220	0.000	0.000	0.000	0.000
8523	0.000	15.920	0.370	0.000	0.190	7.680	21.720	0.000	0.000	0.000	0.560	0.000	0.000	0.000	0.000
8524	0.000	5.210	0.000	0.000	0.000	9.030	15.280	1.740	0.000	0.000	0.350	0.000	0.000	0.000	0.000
8525	0.000	0.000	0.000	0.000	5.970	2.390	48.660	0.600	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8526	0.000	2.660	0.660	1.990	1.000	0.330	69.770	1.990	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8527	0.000	46.100	1.150	0.000	0.000	6.420	4.590	0.000	0.000	0.000	0.460	0.000	0.000	0.000	0.000
8531	0.000	17.920	1.100	0.000	2.930	2.190	24.310	0.550	0.000	0.000	0.730	0.000	0.000	0.180	0.000
8532	0.000	32.410	0.930	0.000	5.250	3.700	14.810	0.000	0.000	0.000	0.930	0.000	0.000	0.000	0.000
8534	0.000	10.440	2.050	0.000	2.780	3.020	14.620	0.000	0.000	0.000	0.310	0.000	0.000	0.000	0.000
8538	0.000	14.330	0.600	0.000	2.000	2.390	13.430	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8541	0.000	35.690	3.000	0.000	0.540	1.630	23.710	0.000	0.000	0.000	1.360	0.000	0.000	0.000	0.000
8542	0.000	47.950	4.420	0.000	0.630	9.780	14.200	0.000	0.000	0.000	0.320	0.000	0.000	0.000	0.000
8543	0.000	54.100	1.370	0.000	0.550	2.730	12.300	0.000	0.000	0.000	1.370	0.000	0.000	0.000	0.000
8545	0.000	54.450	1.530	0.000	0.250	0.760	12.210	0.000	0.000	0.000	3.820	0.000	0.000	0.000	0.000
8546	0.000	59.570	0.300	0.000	0.000	0.300	2.740	0.000	0.000	0.000	3.340	0.000	0.000	0.000	0.000
8547	0.000	6.270	0.720	0.000	60.930	4.300	7.710	0.180	0.000	0.000	0.900	0.000	0.000	0.000	0.000
8602	0.000	1.950	0.000	0.650	0.650	2.600	23.380	2.600	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8902	0.000	53.770	3.770	0.000	0.000	2.010	10.800	0.000	0.000	0.000	1.260	0.750	0.000	0.000	0.000
8903	0.000	52.110	0.280	0.000	0.560	1.130	16.060	0.000	0.000	0.560	2.250	0.560	0.000	0.000	0.000
9001	0.000	17.700	5.310	0.000	0.000	0.290	36.580	0.000	0.000	0.000	1.770	0.000	0.000	0.000	0.000
9005	0.000	46.950	0.250	0.250	0.000	0.760	9.900	0.000	0.000	0.000	1.550	1.270	0.000	0.000	0.000
9006	0.000	44.100	0.840	0.000	0.000	0.000	13.760	0.000	0.000	0.000	8.430	0.000	0.000	0.000	0.000
9007	0.000	26.610	2.070	0.520	0.260	3.000	15.500	0.000	0.000	0.780	9.300	0.000	0.000	0.000	0.000
9008	0.000	18.440	35.840	0.260	0.000	0.520	9.870	0.000	0.000	1.560	18.440	0.000	0.000	0.000	0.000
9009	0.300	0.000	22.660	0.000	0.000	0.000	1.810	0.000	0.000	47.430	2.110	0.000	0.000	0.000	0.000
9010	0.000	0.000	12.100	0.000	0.640	0.000	0.320	0.000	0.000	28.660	2.230	0.000	0.000	0.000	0.000
9011	0.000	8.430	35.110	0.000	0.560	0.000	0.840	0.000	0.000	10.960	6.180	0.000	0.000	0.000	0.000
9013	0.000	2.760	36.550	0.000	0.000	1.380	9.660	0.000	0.000	8.280	6.210	0.000	0.000	0.000	0.000
BC KB	0.000	42.550	7.450	0.000	0.310	0.000	17.700	0.000	0.000	1.240	7.140	1.240	0.000	0.000	0.000
BC 08	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.310	0.000
BC 09	0.000	41.100	1.290	0.000	0.650	0.000	15.210	0.000	0.000	0.320	4.530	0.320	0.000	0.000	0.000
BC 10	0.000	47.080	1.620	0.000	0.000	0.000	16.230	0.000	0.000	0.650	2.920	0.000	0.000	0.000	0.000
BC 11	0.000	47.810	2.190	0.000	0.000	0.000	9.060	0.000	0.000	0.620	2.810	6.870	0.000	0.940	0.000
BC 13	0.000	36.880	4.610	0.000	0.000	1.060	0.350	0.000	0.000	0.710	12.060	4.960	0.000	1.770	0.000
BC 15	0.000	39.940	1.180	0.300	0.000	0.000	15.090	0.000	0.000	0.590	4.730	3.550	0.000	0.890	0.000
BC 18	0.000	24.700	0.300	0.000	0.000	0.000	12.200	0.000	0.000	0.000	5.950	0.300	0.000	1.490	0.000
BC 19	0.000	28.790	1.030	0.000	0.000	1.540	12.850	0.000	0.000	0.000	3.340	0.260	0.260	2.570	0.000
BC 20	0.000	47.910	3.540	0.000	0.640	0.000	14.790	0.000	0.000	0.960	2.870	0.800	0.000	0.000	0.000
BC 22	0.000	22.990	0.290	0.000	0.000	0.290	22.700	0.000	0.000	0.000	3.860	0.000	0.000	2.890	0.000
BC 35	0.000	0.640	19.750	0.000	0.320	0.320	0.640	0.000	0.320	13.690	2.870	0.000	0.000	2.010	0.000
BC 48	0.000	15.360	2.110	0.000	0.300	4.220	31.630	0.000	0.300	0.000	5.120	0.000	0.000	0.000	0.000
BC 51	0.000	1.560	4.370	0.620	0.310	7.500	49.370	0.000	1.250	0.000	0.940	0.000	1.250	0.310	0.000
BC 53	0.000	6.670	7.830	0.000	0.290	1.450	36.230	0.290	0.000	0.000	1.450	0.000	0.870	0.580	0.000
BC 55	0.000	2.570	15.800	1.140	2.000	1.710	34.860	0.000	2.570	0.290	0.570	0.000	0.290	0.000	0.000
BC 56	0.000	12.580	26.730	0.310	0.310	4.090	23.270	0.000	0.310	0.310	2.830	0.000	0.310	0.000	0.000
BC 58	0.000	1.290	26.220	0.260	1.290	2.310	3.080	0.510	0.510	4.880	2.830	0.260	0.000	0.000	0.000
BC 59	0.000	1.630	0.270	0.000	0.000	6.810	35.690	0.820	0.270	0.000	0.540	0.270	0.000	0.270	0.000
BC 70	0.000	36.000	26.000	0.000	0.900	1.510	20.680	0.000	0.000	0.000	4.820	0.300	0.000	0.600	0.000
BC 80	0.000	32.440	5.020	0.000	1.340	2.010	8.700	0.000	0.000	0.000	2.010	0.000	0.000	7.360	0.000
BC 82	0.000	47.950	3.770	0.340	1.030	0.680	11.640	0.000	0.000	0.000	1.370	1.370	0.000	1.260	0.000
BC 83	0.000	51.140	1.710	0.000	0.000	0.000	8.000	0.000	0.000	0.570	5.140	0.290	0.000	1.330	0.000
BC 85	0.000	0.340	1.680	0.000	0.670	0.670	28.190	0.000	0.340	0.000	0.000	0.000	0.000	0.340	0.000
BC 87	0.000	34.990	2.750	0.000	0.830	0.000	12.120	0.000	0.280	0.830	10.740	0.280	0.000	3.030	0.000
BC 89	0.000	16.930	3.760	0.310	0.000	0.310	21.940	0.000	0.000	0.310	11.290	0.310	0.000	9.720	0.000
BC 96	0.000	19.090	7.580	0.000	0.910	0.000	9.700	0.000	0.000	2.420	2.420	0.000	0.000	17.270	0.000
BC 100	0.000	8.250	0.000	0.000	0.330	0.000	51.160	0.000	0.000	0.000	0.000	0.330	0.000	1.650	0.000
BC 104	0.320	1.940	16.500	0.320	1.940	0.970	32.360	0.000	6.470	0.320	0.970	0.000	0.650	0.000	0.000
BC 107	0.000	3.510	27.490	1.170	4.390	0.290	28.360	0.000	0.000	0.880	2.630	0.000	0.000	0.000	0.000
BC 111	0.280	3.590	20.370	0.000	2.840	1.130	15.260	0.000	1.130	0.000	1.700	0.000	0.000	2.740	0.000
BC 112	0.320	0.950	11.990	0.320	1.260	1.890	30.280	0.000	4.730	1.590	0.320	0.000	0.570	0.280	0.000
BC 113	0.000	0.320	16.500	0.650	0.970	0.320	8.410	0.000	2.910	0.650	2.590	0.000	0.000	0.320	0.000
BC 115	0.000	3.880	29.770	0.000	0.000	1.620	3.880	0.000	0.320	7.120	7.770	0.000	0.320	0.000	0.000
GC 11	0.000														

RECENT BENTHIC FORAMINIFERA IN THE KATTEGAT-SKAGERRAK

APPENDIX 3. Continued.

	<i>Fullenia osloensis</i>	<i>Quinqueloculina seminulum</i>	<i>Quinqueloculina stalkerii</i>	<i>Textularia bocki</i>	<i>Textularia eurlandi</i>	<i>Trifarina angulosa</i>	<i>Cibicides kosterensis</i>	<i>Uvigerina peregrina</i>	<i>Stainforthia fusiformis</i>	<i>Cibicides jeffreysi</i>	<i>Trochamminaean species</i>	<i>Elphidium genitum</i>	<i>Reophax fusiformis</i>	<i>Elphidium magellanicum</i>	<i>Reophax subfusiformis</i>
8301	0.000	0.290	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.180	0.000
8402	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.170	0.000
8411	0.000	0.200	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8413	0.000	0.140	0.000	0.000	0.000	0.000	0.000	0.000	0.140	0.000	0.000	0.000	0.000	1.290	0.000
8414	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8501	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8503	0.000	0.180	0.000	4.490	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.070	0.000
8508	0.000	0.000	0.000	0.210	0.000	0.000	0.000	0.180	0.000	0.000	0.000	0.000	0.000	0.180	0.000
8510	0.000	0.280	0.000	1.110	0.000	0.000	0.000	0.550	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8521	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8522	0.000	2.220	0.220	0.220	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.330	0.000	3.110	0.000
8523	0.000	0.000	0.190	0.000	0.000	0.000	0.000	0.000	2.250	0.000	0.000	0.000	0.000	0.190	0.000
8524	0.000	0.000	1.040	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.740	0.000
8525	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	18.210	0.000
8526	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.330	2.090	0.000	0.000	0.300	0.000	1.990	0.000
8527	0.000	0.000	0.000	0.460	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.330	0.000	0.690	0.460
8531	0.000	0.180	0.000	0.000	0.000	0.000	0.000	1.380	0.000	0.000	0.000	0.000	0.000	2.930	0.000
8532	0.000	0.000	0.000	0.930	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8534	0.000	0.930	0.000	2.320	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8538	0.000	0.000	0.000	0.000	0.000	0.000	0.000	22.970	0.000	0.000	0.000	0.000	0.000	1.160	0.460
8541	0.000	0.270	0.000	0.000	0.000	0.000	0.000	0.900	0.000	0.000	0.000	0.000	0.000	0.600	0.600
8542	0.000	0.000	0.000	1.580	0.000	0.000	0.000	0.270	0.000	0.000	0.000	0.000	0.000	1.260	0.000
8543	0.000	0.000	0.000	0.270	0.000	0.000	0.000	0.270	0.000	0.000	0.000	0.000	0.000	0.820	0.000
8545	0.000	0.250	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8546	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8547	0.000	0.180	0.000	2.870	0.000	0.000	0.000	0.300	0.000	0.000	0.000	0.000	0.000	0.610	0.000
8602	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.180	0.000	0.000	0.000	0.000	0.000	1.610	0.000
8603	0.000	0.000	0.000	0.000	0.000	0.000	0.000	11.040	0.000	0.000	0.000	0.000	0.000	11.690	0.000
8902	0.000	0.000	0.000	0.000	0.250	0.000	0.000	0.000	1.270	0.000	0.000	0.000	0.000	0.500	0.000
8903	0.000	0.000	0.000	0.560	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.280
9001	0.000	1.180	0.000	0.290	0.000	0.000	0.000	0.880	3.240	0.000	0.000	0.000	0.000	0.590	0.000
9005	0.000	0.000	0.000	2.280	0.000	0.000	0.000	0.000	0.510	0.000	0.000	0.000	0.000	0.000	0.000
9006	0.000	0.000	0.000	2.250	0.000	0.000	0.000	3.090	0.560	0.000	0.000	0.000	0.000	0.280	0.000
9007	0.000	0.260	0.000	3.620	0.260	0.260	0.000	0.780	0.260	0.000	0.000	0.000	0.000	0.000	0.000
9008	0.000	1.300	0.000	0.520	0.260	0.000	0.000	0.780	0.260	0.000	0.000	0.260	0.000	1.820	0.000
9009	0.000	0.600	0.000	0.000	0.000	0.300	0.000	2.110	0.600	0.000	0.000	0.000	0.000	0.600	0.000
9010	0.000	0.960	0.000	0.000	0.000	1.910	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.320
9011	0.000	0.560	0.000	0.000	0.000	0.560	0.000	0.000	0.280	0.000	0.000	0.000	0.000	0.000	0.000
9013	0.000	0.690	0.690	0.000	0.000	0.000	0.000	0.690	3.450	0.000	0.000	0.690	0.000	6.900	0.000
BC 02	0.000	0.310	0.000	0.930	0.310	0.000	0.000	0.930	0.310	0.000	0.000	0.000	0.000	0.000	0.310
BC 08	0.000	0.000	0.000	0.000	2.760	7.640	10.420	0.000	0.000	0.000	38.190	0.000	0.000	0.350	4.860
BC 09	0.000	0.320	0.320	1.290	2.590	0.000	0.000	0.320	5.900	0.000	0.000	0.000	0.000	0.970	0.320
BC 10	0.000	1.300	0.000	0.650	0.000	0.000	0.000	0.320	1.950	0.000	0.000	0.000	0.000	0.320	0.320
BC 11	0.000	0.310	0.000	0.940	0.000	0.000	0.000	0.310	0.000	0.000	0.000	0.000	0.000	0.310	1.560
BC 13	0.000	0.710	0.000	2.130	1.060	0.000	0.000	0.000	3.550	0.000	0.000	0.000	0.350	0.350	0.000
BC 15	0.300	0.000	0.000	2.370	0.590	0.000	0.000	0.000	1.480	0.000	0.000	0.000	0.000	1.180	0.300
BC 18	0.000	0.000	0.300	2.680	0.300	0.000	0.000	0.890	5.650	0.000	0.000	0.000	0.000	4.170	0.300
BC 19	0.000	0.000	0.000	4.370	0.260	0.000	0.000	0.000	5.680	0.000	0.000	0.000	0.260	1.030	0.260
BC 20	0.000	0.320	0.640	0.320	0.000	0.000	0.000	0.000	1.290	1.930	0.000	0.000	0.000	0.320	0.320
BC 22	0.290	0.290	0.000	5.460	0.290	0.000	0.000	0.000	2.300	0.000	0.000	0.290	0.000	1.720	0.290
BC 35	5.100	1.270	0.000	0.000	6.690	0.000	0.000	0.960	5.100	0.000	0.000	0.000	0.000	0.320	17.900
BC 48	0.900	0.000	0.000	0.600	5.120	0.000	0.000	0.000	8.730	0.000	0.000	1.200	0.000	3.920	0.000
BC 51	0.000	0.310	0.310	0.000	1.560	0.000	0.000	0.000	1.870	0.620	0.000	1.870	0.310	3.130	0.940
BC 53	0.000	0.000	0.000	0.290	3.190	0.000	0.290	0.000	8.120	0.000	0.000	1.160	0.000	7.830	0.580
BC 54	0.000	0.000	0.000	0.000	0.570	0.000	0.000	0.000	2.000	0.290	0.000	0.290	0.000	0.290	0.290
BC 56	0.310	1.260	0.000	0.000	3.460	0.000	0.000	0.000	6.920	0.000	0.000	0.310	0.000	0.630	0.310
BC 58	1.540	0.770	0.510	0.000	3.080	0.000	0.000	0.000	10.800	0.000	0.000	0.510	0.000	25.190	0.000
BC 59	0.000	0.820	0.000	0.000	5.180	0.000	0.270	0.000	0.820	0.000	0.000	1.360	0.270	5.180	0.820
BC 70	0.300	0.000	0.000	4.220	1.200	0.000	0.000	0.300	1.510	0.000	0.000	0.000	0.900	1.510	0.300
BC 80	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	1.670	0.000	0.000	0.000	0.000	0.330	1.000
BC 82	0.000	0.340	0.000	0.340	7.530	0.000	0.000	0.000	1.370	0.000	0.000	0.000	0.340	0.680	0.000
BC 83	0.000	0.290	0.000	1.430	0.000	0.000	0.000	1.140	0.000	0.000	0.000	0.000	0.570	0.570	0.290
BC 85	0.000	0.670	0.340	0.000	0.000	0.000	0.000	0.000	2.010	1.340	0.000	6.710	0.340	40.940	0.000
BC 87	0.280	0.000	0.000	1.930	0.280	0.000	0.000	1.100	8.540	0.000	0.000	0.000	0.000	0.280	0.550
BC 89	1.050	0.000	0.000	0.000	0.000	0.000	0.000	0.000	10.340	0.000	0.000	0.310	0.310	1.570	0.000
BC 95	3.940	0.300	0.300	0.610	0.910	0.000	0.000	0.610	14.240	0.000	0.000	0.610	0.610	0.910	0.000
BC 100	0.000	0.000	0.000	0.000	0.330	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
BC 104	0.650	1.940	0.320	9.060	0.650	0.320	0.000	0.970	0.000	0.320	0.000	0.320	0.650	0.650	0.320
BC 107	0.580	0.290	0.290	6.730	0.580	0.880	0.880	2.340	2.050	0.000	0.000	0.580	0.000	0.000	0.290
BC 111	1.990	0.280	0.000	4.830	0.280	0.570	0.000	1.420	6.530	0.280	0.000	0.850	1.140	1.420	0.280
BC 112	0.630	0.320	0.320	9.150	0.320	0.320	0.000	0.950	0.950	0.320	0.000	0.630	1.890	0.320	0.950
BC 113	1.620	0.320	0.970	1.290	2.270	0.000	2.270	0.320	22.010	2.270	0.000	0.970	5.500	2.910	0.650
BC 115	1.290	0.970	0.000	0.650	2.590	0.320	0.320	2.270	3.560	0.000	0.000	0.000	2.590	1.620	

APPENDIX 3. Continued.

	<i>Vernicilia media</i>	<i>Eggerelloides scabrus</i>	<i>Haynesia germanica</i>	<i>Haynesia depressula</i>	<i>Armonia beccarii</i>	<i>Bulimicella elegantissima</i>	<i>Nonionellina labradortica</i>	<i>Planorbulina distoma</i>	<i>Melonis bartkeanus</i>	<i>Liebusella goëti</i>	<i>Bolivina skagensensis</i>	Other species	Specimens per 100 g.	Number of species
8301	0.000	56.360	0.000	0.000	7.230	0.000	7.510	0.000	0.000	0.000	0.000	1.450	7486	18
8402	0.000	66.860	1.780	0.000	7.300	0.000	1.380	0.000	0.000	0.000	0.000	0.990	4803	13
8411	0.000	51.020	0.000	0.000	8.370	0.000	6.330	0.000	0.000	0.000	0.000	0.000	7603	9
8413	0.000	41.400	0.000	0.000	4.730	0.000	9.740	0.000	0.000	0.000	0.000	1.150	6843	18
8414	0.000	25.930	2.780	0.000	3.400	0.000	0.310	0.000	0.000	0.000	0.000	0.930	3356	10
8501	0.000	22.510	0.000	0.870	14.290	0.000	0.000	0.000	0.000	0.000	0.260	1.080	4892	9
8503	0.000	0.000	0.000	0.000	5.030	0.000	13.640	0.000	1.260	0.000	0.000	0.870	183	1
8508	0.000	15.720	0.000	0.000	7.550	0.000	17.400	0.000	0.000	0.000	0.000	2.310	6195	25
8510	0.000	0.550	0.000	0.000	7.200	0.000	15.790	0.000	0.280	0.000	0.000	2.770	2976	20
8521	0.000	80.900	0.000	0.000	1.750	0.190	0.190	0.000	0.000	0.000	0.000	5.650	1060	12
8522	0.000	50.440	0.890	0.000	1.560	0.000	0.890	0.000	0.000	0.000	0.000	2.670	914	19
8523	0.000	30.520	0.000	0.000	7.870	0.000	8.240	0.000	0.000	0.000	0.000	3.370	2960	19
8524	0.000	60.760	0.000	0.000	1.040	1.040	1.390	0.000	0.000	0.000	0.000	1.390	?	13
8525	0.000	4.480	2.090	6.870	2.390	5.370	0.000	0.000	0.000	0.000	0.000	0.600	1201	14
8526	0.000	0.000	0.000	0.000	10.960	0.330	0.660	0.000	0.000	0.000	0.000	4.980	383	22
8527	0.000	11.000	0.000	0.000	1.830	0.690	19.270	0.000	0.000	0.000	0.000	4.590	4545	18
8531	0.000	27.060	0.000	0.000	8.590	0.000	6.330	0.000	0.000	0.000	0.000	5.300	3077	21
8532	0.000	5.560	0.000	0.000	23.770	0.000	7.410	0.000	0.620	0.000	0.000	3.400	3314	19
8534	0.000	0.930	0.000	0.930	2.780	2.550	16.010	0.000	0.000	0.000	0.000	14.620	231	26
8538	0.000	28.360	0.000	0.000	2.990	0.000	11.040	0.000	0.000	0.000	0.000	4.780	2070	15
8541	0.000	13.080	0.000	0.000	6.540	0.000	11.720	0.000	0.000	0.000	0.000	2.180	2579	18
8542	0.000	1.260	0.000	0.000	3.470	0.000	10.090	0.000	0.000	0.000	0.000	3.470	2210	18
8543	0.000	1.640	0.000	0.000	2.730	0.000	21.310	0.000	0.000	0.000	0.000	0.550	9746	14
8545	0.000	4.070	0.000	0.000	6.110	0.000	15.520	0.000	0.000	0.000	0.000	1.020	5895	14
8546	0.000	1.520	0.000	0.000	11.550	0.000	17.930	0.000	0.300	0.000	0.300	1.220	3701	14
8547	0.000	3.570	0.000	0.000	7.030	0.000	0.360	0.360	0.260	0.000	0.000	1.610	8370	23
8602	0.000	17.530	0.000	0.000	18.830	0.000	0.850	0.000	0.000	0.000	0.000	3.250	2118	16
8902	0.000	2.760	0.000	0.000	1.760	0.000	16.582	0.000	0.000	0.000	0.000	2.510	1897	15
8903	0.000	0.850	0.060	0.000	1.970	0.000	20.850	0.000	1.130	0.000	0.000	0.850	13279	16
9001	5.900	2.950	0.000	0.000	2.360	0.000	1.470	0.000	0.000	5.010	0.000	14.450	11948	23
9005	9.900	2.030	0.000	0.000	6.600	0.000	7.360	0.000	0.000	0.000	0.510	7.870	1718	19
9006	6.180	2.530	0.000	0.000	8.990	0.000	2.250	0.000	0.280	0.000	0.000	6.460	12905	17
9007	0.000	26.100	0.000	0.260	4.910	0.000	4.390	0.000	0.000	2.840	0.000	1.030	6450	21
9008	1.040	0.520	0.000	0.000	0.000	0.000	1.820	0.000	0.260	1.040	3.380	1.820	?	26
9009	6.040	0.000	0.000	0.000	0.000	0.000	2.420	0.000	1.510	4.830	2.720	3.930	1194	19
9010	8.900	2.550	0.000	0.000	0.000	0.000	0.000	0.000	17.520	9.240	3.410	8.600	1536	25
9011	4.780	0.000	0.000	0.280	0.000	0.000	0.600	0.000	2.250	6.460	10.960	8.710	11752	23
9013	0.690	5.520	0.000	0.000	0.690	0.000	1.380	0.000	2.760	0.000	4.140	6.800	5100	26
BC KB	0.000	5.590	0.000	0.000	4.970	0.000	6.210	0.000	0.000	0.620	0.000	1.550	6469	23
BC 08	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.350	0.000	0.000	35.420	2160	27
BC 09	0.000	3.240	0.000	0.000	1.620	0.000	10.680	0.000	0.320	0.000	0.970	5.180	6208	33
BC 10	0.000	1.620	0.000	0.000	1.300	0.000	19.480	0.000	0.320	0.320	0.320	3.250	2772	21
BC 11	0.000	4.060	0.000	0.000	9.690	0.000	8.440	0.000	0.620	0.310	0.940	1.880	36000	21
BC 13	0.000	12.410	0.000	0.000	8.870	0.000	5.670	0.000	0.000	0.000	0.000	2.480	15862	21
BC 15	0.000	5.920	0.000	0.000	12.130	0.000	5.030	0.000	0.590	0.000	0.590	2.370	19012	27
BC 18	0.000	21.130	0.000	0.000	8.630	0.600	4.460	0.000	0.000	0.000	0.000	6.250	26526	26
BC 19	0.000	18.850	0.000	0.000	7.030	0.260	3.340	0.000	0.000	0.000	0.000	4.110	26127	25
BC 20	1.290	2.570	0.000	0.000	0.960	0.000	8.680	0.000	0.000	0.000	0.000	6.750	15804	26
BC 22	0.000	22.410	0.000	0.570	6.900	0.290	1.720	0.000	0.000	0.000	0.000	5.170	11186	27
BC 35	1.910	0.000	0.000	0.000	0.000	0.000	0.640	0.000	0.960	12.100	0.320	8.210	1956	30
BC 40	0.000	6.330	0.000	0.000	4.520	0.000	3.010	0.000	0.000	0.000	0.000	4.820	7781	22
BC 51	0.000	10.000	0.000	0.310	2.810	0.000	0.310	0.000	0.000	0.310	0.620	7.190	12000	41
BC 53	2.320	2.030	0.870	2.320	6.090	1.160	0.290	0.000	0.000	0.000	0.000	7.830	5750	32
BC 55	0.000	13.140	0.000	1.140	4.570	0.570	0.860	0.000	0.000	0.290	0.290	13.060	8725	47
BC 56	0.310	0.940	0.000	0.310	3.770	0.940	0.310	0.000	0.000	0.000	0.310	8.810	3975	43
BC 58	1.290	0.260	0.000	0.000	0.510	0.510	0.260	0.000	0.260	1.290	0.510	6.940	3501	46
BC 59	0.000	19.070	0.000	1.090	9.810	0.270	1.170	0.000	0.000	0.000	0.000	7.080	11010	37
BC 70	0.000	18.370	0.000	0.000	7.830	0.000	4.520	0.000	0.300	0.000	0.000	2.710	15884	29
BC 80	1.670	6.690	0.000	0.000	0.330	0.000	23.410	0.000	0.000	0.330	0.000	2.680	2691	23
BC 82	0.000	3.080	0.000	0.000	2.050	0.000	13.010	0.000	0.000	0.000	0.340	0.000	6317	19
BC 83	0.000	1.430	0.000	0.000	3.140	0.000	18.000	0.000	1.140	0.290	0.570	2.860	17500	27
BC 85	0.000	0.340	0.000	1.340	2.350	0.000	0.340	0.000	0.000	0.000	0.340	10.400	5004	37
BC 87	0.000	6.610	0.000	0.000	3.310	0.000	5.510	0.000	0.830	0.000	1.380	3.580	33337	28
BC 89	0.000	9.400	0.310	0.310	1.880	0.000	0.630	0.000	0.000	0.000	0.000	6.270	21267	33
BC 96	3.330	1.210	0.000	0.000	1.210	0.000	2.420	0.000	0.300	0.610	2.420	6.670	8115	33
BC 100	0.000	17.490	0.000	0.000	1.980	0.660	7.260	0.000	0.000	0.000	0.000	3.300	2525	16
BC 104	1.940	0.970	0.000	0.320	0.970	0.320	0.000	3.880	0.320	1.620	0.320	10.360	6952	53
BC 107	1.460	0.000	0.000	0.000	0.290	0.000	0.290	0.000	2.340	0.290	1.750	7.600	51300	43
BC 111	6.930	1.820	0.000	0.280	1.990	0.000	1.990	0.000	0.850	1.420	0.850	7.390	15800	53
BC 112	7.570	1.260	0.000	0.320	4.730	0.320	0.320	1.260	0.000	2.840	0.000	9.460	14265	56
BC 113	1.290	0.000	0.000	0.320	0.970	0.970	0.000	1.940	0.000	0.000	0.000	17.480	9932	49
BC 115	2.300	0.000	0.000	0.320	1.290	0.320	0.320	0.000	0.970	3.240	2.590	7.770	2897	38
GC 11	0.000	0.000	0.000	0.660	13.910	0.000	0.000	0.000	0.000	0.000	0.000	3.310	686	13
GC 14	0.000	1.150	0.000	0.580	4.320	0.860	0.000	2.310	0.000	0.000	0.000	3.750	15934	25
GC 18	0.000	3.670	0.000	2.200	6.360	0.490	0.000	2.200	0.000	0.000	0.000	3.670	23006	18
GC 22	0.000	3.730	0.310	1.240	4.970	0.310	0.310	1.240	0.000	0.310	0.310	9.010	13417	45
GC 30	1.590	0.000	0.000	1.590	0.960	0.640	0.320	2.870	0.320	0.320	0.000	11.710	11004	49
GC 39	0.000	0.000	0.000	0.000	0.630	0.000	0.310	0.000	9.120	0.000	0.310	4.090	17887	29
GC 40	0.000	0.000	0.000	0.000	0.000	0.000	4.170	0.000	3.870	0.000	0.300	4.170	4667	26
GC 42	0.000	0.000	0.000	0.000	0.000	0.000	1.220	0.000	6.420	0.000				

SUMMER AND WINTER DISTRIBUTION OF FORAMINIFERA IN TOMALES BAY, NORTHERN CALIFORNIA

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ABSTRACT

Summer and winter distribution of foraminifera are similar in Tomales Bay, a long narrow embayment, 64 km north of San Francisco, California. Using three different numerical techniques (cluster analysis, multiple discriminant analysis, and multidimensional scaling), three groups of foraminifera were distinguished. One group including *Glabratella ornatissima*, *Rotobinella campanulata*, and *Cribronion lene* characterizes the nearshore turbulent zone near the mouth of the bay, an area of direct marine influence in which wind-driven waves impinge upon the shoreline. Two estuarine groups occupy the bay proper: a middle bay group is composed of *Bulimina denudata*, *Fursenkoina pontoni*, *Hopkinsina pacifica*, *Nonionella basispinatus*, *N. stella*, *Quinqueloculina ackneriana*, and several species of *Brizalina*; and a group at each end of the bay is composed of *Buliminella elegantissima*, *Buccella tennerrima*, *Elphidiella hannai*, and other less common species. Nearshore turbulent conditions at the northern mouth of the bay grade to estuarine conditions towards

the south. Several of the species present in the middle bay group are more characteristic of warmer waters found in southern California and Baja California; these may represent a relict fauna from a time of warmer coastal waters or incursions of species brought by El Niño conditions. In contrast, most species found in the rest of the bay are typical of the colder-water Oregonian Province that reaches from Point Conception in the south to Vancouver Island in the north. The only apparent environmental factor that distinguishes the middle bay from the bay ends is the fine-grained sediment size of the middle bay region.

Summer and winter samples showed similar foraminiferal composition and abundance, except in some stations where certain species dominate at one season or the other. The winter middle bay is dominated by *Hopkinsina pacifica* and *Bulimina denudata*. *Glabratella ornatissima* dominated the summer samples in the northernmost turbulent zone at the mouth of the bay.

INTRODUCTION

Foraminiferal distributions along the northern central California coast are known from areas with strong fluvial influence (Erskian and Lipps, 1977; Arnal and others, 1980) or areas clearly within the oceanic environment (Quinterno and Gardner, 1987). These two environments have very different foraminiferal faunas. Tomales Bay provides a distinct type of environment, with little direct marine or fluvial influence, unlike those previously described for foraminifera in central and northern California.

Herein we describe the summer and winter distribution of living benthic foraminifera in Tomales Bay. We used multiple discriminant analysis, multidimensional scaling, and cluster analysis to distinguish unique faunal elements and their distributions and abundances.

TOMALES BAY

Tomales Bay (Fig. 1), 64 km north of San Francisco, is a relatively large, long and narrow, protected estuary (see Table 1; Fig. 2). Most of the bay is roughly sym-

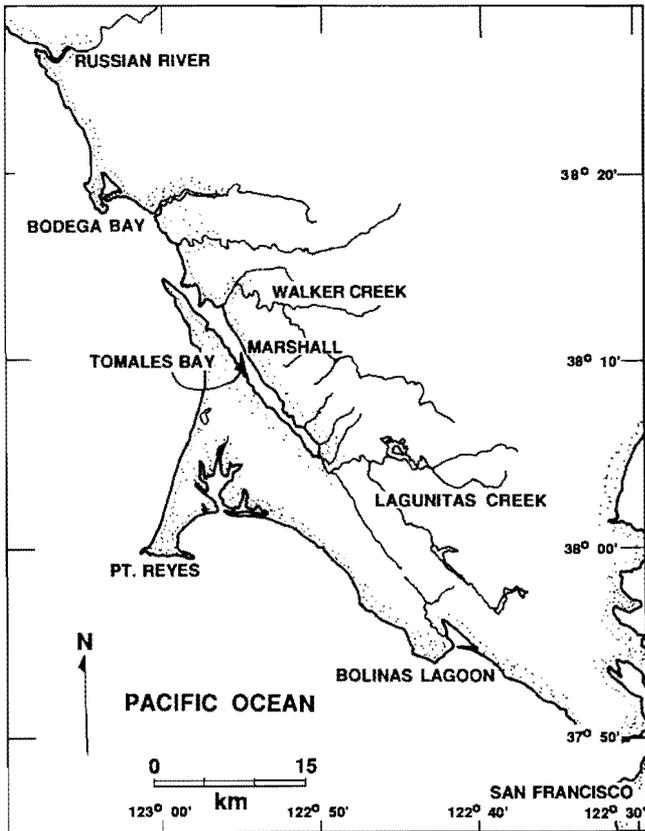


FIGURE 1. Location of Tomales Bay, Marin County, California, with other localities noted in the text.

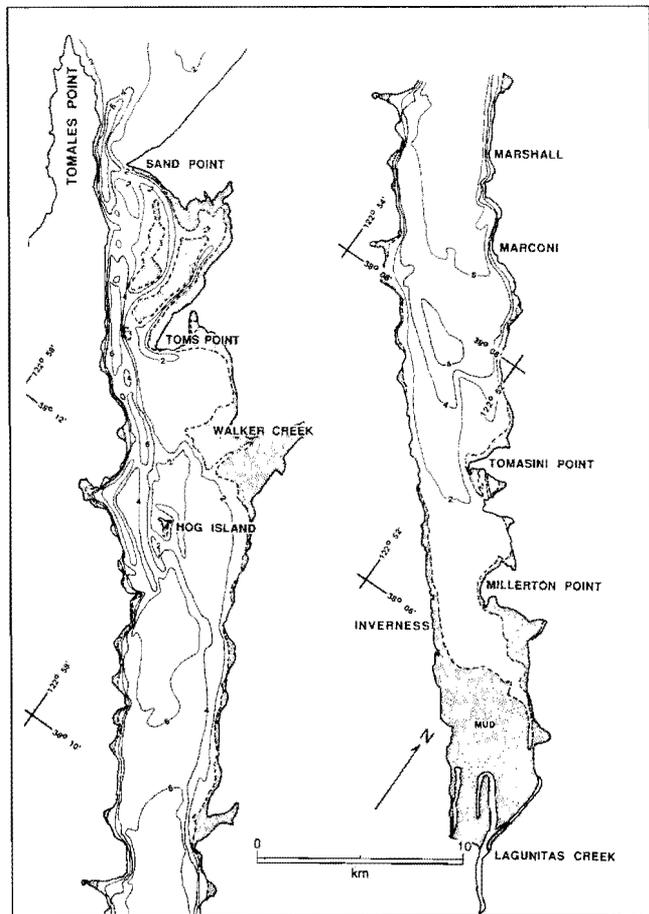


FIGURE 2. Bathymetry and place names of Tomales Bay. Depths shown in meters. Northwestern half of Tomales Bay is on the left, southeastern half on the right.

metrical about its long axis and its floor is relatively flat (Fig. 2). The mouth of the bay shoals to about 3 m near Sand Point. Tidal channels in this area reach depths of about 12 m, and to the southwest, the main tidal channel splits, with the deepest channel running along the southwest shore and subsidiary channels dissecting shoals between Sand Point and Toms Point. South of this area, the bathymetry is markedly asymmetrical, with a deep channel continuing along the southwest shore to just south of Hog Island; this channel reaches its greatest depth (18.6 m) southwest of Toms Point.

The surface sediments of Tomales Bay (Daetwyler, 1966) generally decrease in grain size to the south east (Fig. 3). In the Sand Point-Toms Point area, sediment size is greater in the tidal channels than in the adjacent shoals. To the southwest of Toms Point grain size increases. A shoal northwest of Tomasini Point has a coarser median grain size than the surrounding area. Locally-derived sediments produce small areas of coarser beaches. Daetwyler (1966) noted structureless sediments south of the area of tidal action. The ho-

mogeneous nature of these sediments could be due to bioturbation which may have a significant effect on the benthic foraminifera (Lipps, 1983).

The general conditions of Tomales Bay are listed in Table 1. Occasionally, a major storm may hit the Tomales Bay region. Such a storm hit January 3-5, 1982 (see Ellis and Wiczorek, 1988) just 20 days before our winter collections were made. Weather conditions can vary over a rather short distance. Daetwyler (1966) noted that a difference of 11°C between the north and south ends of the bay during a summer day is common.

Tomales Bay is a large body of water with restricted oceanic and fluvial influence. Thus, the oceanographic conditions do not necessarily correspond closely to the prevailing conditions of the open waters near the bay. Moreover, because there is little fluvial influence, conditions in the bay are not necessarily similar to those of other estuarine environments in which freshwater influence is more prevalent.

The bay has a temperature stratification of only 2–3°C, which suggests good vertical mixing, and probably well oxygenated water at the sediment surface. Likewise, salinity stratification is absent during the summer; in winter only minor stratification occurs in the middle and upper bay due to runoff. In general, good tidal action and limited runoff combine to produce an unstratified estuary. Tomales Bay has mixed, semi-diurnal tides, with two unequal high and low tides in each 25 hour period (Table 1). The tides lag about one hour between the ends of the bay. The swell along the coast in the Tomales Bay region is over 80% from the west, west-northwest, or northwest (Cherry, 1965), but within the bay, wind-induced water movement is minor compared with tidal effects (Daetwyler, 1966). Thus, tides are the primary agents of sediment movement in the bay (Johnson and others, 1961); they are greatest northwest of Hog Island and decrease to the south, but can still move sediments south of there (Daetwyler, 1966).

In September and October, 1985, dissolved C and fixed N were imported into the bay hydrographically, while Si and P were exported (Smith and others, 1987). The bay system was net heterotrophic by 8% (Smith and others, 1989); the organic material responsible for this heterotrophy may have been either terrestrial or marine in origin (Dollar and others, 1991; Smith, 1991). Most of the nutrient flux to the bay comes through mixing at its mouth or, for N₂, across the air-water interface over the entire bay (Oberdorfer and others, 1990). Ground water and stream flow contribute significantly to the terrestrial nutrient and freshwater load to the bay; in the summer months these two are about equal in their contributions, but groundwater is only 20% of streamflow in the winter (Oberdorfer and others, 1990).

PREVIOUS FORAMINIFERAL WORK

The distribution of foraminifera along the west coast of North America has been described several times. Bandy (1953) examined three transects across the California shelf, including one transect off San Francisco that included San Francisco Bay. He reported a brackish water fauna in the bay dominated by *Ammonia beccarii*, a typical coastal fauna to a depth of 50 m included *Buliminella elegantissima*, *Nonionella basispinatus*, and *N. stella*. *Elphidiella hannai* and *Gaudryina arenaria* were restricted to the northern area in these shallower waters. Beach and tide pool samples collected along the California and Oregon coasts, and stained with rose Bengal to distinguish live specimens, defined four major foraminiferal faunas—southern,

TABLE 1. Characteristics of Tomales Bay (from Cherry, 1965; Daetwyler, 1966; Johnson, Bryant, and Hedgpeth, 1961; U.S. Weather Bureau, 1930, 1952).

Surface area	28.5 km ²
Volume	1.1 × 10 ⁸ m ³
Tidal prism	4.5 × 10 ⁷ m ³
Average depth	4 m at mean lower low water
Maximum depth	18.5 m
Dry season	May to September
Precipitation	90% of all rain falls from October to April
Air temperature, mean	11.2°C
Air temperature, range	8.7–13.8°C
Winds, spring and summer	West to northwest
Winds, winter	South
Water temperature	7–12°C
Salinity, summer	32.22–37.5‰
Salinity, winter	20.32–33.48‰
Mean tidal range	1.1 m
Diurnal tidal range	1.6 m
Spring tides	up to 2.4 m

central, and northern faunas, plus a cosmopolitan fauna (Cooper, 1961). The central fauna, from Gaviota to Point Arena, include many species found in Tomales Bay in the present study: *Buccella tenerrima*, *Cassidulina limbata*, *Elphidiella hannai*, and *Glabratella ornatissima*. The cosmopolitan fauna includes *Buliminella elegantissima*, *Cibicides lobatulus*, and *Quinqueloculina ackneriana*, as well as other species. Cooper (1961) correlated the effects of oceanic currents with faunal distribution and noted a general increase in diversity to the south, related to warmer temperatures and higher salinities. The foraminifera of the nearshore turbulent zone from Baja California to Washington state were divided into three faunal provinces—the Oregonian, Californian, and Panamanian provinces—related to water masses and environmental factors such as temperature, salinity, precipitation and river discharge, suspended load, and upwelling (Lankford and Phleger, 1973). Tomales Bay lies in the Oregonian province, which ranges from Vancouver Island in the north to Point Conception in the south. Many of the species reported by Lankford and Phleger (1973) occur in Tomales Bay.

Modern bay assemblages from northern California have been documented in several studies as well. McDonald and Diediker (1930) compiled a preliminary report of the foraminifera of San Francisco Bay, identifying 15 species and relating their distribution to the local substrate. These species include *Cibicides* sp., *Glabratella ornatissima*, *Elphidium hannai*, *Elphidium hughesi*, *E. crispum*, *E. sp.*, *Ammonia beccarii*, *Rotalia hosea*, *R. turbinata*, *Quinqueloculina lamarckiana*, *Q. sp.*, *Eponides sp.*, *Planulina ornata*, *Tro-*

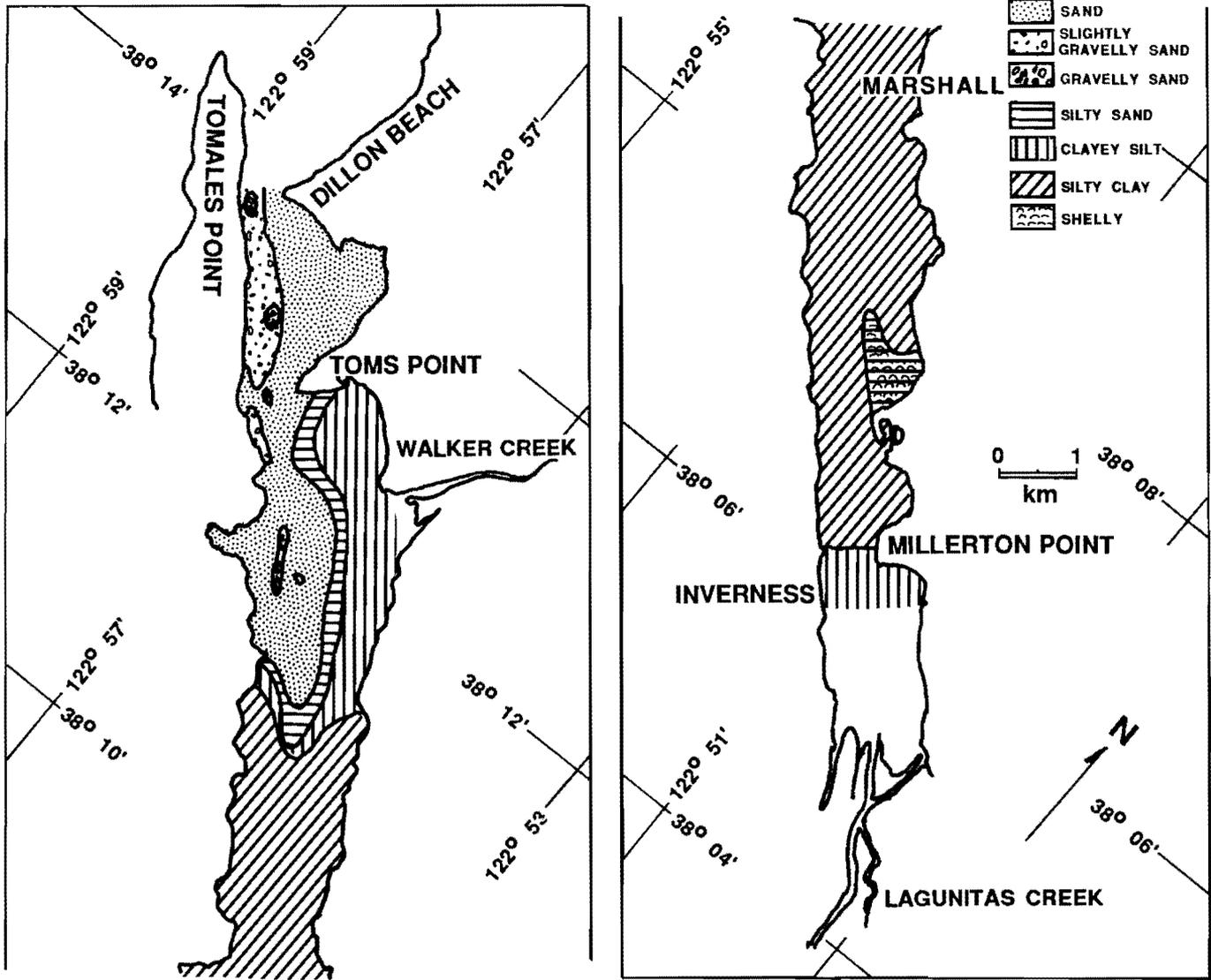


FIGURE 3. Surface sediments of Tomales Bay (from Daetwyler, 1966).

chammina sp., and *Cassidulina limbata*. Much later, Arnal and others (1980) reported four ecological zones in San Francisco Bay based on qualitative observations of species, and four foraminiferal assemblages based on Q-mode cluster analysis, which were in good agreement with the ecological zones. Factors affecting those foraminiferal distributions include salinity, substrate type, organic matter, and possibly biological competition.

In the Russian River estuary, an area highly affected by seasonal freshwater runoff and 24 km north of Tomales Bay, Erskian and Lipps (1977) reported an incursive marine fauna in the estuary and a typical marine fauna offshore during the summer months. During

the winter months the high river discharge entirely removed the marine fauna from the estuary. Cluster analysis of these foraminifera revealed three groups: an offshore marine group and two groups of estuary channel species. Quintero and Gardner (1987) defined depth-related faunas, which included species found in the shallower waters of Tomales Bay, offshore of the mouth of the bay.

Several authors have conducted preliminary foraminiferal work in Tomales Bay. Bush (1930) recorded a reconnaissance of 10 species of foraminifera from 11 samples from around the bay margin and concluded that "Foraminifera of Tomales Bay are neither abundant in numbers or species . . ." (p. 40). In another

preliminary report, Maurer (1968) listed foraminifera species and noted their similarity to the tide pool fauna of Sunset Bay in Coos County, Oregon, reported by Detling (1958). He suggested using Tomales Bay as a model for the assemblages of the Pleistocene Millerton Formation and other rocks in the surrounding area.

MATERIALS AND METHODS

The sampling scheme used in this study was designed to allow the data to be analyzed by multiple discriminant analysis. Ten transects, perpendicular to the long axis of Tomales Bay, of three stations each (four stations in transect 4) were made in winter and in summer (Table 2; Fig. 4). Two replicates were collected at each station. One replicate each from summer stations 7B and 8B was lost. Samples were collected on January 23 and 24, 1982 (winter) and on July 23, 1982 (summer). Winter and summer stations were re-occupied as closely as reckoning from shore-based landmarks allowed. The top 20 ml sediment from a 35 mm diameter plastic core-liner were washed over a 63 μm sieve, and preserved in buffered formalin. Samples were placed in 95% ethanol for long term storage.

About 24 hours prior to picking or counting, samples were stained with rose Bengal (Walton, 1952). Samples were then rewashed over a 63 μm sieve, wet picked, mounted on micropaleontological slides, and identified (Appendix II). One entire set of summer replicates was counted wet without picking. All specimens are deposited in the Museum of Paleontology, University of California, Berkeley (UCMP).

Numerical methods include cluster analysis, multiple discriminant analysis, and multidimensional scaling. Cluster analyses were performed using the University of California, Davis, Geology Department program CLUSTER; the multiple discriminant analyses and multidimensional scaling analyses were performed with programs in the Statistical Package for the Social Sciences (SPSS).

The data collected for this study consisted of absolute numbers of living individuals. Because of this, all abundances were transformed [$\ln(x + 1)$] to increase normality and ensure stability of variances. While this was not strictly necessary for the non-statistical (cluster and multiple dimensional scaling) analyses, we decided that it was more reasonable to compare the analyses when they were performed on identical data.

We performed three kinds of numerical analyses in order to contrast their results. Multiple discriminant analysis is the most demanding numerical method we

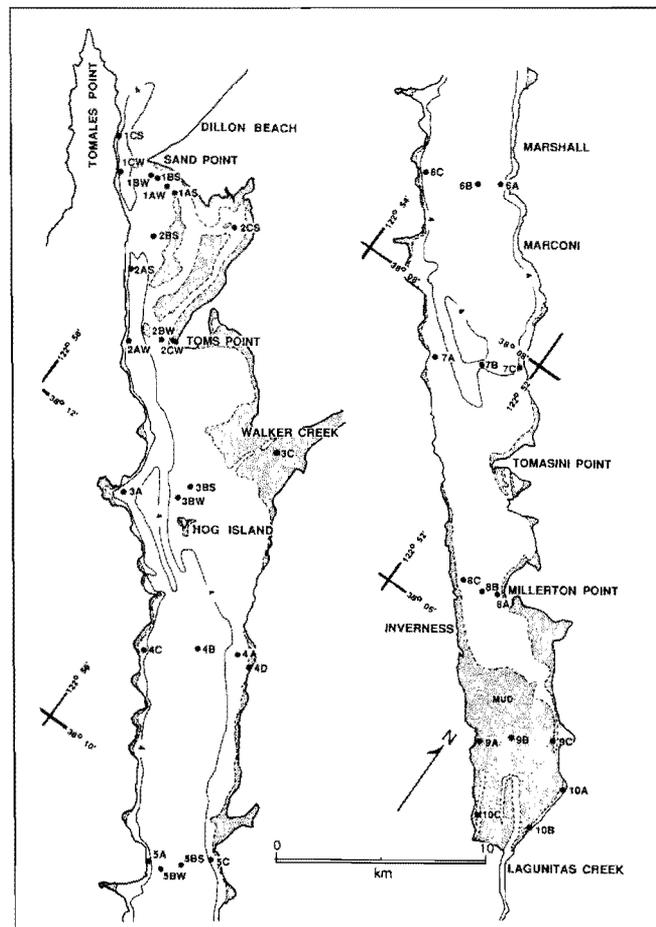


FIGURE 4. Sample locations in Tomales Bay used in this study. Both summer and winter replicate samples were taken at each location.

used in the sense that for each statistical sample we need to know not only a metric value, such as number of individuals, but also some estimate of the variance of that value. In other words, we need at least two field samples for each statistical sample. Our sampling program was planned with that in mind.

Cluster analysis and multidimensional scaling do not require an estimate of the variance of a metric and can be used when only a single value of the metric of interest is known. They are not, however, statistical techniques and cannot be used to test hypotheses about the data.

RESULTS

GENERAL TRENDS OF FORAMINIFERAL DISTRIBUTION

A total of 18,645 live specimens (as indicated by rose Bengal stain) from 58 taxa (plus other unidentified

TABLE 2. Collecting stations in Tomales Bay used in this study (see Fig. 4) with the numbers of living individuals and species of foraminifera found at each station.

Station	Location 38°N, 122°W	Depth (meters)	Sediment	Species	
				# individuals	# spp.
1A summer	13°50", 58°13"	2	Medium sand	218	7
1A winter	13°49", 58°09"	1		10	5
1B summer	13°50", 58°03"	2	Medium sand	244	4
1B winter	13°48", 58°20"	3		95	9
1C summer	13°56", 58°50"	2	Medium-coarse sand	297	23
1C winter	13°42", 58°34"	6		561	27
2A summer	13°09", 57°57"	5		283	14
2A winter	12°41", 55°34"	6	Silty sand, sulfur smell	877	29
2B summer	13°27", 57°58"	2		54	9
2B winter	12°51", 55°18"	2	Silty sand	13	7
2C summer	13°50", 57°19"	3		3	2
2C winter	12°53", 55°11"	mud flat	Mud in sea grass	15	7
3A summer	11°40", 56°10"	6		486	7
3A winter	11°40", 56°10"	6		595	16
3B summer	12°05", 56°10"	1	Silty mud	0	0
3B winter	11°57", 56°13"	2		0	0
3C summer	12°40", 55°42"	mud flat	Silty mud	756	13
3C winter	12°40", 55°42"	mud flat		0	0
4A summer	11°14", 54°53"	2	Silty sand	3	3
4A winter	11°14", 54°53"	2		97	10
4B summer	11°05", 55°13"	7	Muddy silt	2,292	15
4B winter	11°05", 55°13"	7		1,096	15
4C summer	10°51", 55°38"	4	Medium-coarse sand/gravel, shells	7	2
4C winter	10°51", 55°38"	4		760	16
4D winter	11°12", 54°44"	mud flat		1	1
5A summer	09°50", 54°57"	4	Silty sand	33	9
5A winter	09°50", 54°57"	4		404	22
5B summer	09°39", 54°09"	6	Muddy silt	540	16
5B winter	09°32", 54°17"	8		682	16
5C summer	09°32", 53°25"	3	Muddy silt	449	20
5C winter	09°32", 53°25"	3		424	18
6A summer	08°57", 53°17"	8	Silty fine sand	24	6
6A winter	08°57", 53°17"	8		536	17
6B summer	08°52", 53°30"	7	Mud	937	19
6B winter	08°52", 53°30"	7		541	20
6C summer	08°44", 53°58"	4		3	3
6C winter	08°44", 53°58"	4		400	22
7A summer	07°36", 52°51"	2	Mud	340	24
7A winter	07°36", 52°51"	2		1,466	21
7B summer	07°46", 52°28"	6	Mud	180	20
7B winter	07°46", 52°28"	6		144	18
7C summer	07°54", 52°12"	3	Silty sand	133	7
7C winter	07°54", 52°12"	3		277	23
8A summer	06°24", 51°03"	<1	Mud	163	3
8A winter	06°24", 51°03"	<1		5	1
8B summer	06°21", 51°12"	1	Muddy, medium-coarse sand	321	11
8B winter	06°21", 51°12"	1		301	13
8C summer	06°19", 51°24"	<1		1	1
8C winter	06°19", 51°24"	<1		1	1
9A summer	05°24", 50°20"	mud flat	Muddy fine sand	54	2
9A winter	05°24", 50°20"	mud flat		25	6
9B summer	05°35", 50°10"	mud flat	Mud	466	4
9B winter	05°35", 50°10"	mud flat		5	3
9C summer	05°43", 49°49"	mud flat	Silty sand	128	2
9C winter	05°43", 49°49"	mud flat		15	4
10A summer	05°27", 49°28"	<1	Medium-coarse sand	6	2
10A winter	05°27", 49°28"	<1		5	2
10B summer	05°06", 49°30"	<1	Mud	650	4
10B winter	05°06", 49°30"	<1		27	6
10C summer	04°56", 50°00"	<1		22	3
10C winter	04°56", 50°00"	<1		174	14

specimens) were collected and identified (Appendix II) in the two seasonal sample sets. The winter set consisted of 9,552 and the summer of 9,093 individuals. Of the 58 species identified, only 14 species made up more than 1% of either seasonal population; these 14 species were chosen for the numerical analyses discussed later: *Ammonia beccarii*, *Brizalina acuminata*, *B. vaughani*, *Buccella tenerrima*, *Bulimina denudata*, *Buliminella elegantissima*, *Criboelphidium excavatum*, *C. lene*, *Elphidiella hannai*, *Fursenkoina pontoni*, *Glabratella ornatissima*, *Hopkinsina pacifica*, *Quinqueloculina ackneriana* var. *bellatula*, and *Rotorbinella campanulata*.

Foraminifera were found throughout the bay (Appendix II), although stations 3B and 3C (winter) and 3B (summer) were barren. Plots of species abundance by station proved to be too complex to interpret. Plots of species abundance by transect for the 14 most abundant species (Figs. 5, 6), however, showed both spatial and temporal patterns. These plots were produced simply by summing the abundance in each sample in a given transect for either the winter or summer collection and are discussed below. Although the transect plots of the most abundant species are still somewhat complex, they do indicate Tomales Bay can be divided approximately into three regions based on living foraminifera: the northern region (Transects 1–4), the midbay region (Transects 5–7), and the southern region (Transect 8–10).

Criboelphidium excavatum was the only species found in all transects, both summer and winter, and it had the greatest overall abundance. *Buliminella elegantissima* and *Ammonia beccarii* were found in most transects, with *B. elegantissima* more abundant in the northern transects and *A. beccarii* more abundant in the southern transects.

Cribronion lene, *Glabratella ornatissima*, and *Rotorbinella campanulata* were most common in the northern parts of the bay (Transect 1–4), as were the less common species *Cassidulina limbata*, *Cibicides fletcheri*, *C. lobatulus*, and *Nouria polymorphinoides* (Appendix II). Transects 5–7, located in the midbay region between the mouth and head of Tomales bay, contained abundant *Brizalina acuminata*, *B. vaughani*, *Bulimina denudata*, *Fursenkoina pontoni*, and *Hopkinsina pacifica* (the most abundant species in the midbay region). Less abundant species that had their max-

imum abundances in the midbay region were *B. acutula*, *Nonionella basispinatus* and *N. stella*.

None of the abundant species were restricted exclusively to Transects 8–10, the southern part of the bay, although the less abundant *Miliammina fusca* was found mainly in this region.

Abundant species occurring in both the north and central bay (Transects 1–7) were *Buccella tenerrima*, *Elphidiella hannai*, and *Quinqueloculina ackneriana* var. *bellatula*. Less common species that had their maximum abundances in the north and midbay were *Bolivina compacta*, *B. subexcavata*, *Q. laevigata*, and *Q. vulgaris*. *Buccella tenerrima* and *E. hannai* comprised the largest part of the total foraminiferal population in these transects. Although *B. vaughani* occurred in both the north and midbay, it was by far more abundant in the midbay region (Transects 5–7).

Haplophragmoides columbiense and *Trochammina* spp. occurred both in the north and south part of the bay but were absent from the midbay. They each made up about 1/2% of the total population found in the bay.

Several species exhibited seasonal trends, such as geographical shifts, distinctive life cycle phases, or seasonal dominance (Figs. 5, 6). During the summer *Brizalina vaughani* and *Quinqueloculina ackneriana* var. *bellatula* were restricted to the midbay; in winter these species also occurred in the north bay. *Haplophragmoides columbiense* was found in the north during winter, but in the south during summer. *Q. laevigata* and *Q. vulgaris* were restricted to the north bay in winter; in summer these species were found in both the north and midbay. Both species contributed only minor numbers to the total population (26 and 29 individuals respectively). *Trochammina* spp. were found only in the south during summer, but in winter were found predominantly in the north.

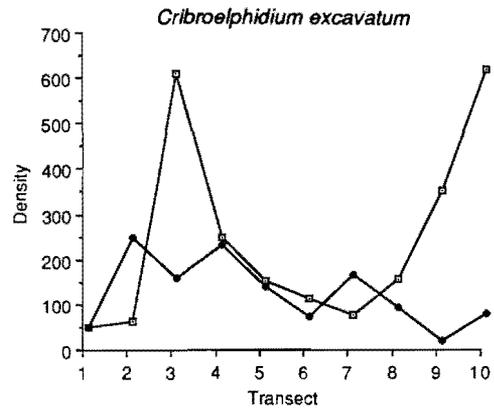
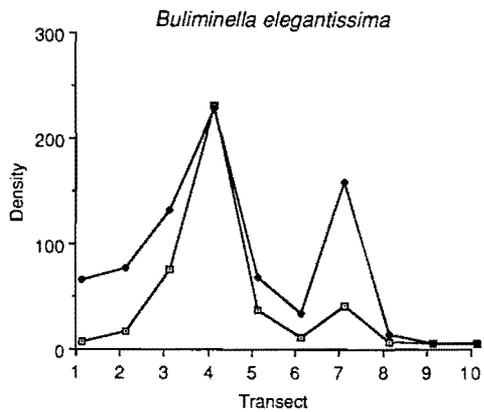
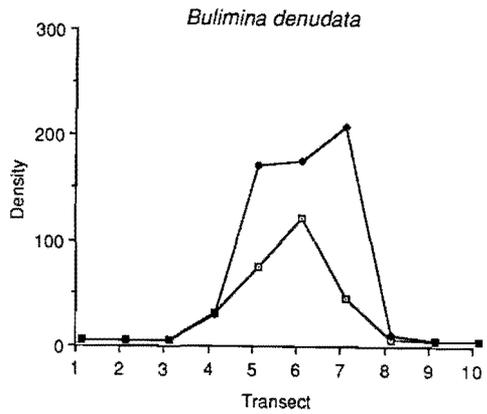
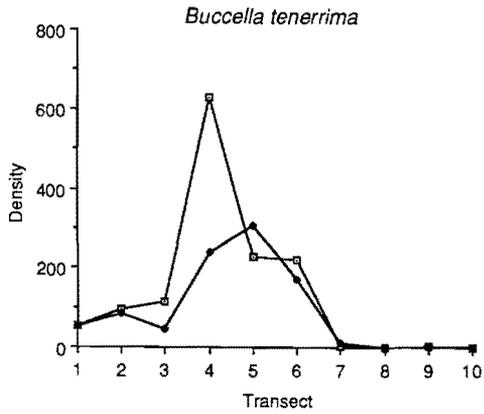
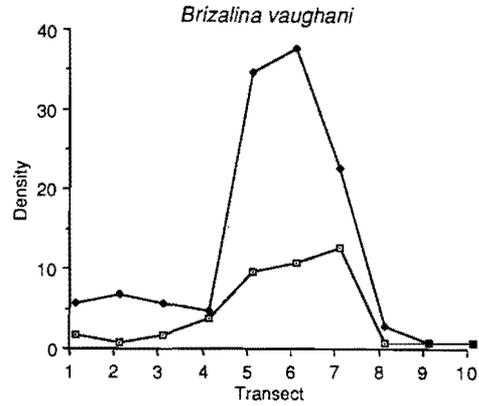
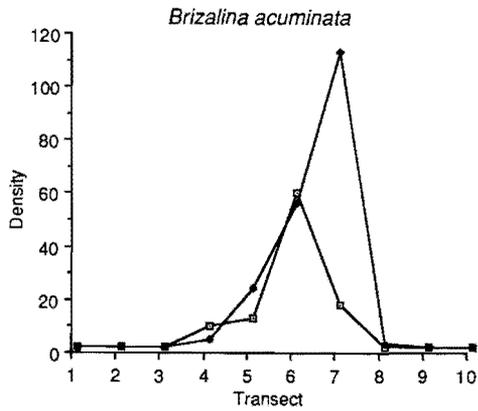
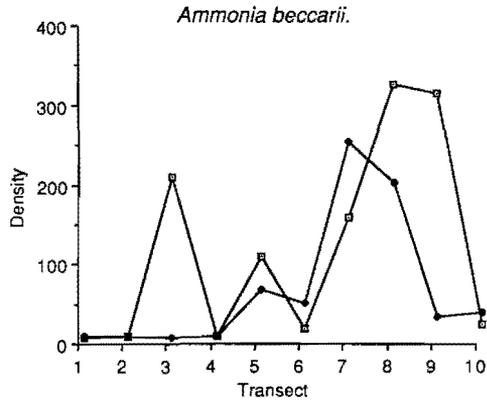
Juvenile foraminifera (probably *Rosalina columbiensis*) occurred in one north bay summer sample. *Glabratella ornatissima* was present in several life cycle phases throughout the seasonal samples, as reported for the nearby outer coast by Erskian and Lipps (1987). In summer, adult megalospheres dominated the microsphere generation by a ratio of about 4:1, very near the ratio of 3.5:1 found by Lankford and Phleger (1973). These megalospheres included many plastogamous pairs, indicating active reproduction. Juvenile microspheres were observed only in winter samples.

FIGURE 5. Summer and winter abundance of seven species of foraminifera in ten transects across Tomales Bay.

FIGURE 6. Summer and winter abundance of seven species of foraminifera in ten transects across Tomales Bay.

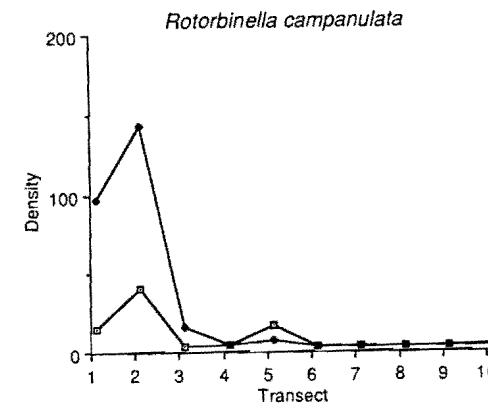
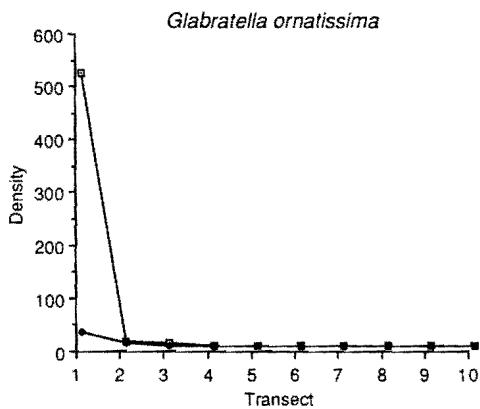
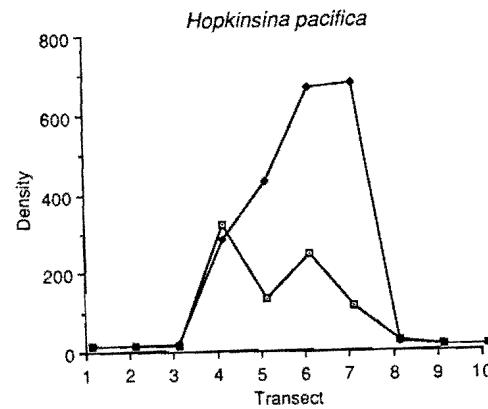
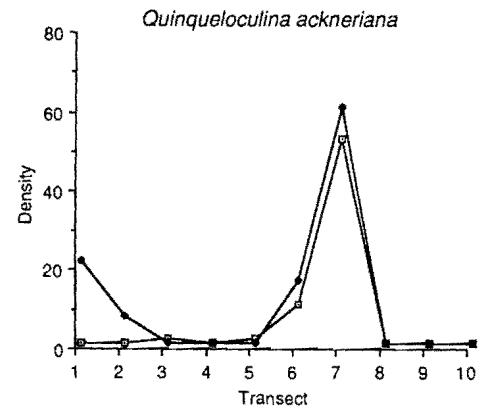
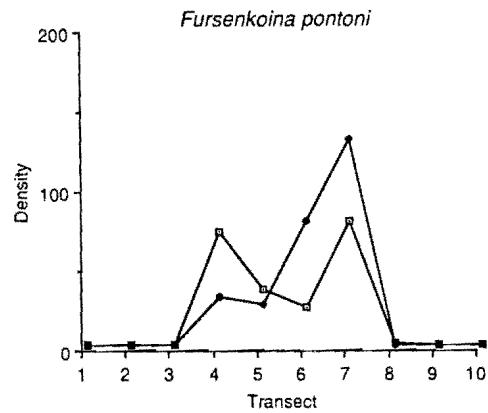
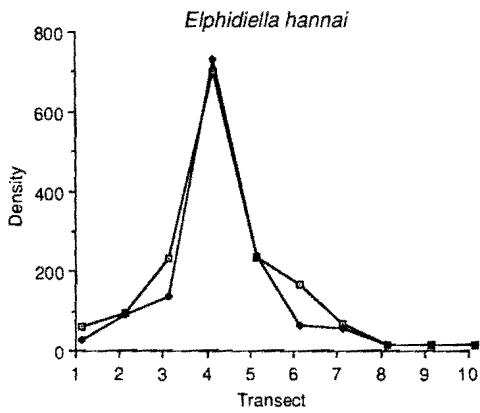
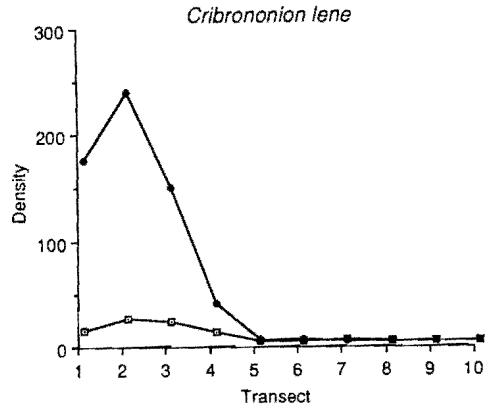
→

□ SUMMER
● WINTER



SUMMER AND WINTER DISTRIBUTION OF FORAMINIFERA

□ SUMMER
● WINTER



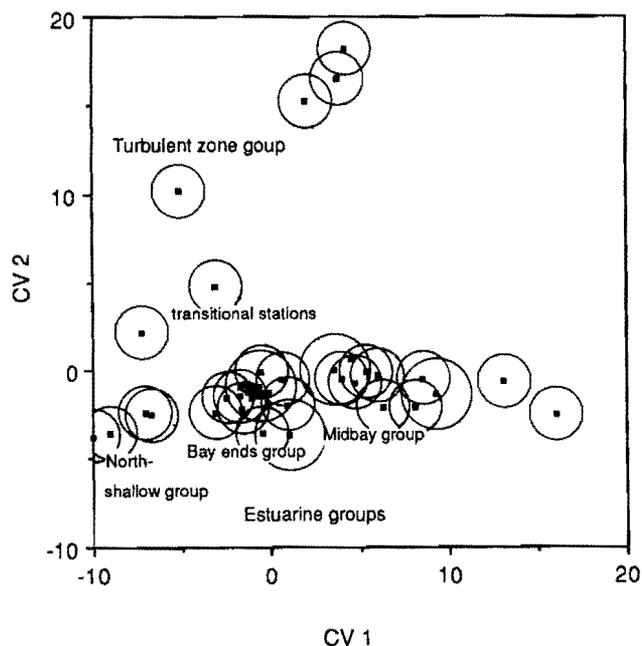


FIGURE 7. Canonical variate 1 vs. canonical variate 2 for summer and winter stations. Circles represent 95% confidence levels for the data points.

Several species showed a seasonal dominance, in which the number of a species during one season was about twice the number of the same species during the other season (Figs. 6, 7). All species reported here had at least 100 individuals total. Summer dominant species included *Criboelphidium excavatum* (2,309:904) and *Glabratella ornatissima* (531:33). Species showing winter dominance included: *Brizalina acuminata* (201:93), *B. vaughani* (115:36), *Bulimina denudata* (567:253), *Buliminella elegantissima* (856:381), *Cibicides lobatulus* (85:22), *Cribrononion lene* (587:59), *Hopkinsina pacifica* (2,013:764), and *Rotorbinella campanulata* (250:62).

NUMERICAL ANALYSES

While a general idea of the foraminiferal distribution in Tomales Bay is apparent in Figures 5 and 6 and Appendix II, patterns in 14 species (those comprising more than 1% of the total collection) at some 30 stations, each occupied at two separate times, is difficult to understand. We examined the station-wise data with multiple discriminant analysis, cluster analysis, and multidimensional scaling. Ideally, all three techniques should reveal the same patterns within the data rather than patterns generated by the numerical techniques.

TABLE 3. Eigenvalues, percent of variance accounted for by each, and cumulative percent for the canonical discriminant functions.

Function	Eigenvalue	Percent of variance	Cumulative percent
Grouping by stations			
1	72.04375	27.74	27.74
2	61.51948	23.69	51.42
3	47.08467	18.13	69.55
4	27.12540	10.44	79.99
5	14.92758	5.75	85.74
6	11.99494	4.62	90.38
7	8.07049	3.11	93.47
8	4.86709	1.87	95.34
9	4.08848	1.57	96.91
10	3.27463	1.26	98.17
11	1.56032	0.60	98.77
12	1.38033	0.53	99.31
13	0.96356	0.37	99.68
14	0.83900	0.32	100.00
Grouping by transects			
1	9.03137	43.68	43.68
2	5.44195	26.32	70.00
3	1.93731	9.37	79.37
4	1.50594	7.28	86.65
5	1.01189	4.89	91.55
6	0.52593	2.54	94.09
7	0.37160	1.80	95.89
8	0.32425	1.57	97.46
9	0.17868	0.86	98.32
10	0.12500	0.60	98.92
11	0.08827	0.43	99.35
12	0.07125	0.34	99.70
13	0.04895	0.24	99.93
14	0.01399	0.07	100.00

Multiple Discriminant Analysis

The sampling requirements for multiple discriminant analysis (MDA) are greater than for cluster analysis or multidimensional scaling because MDA requires an estimate of the variance of each metric; thus at least two field samples are required for each statistical sample. In the station-wise analysis of the 14 species comprising more than 1% of a seasonal population 61 pairs of field samples representing the replicate samples from each station were used; 31 of these were from the winter sampling and 30 from the summer. One sample for each of the summer stations 4B and 6B was very heavily stained, making distinction between the live specimens and empty tests difficult. These two samples were excluded from the statistical analysis. One replicate was lost from each of the summer stations 7B and 8B. In addition to performing an MDA on the station-wise data, an MDA was done on the data grouped by transects. As the results of the two analyses were similar (Table 3), only the MDA on the transect data is presented briefly.

Of the 14 eigenvalues computed in the station-wise MDA, the first three, which accounted for 69.6% of

TABLE 4. Canonical variates 1–3 for each station based on grouping by winter sample stations.

Winter sample station	CV 1	CV 2	CV 3
1A	-0.55838	-0.11597	-0.34246
1B	-1.75091	-1.47079	-0.53126
1C	-5.07504	10.19252	12.52651
2A	-7.19279	2.08009	14.21066
2B	-0.93267	-1.51145	-0.36651
2C	-0.76133	-1.26282	0.85923
3A	-9.95699	-3.74307	11.99714
3B	-0.94125	-1.22880	-1.41523
3C	-0.94125	-1.22880	-1.41523
4A	-6.99203	-2.38723	-1.89106
4B	-0.50751	-3.61660	5.72655
4C	-9.00690	-3.61744	3.68243
4D	-1.00208	-1.20383	-1.40336
5A	6.27262	-2.15499	-0.90113
5B	8.07557	-2.08183	-2.67208
5C	-1.59290	-2.16084	-0.73933
6A	4.74080	-0.77879	-1.70691
6B	8.50590	-0.51251	-1.64068
6C	3.96236	-0.48338	0.00074
7A	4.48538	0.59381	-1.19514
7B	5.96089	-0.03594	-0.94089
7C	13.13005	-0.65418	-0.18590
8A	-1.09850	-1.16426	-1.38454
8B	-0.63786	-0.92986	-1.75385
8C	-1.00208	-1.20383	-1.40336
9A	-1.06709	-1.09758	-1.42959
9B	-1.03107	-1.16798	-1.40942
9C	-1.23743	-1.08328	-1.36914
10A	-0.99923	-1.15709	-1.42734
10B	-1.25606	-1.21128	-1.38600
10C	-1.77312	-0.91951	-1.52586

TABLE 5. Canonical variates 1–3 for each station based on grouping by summer sample stations.

Summer sample station	CV 1	CV 2	CV 3
1A	4.22062	18.24148	-1.59962
1B	3.81259	16.57544	-0.40884
1C	1.97773	15.25539	3.30986
2A	-3.09567	4.68526	6.26361
2B	-3.08303	-2.46883	-1.76206
2C	-0.94125	-1.22880	-1.41523
3A	-1.33952	-0.68653	-1.46623
3B	-0.94125	-1.22880	-1.41523
3C	-5.46335	2.72142	4.51194
4A	-1.00208	-1.20383	-1.40336
4B	1.02902	-3.63781	4.54672
4C	-1.12268	-1.61259	-1.42997
5A	-2.50417	-1.54877	-1.43103
5B	16.12809	-2.50597	-2.09242
5C	-6.74561	-2.48844	-2.21546
6A	-1.09703	-0.88675	-1.32544
6B	9.28324	-1.33644	-1.41367
6C	-1.04839	-1.38990	-1.40013
7A	5.33260	-0.11830	-0.38600
7B	3.58802	-0.01835	-0.74097
7C	0.87443	-2.02750	-1.53001
8A	-1.34471	-0.83905	-1.44611
8B	0.58721	-0.48986	-1.60278
8C	-1.00208	-1.20383	-1.40336
9A	-1.09805	-1.02412	-1.45325
9B	-1.30629	-0.74544	-1.65237
9C	-1.44258	-0.86753	-1.39344
10A	-1.08361	-1.13240	-1.40602
10B	-0.64771	-1.12844	-1.58051
10C	-1.09982	-1.06790	-1.43114

the variance, showed interpretable trends (Tables 4, 5). The discriminant function scores for each station are found in Table 6.

Canonical variate 1 (CV 1) distinguished the midbay group (stations in transects 5, 6, and 7) from the north and south portions of the bay (Fig. 7). This variate also distinguished a smaller group of shallow water samples in the north part of the bay. Winter samples showed a clearer distinction among these groups than did the summer samples (Figs. 8, 9). Eight of the nine winter midbay stations were different from the remainder, only winter station 5C plotted among the bay end stations (Fig. 8). In contrast, only 3 summer stations (5B, 6B, and 7A) were substantially different from the bay end samples (Fig. 9). This distinction among stations occurred in the north bay shallow group as well. Five samples in this group were collected in the winter; only summer station 5C fell into this group, an apparent anomaly. The chief group of points showed no major differences between the southern stations and the northern stations that were not part of the north-shallow group. Table 6 shows the species that were re-

sponsible for the contrasts seen along CV 1. In order of importance, these were: *Bulimina denudata*, which was most abundant in the midbay; *Buliminella elegantissima*, which occurred throughout the middle section of the bay; *Rotorbinella campanulata*, which occurred almost exclusively in the northernmost part of the bay near its mouth; *Hopkinsina pacifica*, a species almost restricted to the midbay; *Brizalina vaughani*, only slightly prominent in the midbay; *Glbratella ornatisissima*, restricted to the northernmost part of the bay near its mouth; *Brizalina acuminata*, which occurred primarily in the midbay; *Quinqueloculina ackneriana* var. *bellatula*, which also occurred primarily in the midbay; *Fursenkoina pontoni*, also a midbay species; *Cribronion lene*, primarily restricted to the north bay; *Elphidiella hannai*, an abundant species in the middle and northern parts of the bay; *Criboelphidium excavatum*, an abundant species found throughout the bay; *Buccella tenerrima*, similar in distribution to *Elphidiella hannai*; *Ammonia beccarii*, abundant primarily in the middle and southern parts of the bay.

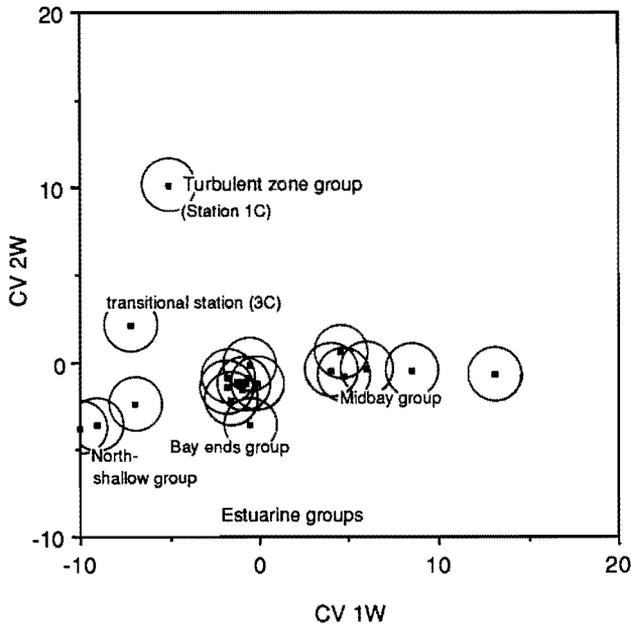


FIGURE 8. Canonical variate 1 vs. canonical variate 2 for winter stations. Circles represent 95% confidence levels for the data points.

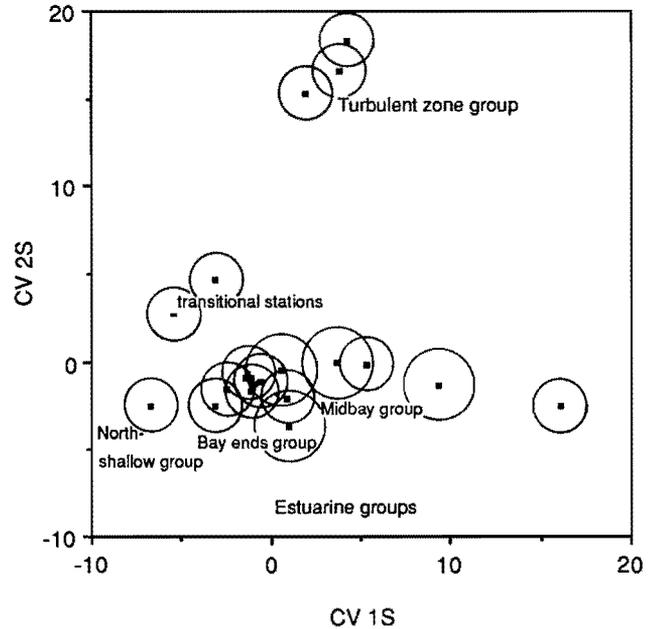


FIGURE 9. Canonical variate 1 vs. canonical variate 2 for summer stations. Circles represent 95% confidence levels for the data points.

Canonical variate 2 (CV 2) distinguished estuarine samples from those more characteristic of nearshore turbulent environments (Figs. 7–9). Samples from the northernmost transect and winter sample 1C were clearly distinguished by CV 2. Other samples (summer 2A and winter 3C) were intermediate between this turbulent zone group and the estuarine groups, showing a slight gradient from the more oceanic to estuarine conditions. The species contributing to this distribution were, in order of importance, *Quinqueloculina ackneriana* var. *bellatula*, *Glabratella ornatissima*, *Bulimina denudata*, *Cribronion lene*, *Hopkinsina pacifica*, *Buccella tenerrima*, *Brizalina acuminata*, *Ammonia beccarii*, *Buliminella elegantissima*, *Rotorbinella*

campanulata, *Elphidiella hannai*, *Brizalina vaughani*, *Fursenkoina pontoni*, and *Cribroelphidium excavatum*.

Canonical variate 3 (CV 3) was difficult to interpret. Four samples were clearly distinct from the remaining groups; these samples occurred in both the summer and winter samples (Figs. 10–12). They were all from deeper water; however, deeper water samples further to the south did not fall into this group. Thus, perhaps CV 3 relates both to water depth and proximity to the bay mouth. In order of importance, the species contributing to this variate were *Glabratella ornatissima*, *Elphidiella hannai*, *Buliminella elegantissima*, *Bulimina denudata*, *Brizalina vaughani*, *Fursenkoina pontoni*, *Ammonia beccarii*, *Brizalina acuminata*, *Buccella*

TABLE 6. Canonical discriminant function coefficients for the 14 species used in the multiple discriminant analysis for grouping by stations.

Species	CV 1	CV 2	CV 3
<i>Ammonia beccarii</i>	0.00153	-0.20521	-0.03179
<i>Brizalina acuminata</i>	-0.31503	0.29956	-0.03110
<i>B. vaughani</i>	0.60461	-0.07992	-0.07956
<i>Buccella tenerrima</i>	0.03445	0.41353	-0.02837
<i>Bulimina denudata</i>	-1.76263	0.54750	-0.21041
<i>Buliminella elegantissima</i>	0.99910	-0.18530	0.25797
<i>Cribroelphidium excavatum</i>	0.04904	-0.01739	0.02689
<i>Cribronion lene</i>	0.09681	0.51182	-0.01145
<i>Elphidiella hannai</i>	0.07748	0.14620	0.70042
<i>Fursenkoina pontoni</i>	-0.23847	0.07037	0.06487
<i>Glabratella ornatissima</i>	-0.31588	0.59074	-0.89752
<i>Hopkinsina pacifica</i>	0.71166	-0.45027	0.48547
<i>Quinqueloculina ackneriana</i>	-0.26365	0.73631	0.02608
<i>Rotorbinella campanulata</i>	0.72918	0.18514	0.01523

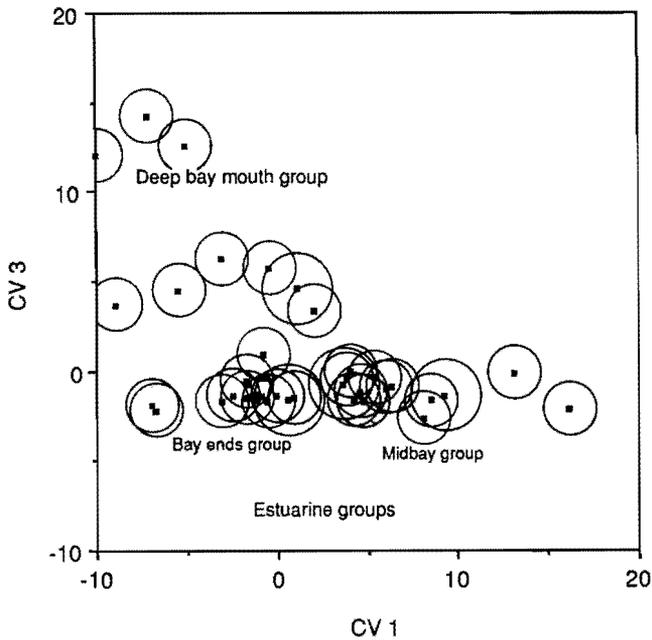


FIGURE 10. Canonical variate 1 vs. canonical variate 3 for summer and winter stations. Circles represent 95% confidence levels for the data points.

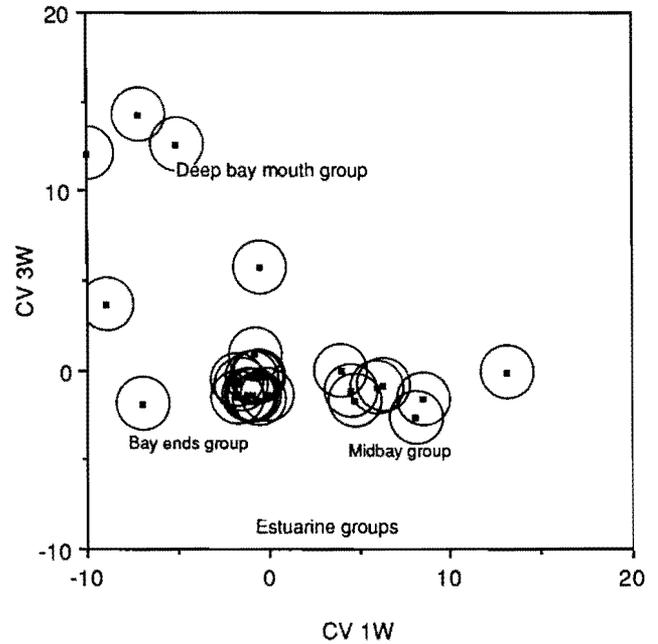


FIGURE 11. Canonical variate 1 vs. canonical variate 3 for winter stations. Circles represent 95% confidence levels for the data points.

tenerrima, *Criboelphidium excavatum*, *Quinqueloculina ackneriana* var. *bellatula*, *Rotorbinella campanulata*, and *Cribrononion lene* (see Table 6).

Transect groupings used 10 transects in both winter and summer. Each transect included 3 stations, except for winter transect 4, which had 4 stations. Each station had a pair of replicate samples, except for those noted above. Thus each transect included 6 samples of two replicates for each of the three stations, except for summer transects 4, 6, 7, and 8, which had 5 replicate samples, and winter transect 4, which had 8 replicate samples.

The first two eigenvalues (Table 3) computed in the MDA for the transect groupings account for about 70% of the total variance. Discriminant scores are presented in Table 7. Canonical variate 1 (CV 1) for the transect groups defined estuarine and turbulent zone groups (Fig. 13). This distinction was clearly seen in the summer transects (Fig. 14); it was also present in the winter transects (Fig. 15), although not as clearly. Particularly striking is the contrast between summer transect one and the rest of the transects. The large number of *Glabratella ornatissima* specimens from this transect (Fig. 6, Appendix II, Table 8) is responsible for this contrast. Other species responsible for the contrasts seen in CV 1 are summarized in Table 8.

Canonical variate 2 (CV 2) distinguished midbay transects (5, 6, and 7) from the ends of the bay (Fig.

13). However, only winter transects (Fig. 15) showed a substantial difference between these two groups. Summer samples (Fig. 14) did show some difference from the rest of the bay, but the 95% confidence intervals about the means for each transect show sub-

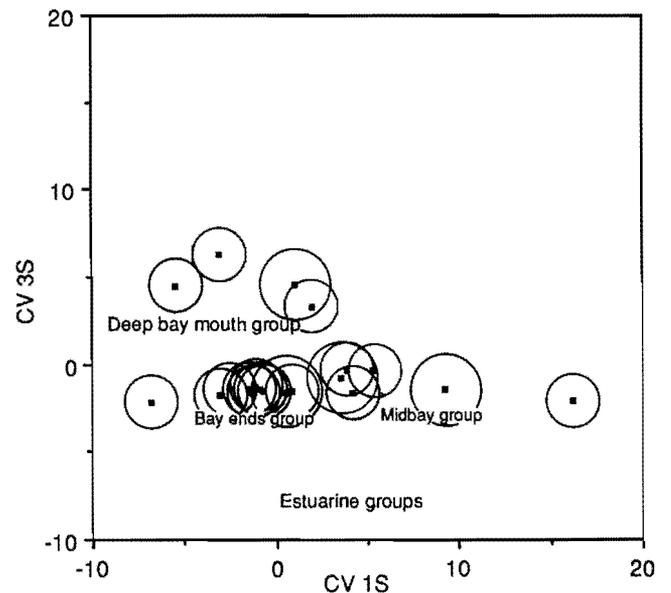


FIGURE 12. Canonical variate 1 vs. canonical variate 3 for summer stations. Circles represent 95% confidence levels for the data points.

TABLE 7. Canonical variates 1–2 for winter and summer transects.

Transect	CV 1	CV 2
Winter		
1	1.06822	-0.64354
2	-0.64803	-0.65251
3	-1.21026	-0.74542
4	-1.16362	-0.77892
5	-0.95626	1.76304
6	-0.74731	2.99996
7	-0.73707	3.78694
8	-0.57964	-0.43330
9	-0.60174	-0.63135
10	-0.60402	-0.65166
Summer		
1	10.81353	-0.51928
2	0.17952	-0.64138
3	0.39767	-0.86216
4	-0.90226	-0.73772
5	-1.10038	0.32037
6	-0.94440	0.61009
7	-0.94144	0.13070
8	-0.44978	-0.72635
9	-0.45810	-0.78673
10	-0.56640	-0.66169

stantial overlap. Thus, this variate showed a seasonal shift in the midbay samples. In summary, the bay was rather homogeneous in the summer, but during winter the middle part of the bay was more distinct from the rest of the bay. Table 8 lists the species responsible for the variation observed in CV 2.

Overall, the transect analysis compared favorably with the analysis based on single-station groupings, and also agreed well with the conclusions based on simple inspection of Figures 5 and 6 and Appendix II. Both methods distinguished a unique, offshore or turbulent zone group and two groups of estuarine faunas, a mid-bay group (transects 5, 6, and 7) and a group of bay-end faunas (transects 2–4 and 8–10). In addition, groups based on stations showed an additional division of the north bay group into stations similar to the south bay groups and shallow water, north bay stations. Both station and transect groupings exhibited seasonal trends in some canonical variates; this seasonality was especially prominent in the midbay and turbulent zone stations. Transect groupings made general trends more visible, whereas station groupings gave greater resolution and made anomalous stations more apparent.

The relative importance of a species in determining a canonical variate is unrelated to the species' abundance. *Bulimina denudata* was the principal species in determining station groupings CV 1, but it was 7th in order of total abundance. *Criboelphidium excavatum* was the most abundant and widespread species, but

TABLE 8. Canonical discriminant function coefficients for the 14 species used in the multiple discriminant analysis using groupings by transects. Magnitude of the absolute values of the coefficients of each canonical variate corresponds to each species' importance in determining that canonical variate. For example, *Glabratella ornatissima* was the most important species in determining CV 1.

Species	CV 1	CV 2
<i>Ammonia beccarii</i>	-0.15792	0.12662
<i>Brizalina acuminata</i>	-0.13556	0.19479
<i>B. vaughani</i>	0.00365	-0.43096
<i>Buccella tenerrima</i>	-0.08883	-0.41442
<i>Bulimina denudata</i>	0.07392	0.92839
<i>Buliminella elegantissima</i>	-0.48926	-0.66663
<i>Criboelphidium excavatum</i>	0.38705	-0.31227
<i>Cribronion lene</i>	-0.03666	0.16618
<i>Elphidiella hannai</i>	-0.32411	0.54016
<i>Fursenkoina pontoni</i>	0.10290	-0.21221
<i>Glabratella ornatissima</i>	1.33040	0.29991
<i>Hopkinsina pacifica</i>	0.22328	0.52434
<i>Quinqueloculina ackneriana</i>	-0.25472	0.65017
<i>Rotorbinella campanulata</i>	-0.37101	-0.12146

was of relatively little importance, as it occurred in almost all the samples and therefore did little to distinguish one sample from another. *Quinqueloculina ackneriana* var. *bellatula*, of primary importance in CV 2 for station groupings, was among the least abundant of the species used in this analysis.

Cluster Analysis

Q-mode and R-mode cluster analyses were done on the 14 major species used in the multiple discriminant analyses. Q-mode analysis (Fig. 16) revealed the three major groups—turbulent zone, middle bay, and bay ends—found in the multiple discriminant analysis. Moreover, a subgroup of south bay samples appeared in the Q-mode cluster analysis. Five stations were anomalous: winter station 8B appeared in the middle bay group rather than in the bay ends group; and winter stations 1B and 2B and summer stations 1A and 1B clustered in the bay end group rather than in the north bay turbulent zone group.

R-mode cluster analysis (Fig. 17) revealed groups of species that reflected the qualitative examination of species distribution discussed above. *Rotorbinella campanulata*, *Glabratella ornatissima*, and *Cribronion lene* comprised the turbulent zone fauna (Plate 1). Estuarine species included *Quinqueloculina ackneriana* var. *bellatula*, *Hopkinsina pacifica*, *Fursenkoina pontoni*, *Bulimina denudata*, *Brizalina acuminata*, *B. vaughani*, *Elphidiella hannai*, *Buccella tenerrima*, and *Buliminella elegantissima*. Of these, *Q. ackneriana* var. *bellatula*, *H. pacifica*, *F. pontoni*, *Bulimina denudata*, *Brizalina acuminata*, and *B. vaughani*

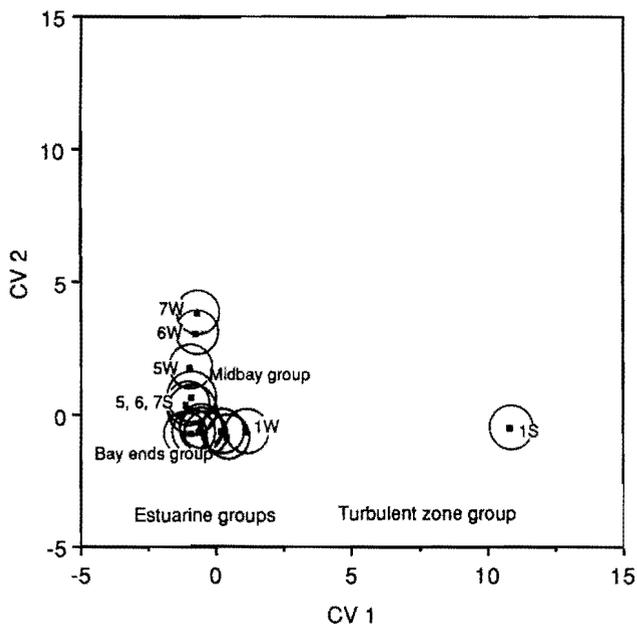


FIGURE 13. Canonical variate 1 vs. canonical variate 2 for summer and winter transects. Circles represent 95% confidence levels for the data points.

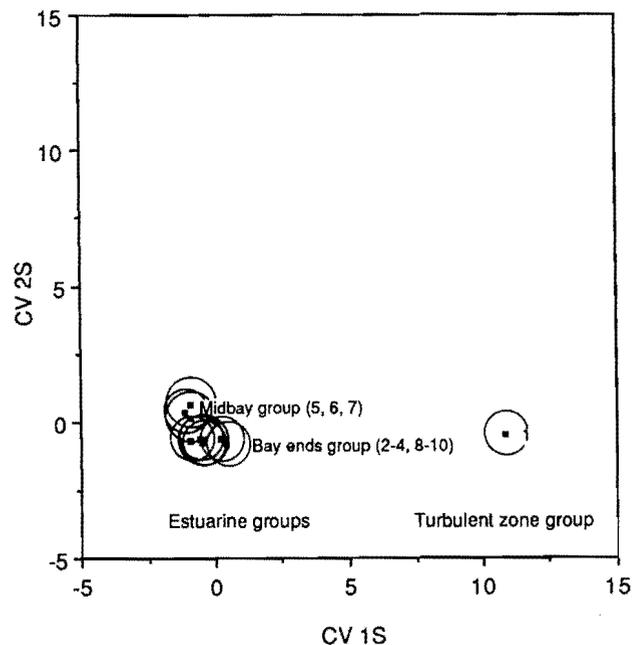


FIGURE 14. Canonical variate 1 vs. canonical variate 2 for summer transects. Circles represent 95% confidence levels for the data points.

occurred predominantly in the middle part of the bay (Plate 2); the other three species were found primarily at the north and south ends of the estuary (Plate 3). *Cribolephidium excavatum* and *Ammonia beccarii* were widespread in distribution, appearing in almost every sample (Plate 3). These species did not fall into any of the other clusters, and formed only a weak cluster themselves.

Multidimensional Scaling

Because of computer limitations we were only able to include 50 samples in the multidimensional scaling analysis. To reduce the number of samples to 50, we first combined the data from each pair of replicates, then selected the fifty samples with the largest numbers of total individuals. After transforming the data [$\ln(x + 1)$], we calculated the Euclidian distance between each pair of samples, obtaining a 50×50 distance matrix. This matrix was scaled with the SPSS program ALSICAL.

After seven iterations stress was reduced to a minimum of 57%. This is comparable to the 43% stress that Hayward and Buzas (1979) found in their analysis of 364 species in 55 samples, but much greater than the 5-10% stress considered good by Kruskal (1964). The two dimensional representation of the samples shows some patterns, but they are not as clear as those

revealed by the cluster and multiple discriminant analyses.

Altogether, the samples plot on a ring (Fig. 18). Overlap occurs, but in general the summer stations plot in the upper right quadrant and the winter stations

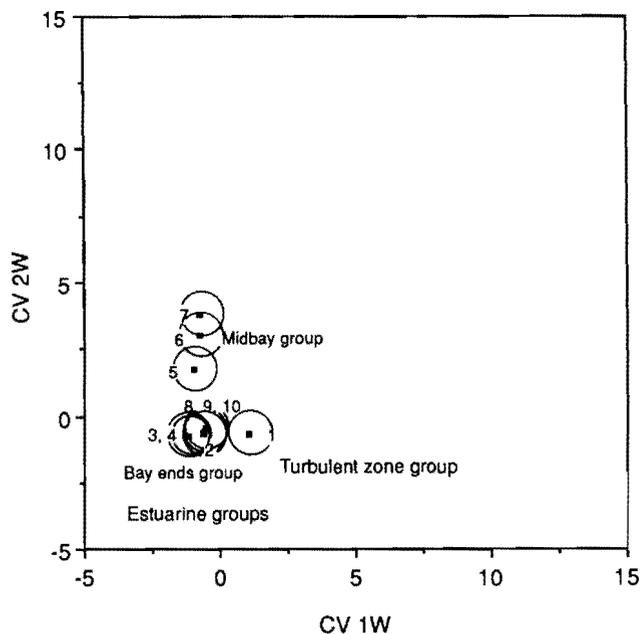


FIGURE 15. Canonical variate 1 vs. canonical variate 2 for winter transects. Circles represent 95% confidence levels for the data points.

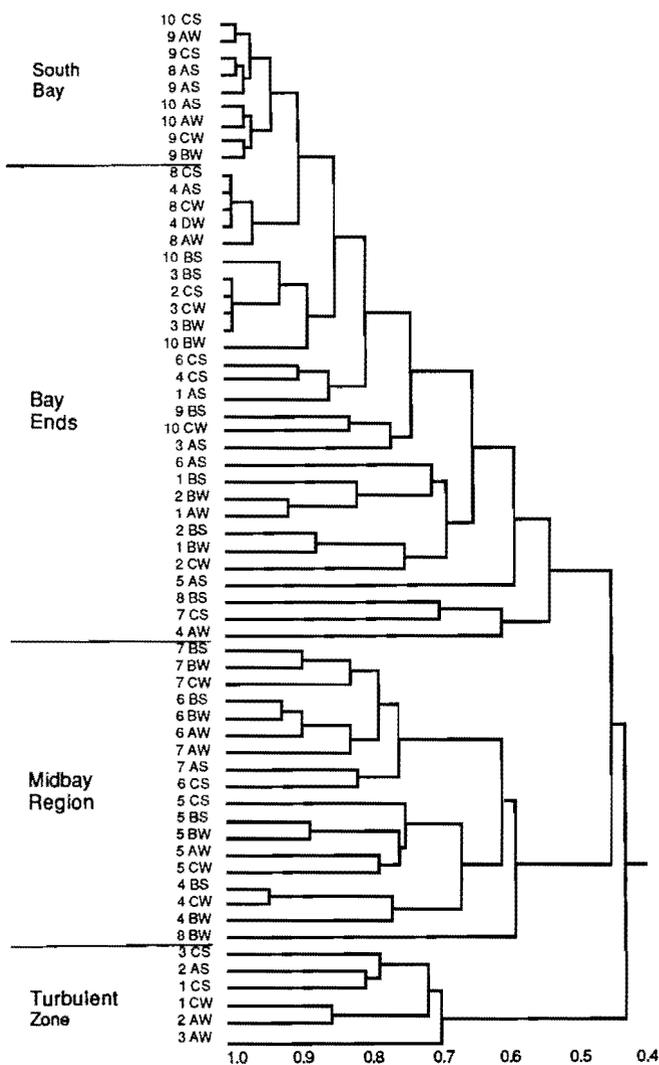


FIGURE 16. Dendrogram of Q-mode cluster analysis, showing station clusters in Tomales Bay.

plot in the lower left quadrant. Among the exceptions, Station 1C (winter) plots in the middle of the summer samples, and Station 3A (summer) plots in the middle of the winter samples. A great deal of effort is required to pick out more patterns, not too surprising in light of the high stress of the matrix.

DISCUSSION

DISTRIBUTION

Three major faunal groups appeared in the numerical analyses—a nearshore turbulent zone group and two estuarine groups. The turbulent zone group, dominated by *Glabratella ornatissima*, *Rotorbinella cam-*

panulata, and *Cribrononion lene*, is influenced by wind-driven waves and is typical of exposed, nearshore foraminiferal faunas along this coast (Erskian and Lipps, 1977). The estuarine assemblages were split into two groups, one which occupied the middle bay region, and the other the bay end sections. The only apparent physical environmental distinction between these groups was the finer grain size in the middle bay region (see Fig. 3). The midbay group was dominated by *Hopkinsina pacifica*, *Bulimina denudata*, *Fursenkoina pontoni*, *Brizalina vaughani*, and *B. acuminata*. The bay end estuarine groups were characterized by *Elphidiella hannai*, *Buccella tenerrima*, and *Buliminella elegantissima*. Canonical variate analysis indicated a subgroup of northern estuarine samples, apparently related to some oceanic influence. Thus a gradient exists between the nearshore turbulent zone assemblage affected by oceanic conditions and the protected estuarine assemblages.

Periodic major floods, such as occurred January 3–5, 1982, just before we collected our winter samples, occur every 5 to 25 years judging from nearby, inland records (Brown, 1988). These floods, and the January 1982 flood in particular, seem to have little effect on the foraminiferal fauna, probably because the flood-derived sediment deposition occurred near stream mouths with minor deposition of very fined-grained sediment in most of the bay (Anima and others, 1988). Soon after the deposition of the flood layer, bioturbation had totally homogenized the sediment in many areas of the bay (Anima and others, 1988). Most storm deposition was at the mouths of Walker Creek and Lagunitas Creek.

Some of the species found in the bay (e.g., *Bulimina denudata*, several species of *Brizalina*, and *Fursenkoina pontoni*) are more characteristic of the warmer water Californian Province, described in various papers (e.g., Bandy, 1953; Uchio, 1960; Lankford and Phleger, 1973), and thus seem out of place in a bay well within the Oregonian Provincial range. However, Addicott (1966) noted many southern mollusks in the Pleistocene Millerton Formation at Tomales Bay, and suggested these could represent a relict fauna from a time when water temperatures may have been warmer along the coast. Alternatively, he wrote these could have been the result of pelagic larvae carried along the coast by the northward moving Davidson Current during an unusually warm period. In any case, these warm water mollusks were able to become established in the shallow, protected waters of Tomales Bay. Although transport by northward flowing currents cannot account for the presence of southern foraminifera with-

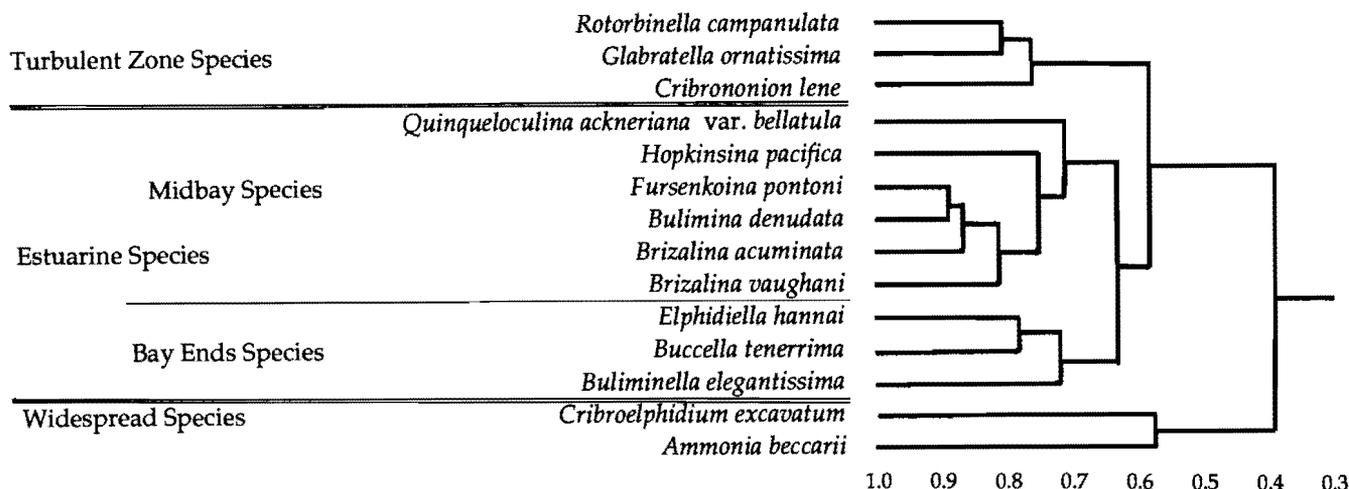


FIGURE 17. Dendrogram of R-mode cluster analysis, showing species assemblages in Tomales Bay.

out pelagic dispersal phases in Tomales Bay, these foraminifera might represent a relict fauna from a time of warmer coastal waters, or may have been transported by birds or other means from areas farther south. Today, the water temperature range in the bay overlaps the temperature range in the San Diego area far to the south. The southern species may be unable to survive in nearby areas affected by northern marine conditions.

Many of the Tomales Bay species occur in San Francisco Bay (Arnal and others, 1980). These include *Ammonia beccarii*, *Brizalina vaughani*, *Bulimina marginata* (possibly related to *B. denudata* of the present study), *Buliminella elegantissima*, *Elphidiella hannai*, *Hopkinsina pacifica*, *Quinqueloculina bellatula* (= *Q. ackneriana* var. *bellatula*?), *Trochammina inflata*, and varieties of *Elphidium incertum*. Most of the individuals were found near the northern part of the bay (i.e., in areas of greater marine influence) or in deeper channels, possibly below the level of salinity stratification. Arnal and others (1980) stated that *H. pacifica* was most closely associated with oceanic waters; however, this suggestion is not supported in the present study. In Tomales Bay, *H. pacifica* was principally restricted to areas of fine grain size. A comparison of the distribution of *H. pacifica* and grain size in San Francisco Bay suggests a correlation between grain size and its distribution there as well. *Ammonia beccarii* was widespread in both Tomales Bay and San Francisco Bay, and was common in marginal environments in both. Arnal and other (1980) suggested *A. beccarii* may be less competitive with other species and thus must occupy less favorable areas. In contrast, they suggested that *Elphidiella hannai* is a good competitor, high in

abundance even when there are many other species present. This pattern was less strongly developed in Tomales Bay and was true only in some parts of the estuarine section of the bay; it did not occur in the nearshore turbulent zone nor in the extreme southern end of the bay. It is likely that competitive abilities of these species do not control their distribution.

No permanent estuarine fauna developed in the Russian River estuary just north of Tomales Bay because

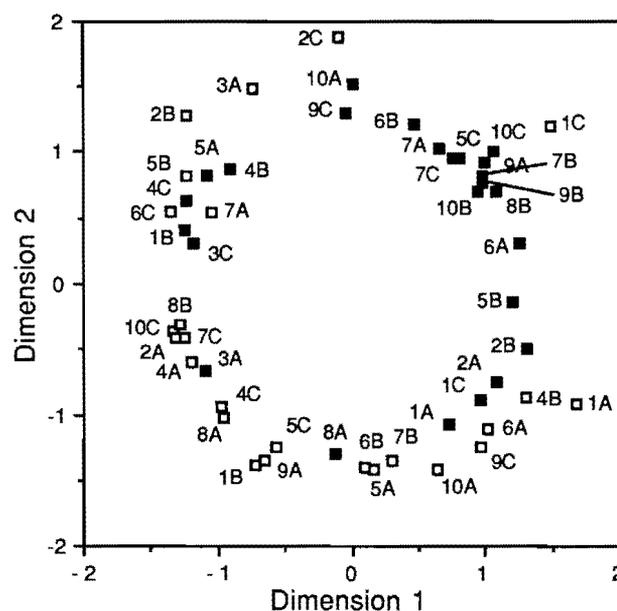


FIGURE 18. Two dimensional configuration obtained by multiple dimensional scaling (winter stations are solid squares, summer stations are open squares).

of the extremely high winter freshwater runoff (Erskian and Lipps, 1977). Only a very few species dominated the incursive marine fauna that developed during the summer months. *Criboelphidium excavatum* strongly dominated the estuary, whereas species diversity and equitability were greater offshore. In contrast, more stable conditions in Tomales Bay allow the development of a diverse and abundant estuarine fauna. Species common to both the Russian River estuary and Tomales Bay included *Buccella tenerrima*, *Bulimina elegantissima*, *Criboelphidium excavatum*, *Elphidium hannai*, *Glabratella ornatissima*, *Haplophragmoides columbiense*, *Quinqueloculina ackneriana* var. *bellatula*, and *Rotorbinella campanulata*. Several species abundant in Tomales Bay were not represented in the Russian River estuary, including *Ammonia beccarii*, *Hopkinsina pacifica*, *Brizalina* spp., and *Fursenkoina pontoni*. *Ammonia beccarii* occupies marginal estuarine environments and thus would not necessarily comprise part of a marine fauna like that which invades the Russian River estuary. *Brizalina* spp. and *F. pontoni* may be part of the southern fauna that can survive only in warmer bays.

SUMMER AND WINTER VARIATION

Overall, foraminiferal abundance in Tomales Bay was roughly constant in both winter and summer, perhaps partly because of the constant conditions in the bay caused by normally limited freshwater runoff and good tidal mixing. Those conditions are low salinity variation, fairly constant temperature, and a protected bay with little direct oceanic influence such as winter storm waves.

Some species showed a seasonal dominance; when such a species is characteristic of a certain environment the seasonality of the species may be expressed as the seasonality seen in some of the stations or transects. For example, *Glabratella ornatissima*, restricted to the nearshore turbulent zone, showed a strong summer dominance (see also Erskian and Lipps, 1987), and thus the northernmost stations showed a seasonal shift towards a more estuarine environment as its population decreased in the winter. Winter middle bay stations were significantly distinct from the remainder of the bay. The middle bay differed slightly from the rest of the bay during the summer. The distinction between the winter middle bay and the rest of the bay results from the winter dominance of *Hopkinsina pacifica* and *Bulimina denudata*, both of which were predominantly middle bay species. Although the seasonality observed in some stations and transects can be attributed to the

seasonality of these species, the underlying reasons for the seasonality of individual species cannot be determined from the data obtained in the present study.

CONCLUSIONS

Tomales Bay differs from many estuaries because of a lack of strong horizontal and vertical salinity or temperature gradients; an analysis of the foraminiferal fauna of this protected bay may provide a new model for paleoecological studies. The distribution of the faunal elements divides the bay into three distinct regions: a nearshore turbulent area with a strong oceanic influence; a middle bay region that contained many of the unusual, southern species and had an overall finer grain size than the rest of the bay; and the remainder of the estuary, with a more typical Oregonian estuarine fauna. Numerical analysis indicated a gradation from the nearshore zone to the northern estuarine zone.

Two of the three types of numerical analyses performed, multiple discriminant (MDA) and cluster analysis, yield approximately the same distributional patterns. Of these, MDA is preferable because it more easily displays trends in the data. The sampling requirements, however, are more rigorous than for cluster analysis. Multidimensional scaling did indicate some trends in foraminiferal distribution, but the patterns it revealed were not as clear or as interpretable as those revealed by the other two methods.

The bay contains a diverse and abundant fauna in both summer and winter that included many species characteristic of the Oregonian Province. In addition, several species characteristic of more southern waters appeared in restricted, well protected parts of the bay. A strong seasonal dominance in some species contributed to seasonal shifts of the nearshore marine environment to more estuarine conditions in the winter and of the middle bay region to more homogeneous estuarine conditions during the summer. Although these changes were statistically significant, this study was conducted over only two seasons and thus may not be typical of longer term trends.

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APPENDIX 1

Alphabetical list of genera and species found in this study. Generic assignments follow Loeblich and Tappan (1988).

- Ammobaculites catenulatus* Cushman and McCulloch, 1939, p. 90, pl. 7, figs. 11–14.
- Ammofrondicularia* sp. One specimen was found that we assigned to this doubtful genus. It could likely be a *Reophax* or another agglutinated species as well.
- Ammonia beccarii* (Linne). *Nautilus beccarii* Linne, 1758, p. 710. *Rotalia beccarii* (Linne), Cushman, 1922, p. 52, pl. 8, figs. 7–9. *Ammonia beccarii* (Linne), Buzas, 1965, p. 62, pl. 4, fig. 1.
- Angulodiscorbis charlottensis* (Cushman). *Discorbis charlottensis* Cushman, 1925, p. 42, pl. 7, fig. 2, Lankford and Phleger, 1973, p. 114, pl. 5, figs. 1–2.
- Bolivina compacta* Sidebottom. *Bolivina robusta* Brady var. *compacta* Sidebottom, 1905, p. 15, pl. 3, fig. 7, Lankford and Phleger, 1973, p. 115, pl. 4, fig. 3.
- Bolivina subexcavata* Cushman and Wickenden, 1929, p. 9, pl. 4, fig. 4, Lankford and Phleger, 1973, p. 115, pl. 4, fig. 8.
- Brizalina acuminata* (Natland). *Bolivina subadvena* Cushman var. *acuminata* Natland, Cushman and Gray, 1946, p. 34, pl. 5, fig. 46, Lankford and Phleger, 1973, p. 115, pl. 4, fig. 5.
- Brizalina acutula* (Bandy). *Bolivina advena* Cushman var. *acutula* Bandy, 1953, p. 180, pl. 24, fig. 7, Lankford and Phleger, 1973, p. 115, pl. 4, fig. 4.
- Brizalina pacifica* (Cushman and McCulloch). *Bolivina acerosa* Cushman var. *pacifica* Cushman and McCulloch, 1942, p. 185, pl. 21, figs. 2, 3, Lankford and Phleger, p. 115, pl. 4, fig. 7.
- Brizalina* spp.
- Brizalina vaughani* (Natland). *Bolivina vaughani* Natland, 1938, p. 146, pl. 5, fig. 11, Lankford and Phleger, 1973, p. 116, pl. 4, fig. 9.
- Buccella tenerrima* (Bandy). *Rotalia tenerrima* Bandy, 1950, p. 278, pl. 42, fig. 3, Lankford and Phleger, 1973, p. 116, pl. 4, fig. 19.
- Bulimina denudata* Cushman and Parker. *Bulimina pagoda* Cushman var. *denudata* Cushman and Parker, 1938, p. 57, fig. 10, figs. 1, 2. *Bulimina denudata* Cushman and Parker, 1947, p. 117, pl. 27, figs. 13, 14, Cushman and McCulloch, 1948, p. 245, pl. 30, fig. 7, Uchio, 1960, p. 31, pl. 6, fig. 3.
- Buliminella elegantissima* (d'Orbigny). *Bulimina elegantissima* d'Orbigny, 1839, p. 51, pl. 7, figs. 13, 14. *Buliminella elegantissima* (d'Orbigny), Cushman, 1919, p. 606, Lankford and Phleger, 1973, p. 116, pl. 4, fig. 2.
- Cassidulina* cf. *C. delicata* (Cushman). ?*Cassidulina delicata* Cushman, 1927, p. 168, pl. 6, fig. 5, Lankford and Phleger, 1973, p. 116, pl. 6, fig. 6.
- Cassidulina limbata* Cushman and Hughes, 1925, pl. 2, fig. 2, Lankford and Phleger, 1973, p. 116, pl. 6, fig. 4.
- Cibicides fletcheri* Galloway and Wissler, 1927, p. 64, pl. 10, figs. 8, 9.
- Cibicides lobatulus* (Walker and Jacob). *Nautilus lobatulus* Walker and Jacob, 1798, p. 642, pl. 14, fig. 36, Cushman, 1944, p. 36, pl. 4, figs. 27, 28.
- Criboelphidium excavatum* (Terquem). *Polystomella excavata* Terquem, 1876, p. 429, pl. 2, fig. 2a–d.
- Cribronion lene* (Cushman and McCulloch). *Elphidium incertum* (Williamson) var. *lene* Cushman and McCulloch, 1940, p. 170, pl. 19, figs. 2, 4, Lankford and Phleger, 1973, p. 118, pl. 3, fig. 18. This species was distinguished from *C. excavatum* by its less distinct sutures and by its greater degree of perforation; it strongly resembles *Elphidium* sp. 1 of Quintero and Gardner (1987). It was the most abundant species in the entire bay, occurring at almost every station. It was one of two summer dominant species and was included in the statistical analyses.
- Cyclogyra involvens* (Reuss). *Operculina involvens* Reuss, 1850, p. 370, pl. 46, fig. 20, Lankford and Phleger, 1973, p. 118, pl. 2, fig. 23. Genus is considered a synonym of *Cornuspira* by Loeblich and Tappan (1988).
- Eggerella advena* (Cushman). *Veneuilina advena* Cushman, 1921, p. 9, Cushman, 1936, p. 51, pl. 5, figs. 12–15, Cushman and Todd, 1947, p. 5, pl. 1, fig. 9.
- Elphidiella hannai* (Cushman and Grant). *Elphidium hannai* Cushman and Grant, 1927, p. 78, pl. 8, fig. 1. *Elphidiella hannai* (Cushman and Grant), Cushman, 1939, pl. 3, fig. 26. Lankford and Phleger (1973) noted that the only distinction between *E. nitida* and *E. hannai* was the presence of short spinose structures on the apertural face of *E. nitida*; however, they believe these are the “same species because they have the same distribution and large and often worn specimens lack the spinose growth while smaller, fresh-appearing specimens possess this delicate growth in the apertural area.” (p. 119).
- Elphidium crispum* (Linne). *Nautilus crispus* Linne, 1758, p. 709. Lankford and Phleger, 1973, p. 119, pl. 3, fig. 25.
- Elphidium translucens* Natland, 1938, p. 144, pl. 5, figs. 3, 4.
- Fissurina lucida* (Williamson). *Entosolenia marginata* var. *lucida* Williamson, 1848, p. 17, pl. 2, fig. 17. *Entosolenia lucida* (Williamson), Cushman and Gray, 1946, p. 30, pl. 5, figs. 16–18. *Fissurina lucida* (Williamson), Bandy, 1950, p. 274, pl. 41, fig. 12, Lankford and Phleger, 1973, p. 119, pl. 3, fig. 7.
- Fursenkoina pontoni* (Cushman). *Virgulina pontoni* Cushman, 1932, p. 17, pl. 3, fig. 7. *Fursenkoina pontoni* (Cushman), Lankford and Phleger, 1973, p. 119, pl. 4, fig. 17.
- Fursenkoina* sp. a.
- Fursenkoina* sp. b. cf. *F.* sp. 1. Lankford and Phleger, 1973, p. 120, pl. 4, fig. 15.
- Gaudryina subglabrata* Cushman and McCulloch, 1939, p. 92, pl. 8, figs. 5–7.
- Glabratella ornatissima* (Cushman). *Discorbis ornatissima* Cushman, 1925, p. 42, pl. 6, figs. 11, 12. *Eponides columbiensis* (Cushman), Cushman and Todd, 1947, p. 22, pl. 4, fig. 1. *Glabratella ornatissima* (Cushman), Lipps and Erskian, 1969, fig. 1. This species is bimorphic, with a large microspheric generation and a small megalospheric generation (Erskian and Lipps, 1987). Megalospheric specimens often occur as plastogamous pairs. Lankford and Phleger assign specimens to *Trichohyalus ornatissima*; however, we follow Lipps and Erskian and use the name *Glabratella ornatissima*. This species is characteristic of the nearshore turbulent zone and is thus restricted to the extreme north part of the bay.
- Haplophragmoides columbiense* Cushman, 1925, p. 39, pl. 6, fig. 2, Cushman and McCulloch, 1939, p. 72, pl. 5, figs. 8–10.
- Hopkinsina pacifica* Cushman, 1933, p. 86, pl. 9, figs. 3, 4.
- Miliammina fusca* (Brady). *Quinqueloculina fusca* Brady, 1870, p. 286, pl. 11, figs. 2a–c, 3, Parker and Athearn, 1959, pl. 50, figs. 11, 12.
- Miliolinella californica* Rhumbler, 1936, p. 215, Lankford and Phleger, 1973, p. 123, pl. 2, fig. 8.
- Millettella glabrella* Cushman and McCulloch, 1939, p. 43, pl. 2, fig. 3. Loeblich and Tappan (1964) consider this genus to be a synonym of the thecamoebian *Centropyxis*.
- Nonionella basispinatus* (Cushman and Moyer). *Nonion pizarrense* var. *basispinata* Cushman and Moyer, 1930, p. 54, pl. 7, fig. 18. *Nonionella basispinatus* (Cushman and Moyer), Bandy, 1950, p. 275, pl. 41, fig. 7.

- Nonionella stella* (Cushman and Moyer). *Nonionella miocenica* Cushman var. *stella* Cushman and Moyer, 1930 p. 56, pl. 7, fig. 17. *Nonionella stella* Cushman and Moyer, Uchio, 1960, p. 61, pl. 4, figs. 15, 16.
- Nouria polymorphinoides* Heron-Allen and Earland, 1914, p. 376, pl. 137, figs. 1–15, Cushman and McCulloch, 1939, p. 111, pl. 12, figs. 5–10, Lankford and Phleger, 1973, p. 123, pl. 3, fig. 1.
- Oolina costata* (Williamson). *Entosolenia costata* Williamson, 1858, p. 9, pl. 1, fig. 18, Lankford and Phleger, 1973, p. 123, pl. 3, fig. 1.
- Protonina* sp. = *Reophax* sp.
- ?*Pseudobolivina* sp.
- Quinqueloculina ackneriana* d'Orbigny var. *bellatula* Bandy, 1950, p. 273, pl. 41, fig. 1, Lankford and Phleger, 1973, p. 125, pl. 2, fig. 7. Reported in Appendix II and Tables as *Q. ackneriana*.
- Quinqueloculina laevigata* d'Orbigny, 1826, p. 301, no. 6, Lankford and Phleger, 1973, p. 126, pl. 2, figs. 5, 6.
- Quinqueloculina* spp. These specimens included broken fragments with stained protoplasm. The distribution was similar to that of other members of the genus *Quinqueloculina*.
- Quinqueloculina vulgaris* d'Orbigny, 1826, p. 302, no. 33, Lankford and Phleger, 1973, p. 126, pl. 2, fig. 1.
- Reophax communis* Lacroix, 1930, p. 4, figs. 5–7, Cushman and McCulloch, 1939, p. 68, pl. 3, fig. 12.
- Reophax scottii* Chaster, 1892, p. 57, pl. 1, fig. 1, Cushman and McCulloch, 1939, p. 61, pl. 3, fig. 11.
- Reophax* spp. These specimens included fragments of tests filled with stained protoplasm.
- Rosalina columbiensis* (Cushman). *Discorbis columbiensis* Cushman, 1925, p. 43, pl. 6, fig. 13. *Rosalina columbiensis* (Cushman), Lankford and Phleger, 1973, p. 127, pl. 5, fig. 10–12.
- Rosalina* sp. Specimens were very small with 4–6 chambers, and may be juvenile *R. columbiensis*. All specimens were found in a single summer replicate sample at station 1C.
- Rotorbinella campanulata* (Galloway and Wissler). *Globorotalia campanulata* Galloway and Wissler, 1927, p. 58, pl. 9, fig. 4. Loeblich and Tappan (1988) synonymized this genus with *Trochulina* but we retain it because of its common usage in California.
- Textularia agglutinans* d'Orbigny, 1839, p. 136, pl. 1, figs. 17, 18, 32, 24, Lalicker and McCulloch, 1940, p. 117, pl. 13, fig. 2.
- Textularia schencki* Cushman and Valentine, 1930, p. 8, pl. 1, fig. 3, Lalicker and McCulloch, 1940, p. 140, pl. 16, fig. 23.
- Textularia* sp.
- Trochammina charlottensis* Cushman, 1925, p. 39, pl. 6, fig. 4, Cushman and Todd, 1947, p. 10, pl. 1, fig. 12.
- Trochammina inflata* (Montagu). *Nautilus inflatus* Montagu, 1808, p. 81, pl. 18, fig. 3. *Trochammina inflata* (Montagu), Cushman, 1944, p. 17, pl. 2, fig. 8. *Trochammina inflata* (Montagu), Cushman and McCulloch, 1939, p. 102, pl. 11, fig. 2.
- Trochammina pacifica* Cushman, 1925, p. 39, pl. 6, fig. 3, Cushman and McCulloch, 1939, p. 102, pl. 11, fig. 2, Lankford and Phleger, 1973, p. 130, pl. 3, fig. 2.

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APPENDIX 2. Tomales Bay foraminifera—census data.

	Station																									
	1A1	1A2	1B1	1B2	1C1	1C2	2A1	2A2	2B1	2B2	2C1	2C2	3A1	3A2	3B1	3B2	3C1	3C2	4A1	4A2	4B1	4B2	4C1	4C2	5A1	
Summer samples																										
<i>Ammobaculites catenulatus</i>																										
<i>Ammofrondicularia</i> sp.													126	77					1							
<i>Ammonia beccarii</i>										1																2
<i>Angulodiscorbis charlot-</i> <i>tensis</i>																							3			
<i>Bolivina compacta</i>																										
<i>B. subexcavata</i>							1	1																		
<i>Brizalina acuminata</i>																						8				
<i>B. acutula</i>							1																			
<i>B. pacifica</i>																										
<i>B. vaughani</i>						1													1			2	1			
<i>B. spp.</i>																										
<i>Buccella tenerrima</i>					2	17	35	44	48	4								59	56			447	184		1	
<i>Bulimina denudata</i>																						15	10			
<i>Buliminella elegantissima</i>						1	2	6		3								22	48			182	44			
<i>Cassidulina</i> cf. <i>C. delicata</i>																										
<i>C. limbata</i>			4		5			4			1															
<i>Cibicides fletcheri</i>						1			2									1								
<i>C. lobatulus</i>					2	2	8	3	1	1													3		1	
<i>Criboelphidium excavatum</i>				1	12	25	7	32	3	9			181	95				145	175			184	49	1	3	9
<i>Cribrononion lene</i>				1	2	7	9	12										5	13			1	7			
<i>Cyclogyra involvens</i>						4																				
<i>Eggerella advena</i>																										
<i>Elphidiella hannai</i>		12	12	19	2	2	18	34	10	19			1					121	95			422	260	2	1	5
<i>Elphidium crispum</i>		8	2	5		2													1							
<i>E. translucens</i>																										
<i>Fissurina lucida</i>						1													2							
<i>Fursenkoina pontoni</i>																						61	10			
<i>F. sp. a</i>																										
<i>F. sp. b</i>																							1			
<i>Gaudryina subglabrata</i>																										
<i>Glabrataella ornatissima</i>	71	149	61	109	103	22	4	5									4	3								
<i>Haplophragmoides colum-</i> <i>biensis</i>							1																			
<i>Hopkinsina pacifica</i>																						248	59			
<i>Miliammina fusca</i>																										
<i>Miliolinella californica</i>																										
<i>Millettella glabrella</i>																										
<i>Nonionella basispinatus</i>					1		1	1											2			26	9			
<i>N. stella</i>																			1			41	12			
<i>Nouria polymorphinoides</i>								2		1																
<i>Oolina costata</i>																										
<i>Proteonina</i> sp.																										
? <i>Pseudobolivina</i>																										
<i>Quinqueloculina ackneriana</i>														1												
<i>Q. laevigata</i>							1			1																
<i>Q. vulgaris</i>			1		1	4		3																	2	
<i>Q. spp.</i>					1	4																				
<i>Reophax communis</i>																										
<i>R. scottii</i>																										
<i>R. spp.</i>																										
<i>Rosalina columbiensis</i>						1								1				1	1							
<i>R. sp. (juveniles?)</i>						26																				
<i>Rotorbinella campanulata</i>					7	4	18	19															1		1	
<i>Textularia agglutinans</i>																					1					
<i>T. schencki</i>																					1					
<i>T. sp.</i>																					1					
<i>Trochammina charlottensis</i>					1	1																				
<i>T. inflata</i>												1	1									1				
<i>T. pacifica</i>																										
Other unidentified specimens							1					2		3									1			
Total	71	173	76	142	151	146	116	167	18	36	3	0	311	175	0	0	358	398	3	0	1,638	654	3	4	21	

APPENDIX 2. Continued.

	Station																											
	1A1	1A2	1B1	1B2	1C1	1C2	2A1	2A2	2B1	2B2	2C1	2C2	3A1	3A2	3B1	3B2	3C1	3C2	4A1	4A2	4B1	4B2	4C1	4C2	4D1	4D2	5A1	
Winter samples																												
<i>Ammobaculites catenulatus</i>																												
<i>Ammofrondicularia</i> sp.																												
<i>Ammonia beccarii</i>				1					1																	1		4
<i>Angulodiscorbis charlot-</i> <i>tensis</i>																												
<i>Bolivina compacta</i>						1	2	1	8							1												
<i>B. subexcavata</i>				5	2	1	5						2	2								2						1
<i>Brizalina acuminata</i>																							3					5
<i>B. acutula</i>																												2
<i>B. pacifica</i>																											1	2
<i>B. vaughani</i>					4	1	3	3					4	1								3			1			9
<i>B. spp.</i>																												
<i>Buccella tenerrima</i>	1	2	3		26	21	60	18	1	3		1	31	14					10	1	56	113	45	14			73	
<i>Bulimina denudata</i>																						5	15	3	1			35
<i>Bulminella elegantissima</i>			2		40	18	65	5			1		79	47					1	1	82	123	80	59			11	
<i>Cassidulina</i> cf. <i>C. delicata</i>																												
<i>C. limbata</i>							1	1			1																	
<i>Cibicides flectcheri</i>						2	1	5	16		2																	
<i>C. lobatulus</i>					13	12	13	45	1	1																		
<i>Criboelphidium excavatum</i>			7	4	17	9	12	18				3	2	79	39				9	3	35	100	48	25			19	
<i>Cribrononion lene</i>		1	1		131	37	147	83	1		3		96	49								12	11	8	4		1	
<i>Cyclogyra involvens</i>						2		6																				
<i>Eggerella advena</i>							2																					
<i>Elphidiella hannai</i>	2	1		2	5	3	65	7	1	1			70	52					25	10	108	299	190	85			69	
<i>Elphidium crispum</i>											1																	
<i>E. translucens</i>																												
<i>Fissurina lucida</i>				1			2												1		1	1	3					
<i>Fursenkoina pontoni</i>																			10		1	3	13	3			2	
<i>F. sp. a</i>																						4						
<i>F. sp. b</i>					1		1													2								
<i>Gaudryina subglabrata</i>																												
<i>Glabratella ornatissima</i>		1			16	9	7																					
<i>Haplophragmoides colum-</i> <i>biensis</i>			1		6	1	5	46																				
<i>Hopkinsina pacifica</i>													3						13	4	16	80	132	24			46	
<i>Miliammina fusca</i>					1			3																				
<i>Miliolinella californica</i>								1	10																		1	
<i>Millettella glabrella</i>																												
<i>Nonionella basispinatus</i>								3	1						1					2	2	4	10	8	5			
<i>N. stella</i>															5					3		5	7	1				
<i>Nouria polymorphinoides</i>				73		3					1	2																
<i>Oolina costata</i>					2										2													
<i>Proteonina</i> sp.																												
? <i>Pseudobolivina</i>																												
<i>Quinqueloculina ackneriana</i>					14	7		7																				
<i>Q. laevigata</i>					3	3		2					1	3														
<i>Q. vulgaris</i>		2			10	12	1	2					1															
<i>Q. spp.</i>								2																				
<i>Reophax communis</i>																												
<i>R. scottii</i>																												
<i>R. spp.</i>											1																	
<i>Rosalina columbiensis</i>																												
<i>R. sp. (juveniles?)</i>																												
<i>Rotorbinella campanulata</i>					65	28	23	116							12									1				
<i>Textularia agglutinans</i>															1													
<i>T. schencki</i>																												
<i>T. sp.</i>																											1	
<i>Trochammina charlottensis</i>			1		2		7	28																				
<i>Trochammina inflata</i>					12	6	7	7																				
<i>T. pacifica</i>					2	3		6			1																	
Other unidentified specimens																						1	1					
Total	3	7	15	80	379	182	432	445	4	9	10	5	366	229	0	0	0	0	0	74	23	327	769	535	225	0	1	281

APPENDIX 2. Extended.

	Summer total	Winter total	Grand total
<i>Ammobaculites catenulatus</i>	0	4	4
<i>Ammofrondicularia</i> sp.	0	1	1
<i>Ammonia beccarii</i>	1,114	608	1,722
<i>Angulodiscorbis charlot-</i> <i>tensis</i>	0	1	1
<i>Bolivina compacta</i>	4	29	33
<i>B. subexcavata</i>	15	28	43
<i>Brizalina acuminata</i>	93	201	294
<i>B. acutula</i>	12	35	47
<i>B. pacifica</i>	0	60	60
<i>B. vaughani</i>	36	115	151
<i>B. spp.</i>	1	4	5
<i>Buccella tenerrima</i>	1,348	909	2,257
<i>Bulimina denudata</i>	253	567	820
<i>Buliminella elegantissima</i>	381	856	1,237
<i>Cassidulina</i> cf. <i>C. delicata</i>	0	2	2
<i>C. limbata</i>	15	3	18
<i>Cibicides fletcheri</i>	4	28	32
<i>C. lobatulus</i>	22	85	107
<i>Cribrorophidium excavatum</i>	2,309	904	3,213
<i>Cribrononion lene</i>	58	587	645
<i>Cyclogyra involvens</i>	7	9	16
<i>Eggerella advena</i>	0	5	5
<i>Elphidiella hannai</i>	1,456	1,241	2,697
<i>Elphidium crispum</i>	18	1	19
<i>E. translucens</i>	0	9	9
<i>Fissurina lucida</i>	13	13	26
<i>Fursenkoina pontoni</i>	209	263	472
<i>F</i> sp. a	0	6	6
<i>F. sp. b</i>	3	11	14
<i>Gaudryina subglabrata</i>	1	0	1
<i>Glaboratella ornatissima</i>	531	33	564
<i>Haplophragmoides colum-</i> <i>biensis</i>	38	62	100
<i>Hopkinsina pacifica</i>	764	2,013	2,777
<i>Miliammina fusca</i>	1	54	55
<i>Miliolinella californica</i>	0	13	13
<i>Millettella glabrella</i>	0	1	1
<i>Nonionella basispinatus</i>	48	67	115
<i>N. stella</i>	59	73	132
<i>Nouria polymorphinoides</i>	4	81	85
<i>Oolina costata</i>	0	4	4
<i>Proteonina</i> sp.	0	1	1
? <i>Pseudobolivina</i>	7	0	7
<i>Quinqueloculina ackneriana</i>	64	104	168
<i>Q. laevigata</i>	10	16	26
<i>Q. vulgaris</i>	27	32	59
<i>Q. spp.</i>	8	6	14
<i>Reophax communis</i>	4	31	35
<i>R. scottii</i>	13	0	13
<i>R. spp.</i>	0	2	2
<i>Rosalina columbiensis</i>	4	9	13
<i>R. sp.</i> (juveniles?)	26	0	26
<i>Rotorbinella campanulata</i>	62	250	312
<i>Textularia agglutinans</i>	10	7	17
<i>T. schencki</i>	1	2	3
<i>T. sp.</i>	1	0	1
<i>Trochammina charlottensis</i>	2	38	40
<i>T. inflata</i>	20	41	61
<i>T. pacifica</i>	7	12	19
Other unidentified specimens	10	10	20
Total	9,093	9,552	18,645

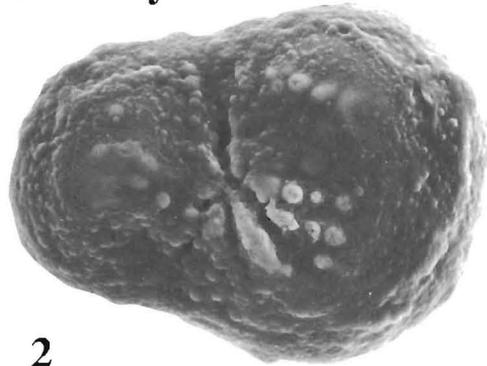
PLATE I

Foraminifera from the nearshore turbulent zone at the north end of Tomales Bay. **1** *Glaboratella ornatissima* (Cushman) adult microsphere, ×83. **2** *Glaboratella ornatissima* (Cushman), juvenile microsphere, ×480. **3** *Glaboratella ornatissima* (Cushman), plastogamous pair, ×143. **4** *Cribrononion lene* (Cushman and McCulloch), ×400. **5** *Rotorbinella campanulata* (Galloway and Wissler), umbilical side, ×305. **6** *Rotorbinella campanulata* (Galloway and Wissler), spiral side, ×200.

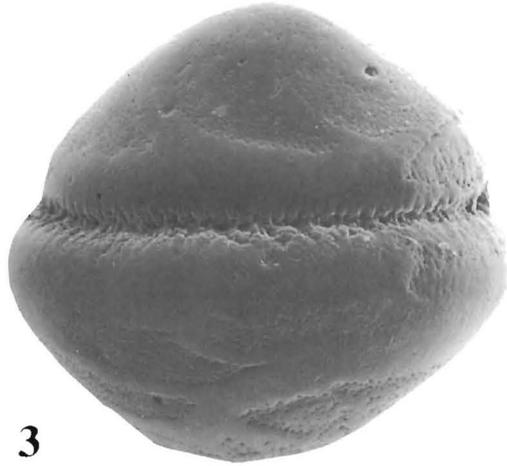
**Foraminifera from the nearshore turbulent zone,
northern Tomales Bay**



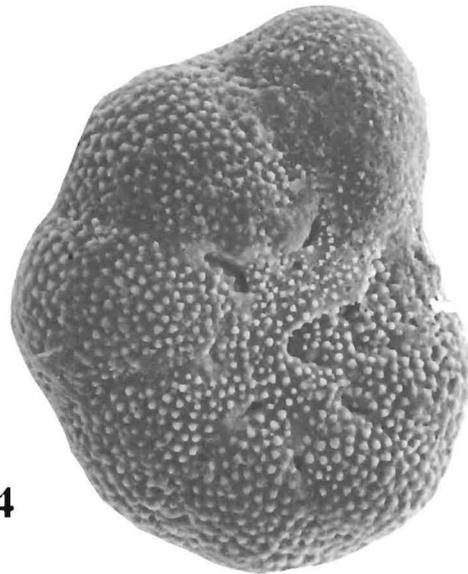
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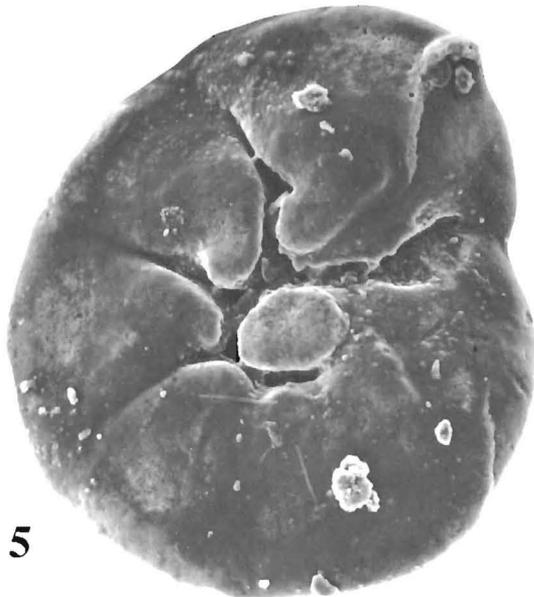
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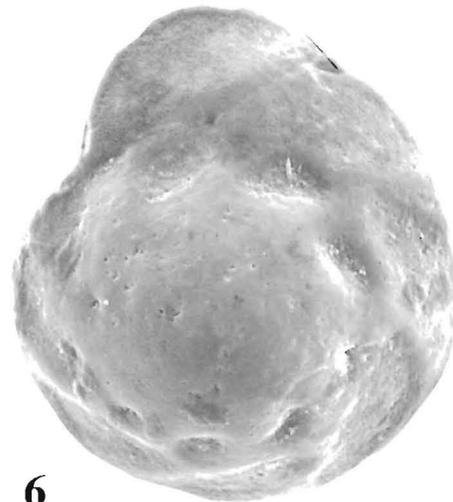
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5



6

PLATE 2

Foraminifera from the midbay region of Tomales Bay. **1** *Brizalina acuminata* (Natland), ×300. **2** *Brizalina vaughani* (Natland), ×650. **3** *Fursenkoina pontoni* (Cushman), ×450. **4** *Bulimina denudata* Cushman and Parker, ×200. **5** *Hopkinsina pacifica* Cushman, ×450. **6** *Quinqueloculina ackneriana* d'Orbigny var. *bellatula* Bandy, ×395.

Foraminifera from the midbay region of Tomales Bay

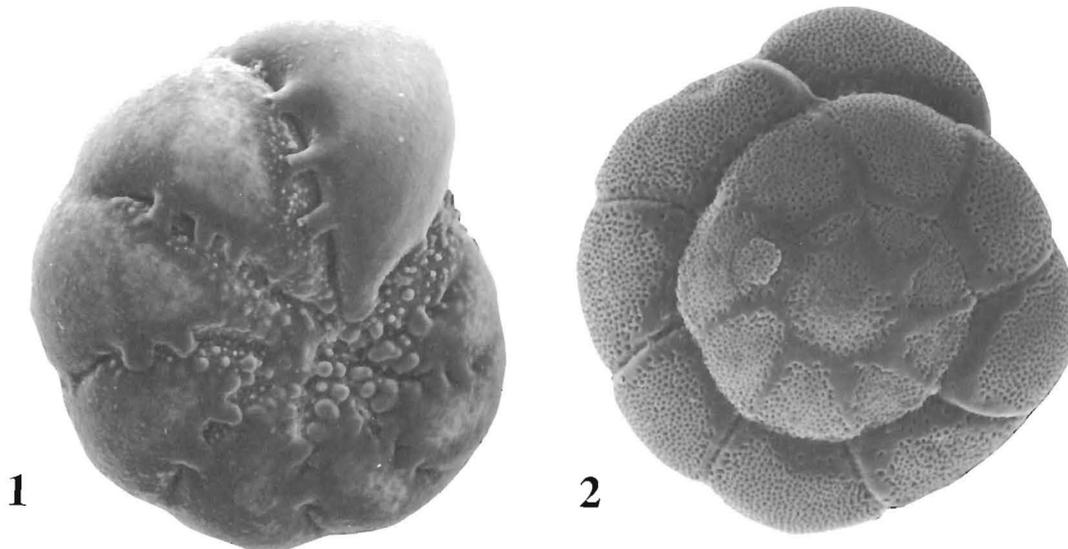


PLATE 3



Foraminifera widespread throughout Tomales Bay. **1** *Criboelphidium excavatum* (Cushman) ×400. **2** *Ammonia beccarii* (Linne), spiral side, ×240. Foraminifera from the ends of Tomales Bay. **3** *Buliminella elegantissima* (d'Orbigny), ×500. **4** *Elphidiella hannai* (Cushman and Grant), ×200. **5** *Buccella tenerrima* (Bandy), spiral side, ×260.

Foraminifera widespread in Tomales Bay



Foraminifera from the ends of Tomales Bay



RECENT SHALLOW WATER BENTHIC FORAMINIFERA FROM WESTERN NORWAY: ECOLOGY AND PALAEOECOLOGICAL SIGNIFICANCE

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ABSTRACT

The benthic foraminiferal assemblages from two shallow (<40 m), but oceanographically distinct, fjord settings from western Norway are discussed in terms of faunal changes along depth transects. At Syslakvåg, a restricted marine influence is reflected in the strong seasonal stratification of the water column and a three-fold subdivision of the faunas is apparent, with the most marked faunal transition corresponding to the zone of steepest temperature-depth and salinity-depth gradients. Below 15 m the dominant taxa are *Adercotryma glomerata*, *Buccella frigida* and *Elphidium albiumbilicatum*, while the shallower stations are dominated by *Eggerelloides scabrum*, *Elphidium williamsoni* and *Ammonia batavus*. At Håvarden, an increasing “open” marine influence is observed, particularly below the surface waters, and a two-fold subdivision of the faunas is

interpreted in response to these factors. The shallower stations are dominated by *A. batavus*, *E. scabrum*, *E. williamsoni* and *Trochammina bullata*; these give way, at depths greater than 10 m, to assemblages dominated by *Bulimina marginata*, *Cibicides lobatulus* and *Cassidulina laevigata*.

The presence of taxa with Arctic affinities are discussed in the context of reworking of older Quaternary sediments and the dissolution of calcareous tests. It is suggested that the shallow, seasonally variable waters of Norwegian fjords may provide southern refugia for these taxa. Equally, species’ northern limits are discussed, particularly in the context of palaeoenvironmental reconstructions from documented last interglacial sites at Bø and Fjøsanger, both from western Norway.

INTRODUCTION

The documentation of foraminiferal faunas within Norwegian fjords is limited and this is particularly true of the fjords of western Norway. In fact, it is probably true to state that the fossil faunas of this region are better documented than their modern counterparts. Since foraminiferal occurrence and composition in Quaternary sediments are commonly used to interpret the environment of deposition, an understanding of modern distribution patterns and their interpretation in terms of environmental variables are desirable.

Here we present the first quantitative account of the

distribution of ‘live’, ‘dead’ and ‘total’ foraminiferal assemblages from two localities within the fjord district of western Norway (Fig. 1); both with distinct oceanographic (hydrographic) settings. The localities were selected in an attempt to characterize the fjord faunas which are influenced by “shelf-type” oceanographic conditions and, by contrast, the conditions which prevail within semi-enclosed basins, as in many of the inner fjord districts. Our rationale has been to describe and quantify foraminiferal assemblages from possible modern analogue environmental settings for those which prevailed in western Norway during the warm phases of the Quaternary period.

Previously documented foraminiferal distributions from Norwegian fjords and adjoining regions include the publications of Kier (1900) on the Oslo Fjord; Höglund (1947) on the Gullmar Fjord, south west Sweden,

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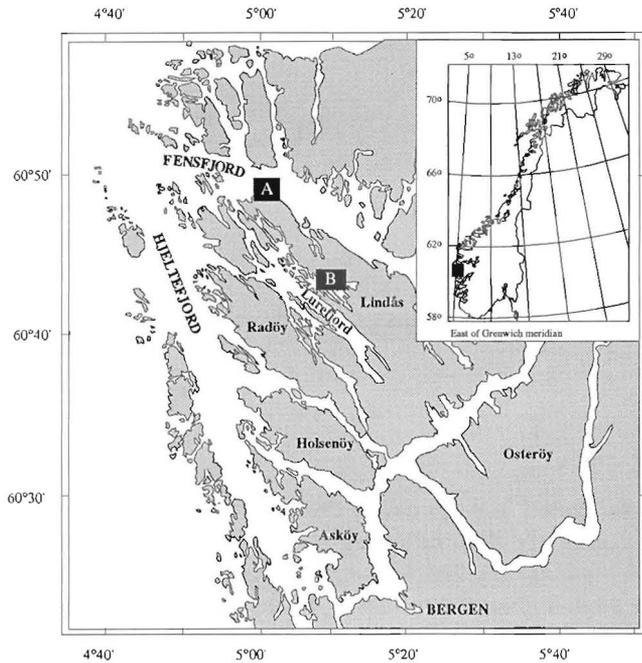


FIGURE 1. Location map of the study area; inset map showing location from western Norway.

and the Skagerrak; Christiansen (1958) on Drøbak Sound; and Risdal (1964) on the Oslo Fjord. More recently, Thiede and others (1981) re-evaluated Risdal's (1964) data, while Qvale and others (1984) discussed foraminiferal distribution in relation to hydrographic conditions from the Oslo Fjord, Gullmar Fjord and Skagerrak. Most recently, foraminiferal distributions have been interpreted in relation to human disturbance of the fjord environments; these include the publications of Alve and Nagy (1986) on Sandebukta, a branch of the Oslo Fjord, Alve and Nagy (1990) on the Oslo Fjord, and Alve (1991) on Drammensfjord, another branch of the Oslo Fjord. The most relevant publication dealing with foraminiferal distribution from shelf waters is that of Sejrup and others (1981) from the Norwegian continental margin between 62°N and 65°N.

MATERIAL AND METHODS

The foraminiferal samples were collected from the University of Bergen's research vessel "Hans Reuch" on 27 August 1987. A small, self-sealing box coring system, measuring 15 × 15 cm in cross-sectional area, was deployed to collect the surface sediment samples and material from the upper 1.5 cm were retained. Thus, each sample processed represents a sediment volume of 337.5 cm³, with an estimated ±10% error.

The samples were preserved with alcohol and subsequently stained with a solution of the protoplasmic stain rose Bengal. A second survey of the region was conducted during August 1992 from the University of Bergen's new research vessel "Hans Brattström", although only sedimentological data from the latter are included here.

Foraminiferal samples were prepared by wet sieving on 63 μm and 1.0 mm sieves. Subsequent floatation of the washed and dried fraction >125 μm was performed according to the methods outlined by Feyling-Hanssen (1958). Foraminifera were dry counted to distinguish between 'live' (stained) and 'dead' (unstained) specimens; with counts of >300 specimens or, alternatively, the entire sample when specimens numbered <300.

Grain size data were derived from dried sediment samples, and all values are expressed in terms of sediment dry weight as opposed to volume of wet sediment for the foraminiferal samples. Wet sieving was performed on 63 μm, 125 μm and 500 μm sieves.

OCEANOGRAPHIC SETTING

Data on the oceanographic conditions prevailing at the two localities were not collected during the sampling programme, but rather come from two independent sources. These are Gade (1973) on the oceanography of the Fensfjord during 1972, and Aure (1972) on the oceanography of Lindåspollene during 1971/72. Nearly twenty years separate the oceanographic and geologic sampling. While no major demographic or pollution changes are known to have occurred, it is always possible that such activities may lead to eutrophication or pollution resulting in oxygen deficit and possibly enhanced carbonate dissolution.

SPJELDNESEN

The first locality comprises a transect along a narrow inlet (Syslavåg) of an isolated, inland basin known as Spjeldnesosen (Fig. 2). Maximum water depths from this basin are a little greater than 80 m, although most of Syslavåg itself is less than 10 m deep. A number of small streams drain into Spjeldnesosen, but connections to more open marine waters are severely limited; the main connection is via a series of narrow and shallow channels which link Straumsosen, the adjoining basin, to the Lurefjord.

The oceanographic development within Spjeldnesosen (Aure, 1972) suggests a marked seasonal stratification of the water column (Fig. 4). The data presented here are from Aure's station F, located

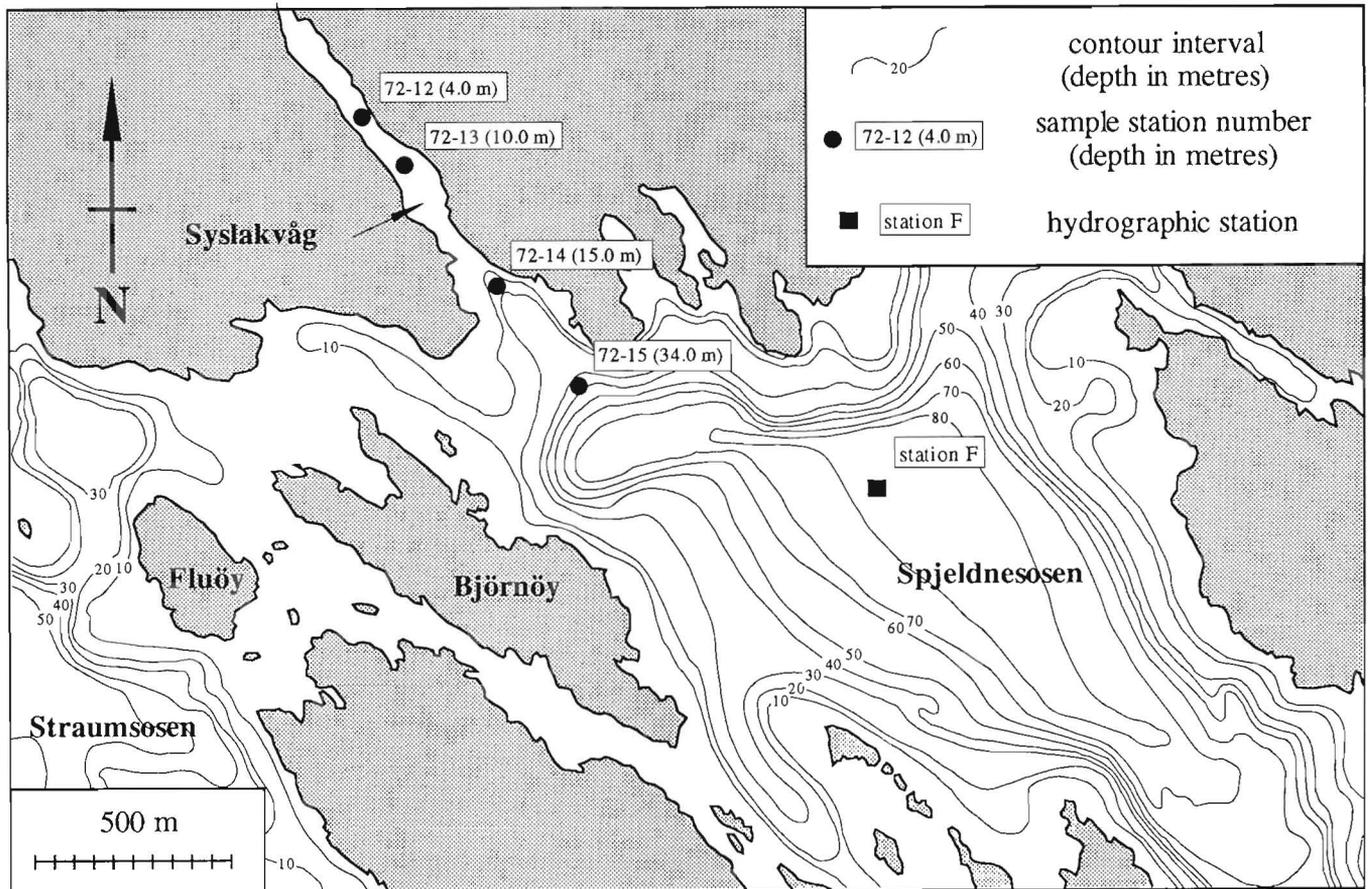


FIGURE 2. Bathymetric map of the Spjeldnesosen basin with sample stations located (after Aure, 1972).

approximately 800 m E.S.E. of station 75-15 (Fig. 2). Temperature profiles from this basin show an annual cycle which begins in January with ca. 7°C at 16 m. Unstable surface temperatures contrast with stable temperatures, close to 3°C, at depths greater than 30–40 m. The winter inversion is lost during the spring, with only a minor temperature-depth gradient developed. Rapid warming during May produces the very steep temperature-depth gradients of June and July, with the most marked changes in the upper 20 m. Again, below 20–30 m, there is little change in temperature with depth.

Salinity variations also follow a seasonal pattern, but with the strongest stratification developed during the late autumn. As with temperature, the salinity-depth gradients are steepest in the upper 20 m, and vary little below 30 m. Dissolved oxygen concentrations are also presented here (Fig. 4) and show similar patterns of stratification. Surface values vary from ca. 6–8 ml·l⁻¹, with highest values during December and lowest values during the late summer. Concentration-depth gradi-

ents are steepest between 10–30 m, and it is interesting to note that the stability of temperature and salinity at depth is not exhibited by oxygen concentrations.

FENSFJORD

The second locality comprises a transect off the south east coast of Håvarden, a small island located off the southern shores of the Fensfjord (Fig. 3). Maximum water depths from the Håvarden embayment are close to 40 m, but water depths in the main fjord quickly increase to >300 m, less than 500 m from the deepest sample station (72-10). The Fensfjord itself opens to the west onto the Norwegian shelf, with a sill depth of ca. 350 m. Ocean-going tankers regularly unload North Sea crude oil to supply Stat Oil's Mongstad refinery less than 1 km distant from the sampling area.

The oceanographic development of the Fensfjord suggests that two major renewals occur during each annual cycle, the first during early spring and the second during the autumn. The first of these renewals,

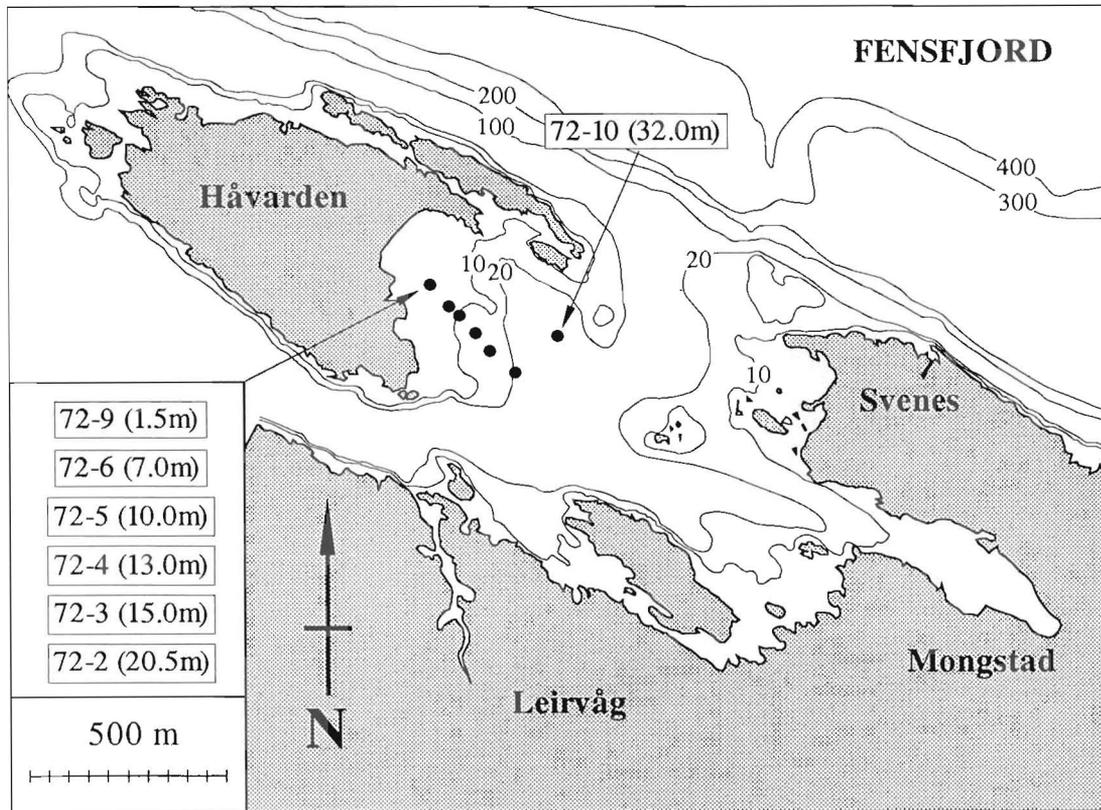


FIGURE 3. Bathymetric map of the area around Håvarden with sample stations located. Contours in metres.

arising from appreciable eddy fluxes within the fjord, occurs as waters of coastal and oceanic origin flow into the basin at depth, rise to 100–150 m, and finally spread outwards. This type of exchange occurs most often during the spring, between February and May. Higher level influxes, not uncommon in the fjords of western Norway, may occur during the autumn; in this situation the volumetric exchange may be greater than earlier during the year, although much of the basin water of the fjord is not involved and remains stagnant. Clearly, however, surface waters within the fjord do not experience the stability of temperature, salinity and dissolved oxygen conditions which are provided by the regular bi-annual exchange between fjord and shelf. Unfortunately, well constrained data which chart the seasonal development of oceanographic conditions within the surface waters of the fjord are not available; these may be particularly pronounced in marginal areas of the fjord, such as the study area.

Oceanographic conditions at Gade's (1973) station III within the main fjord are summarized in Figure 5. Surface temperatures range from ca. 4°C to ca. 12°C, with minimum values recorded during the spring and

maximum values in the late summer. Seasonal variations in temperature decrease with increasing water depth. At 100 m, for example, water temperatures vary by ca. 1.5°C about a mean annual value of ca. 8°C. Salinity data is limited to measurements from February, surface values are 32.5‰ and increase to 34.5‰ at 100 m. Oxygen concentrations show greatest seasonal variation in the surface waters, with values ranging from 6–9 ml·l⁻¹ between early spring and late summer; at 100 m values remain close to an annual mean of 6 ml·l⁻¹.

RESULTS

FORAMINIFERAL ASSEMBLAGES FROM SYSLAKVÅG

The faunas are described as they change with water depth along the Syslakvåg transect (Fig. 2); from 4.0 m at station 72-12, in the inner most part of the inlet, to 34.0 m at station 72-15, from the Spjeldnesosen basin. Subdivision of the faunas into 'live', 'dead' and 'total' are outlined in Table 1. Counts vary considerably, particularly for the 'live' specimens, and range from 125 specimens in sample 72-12 (representing 38%

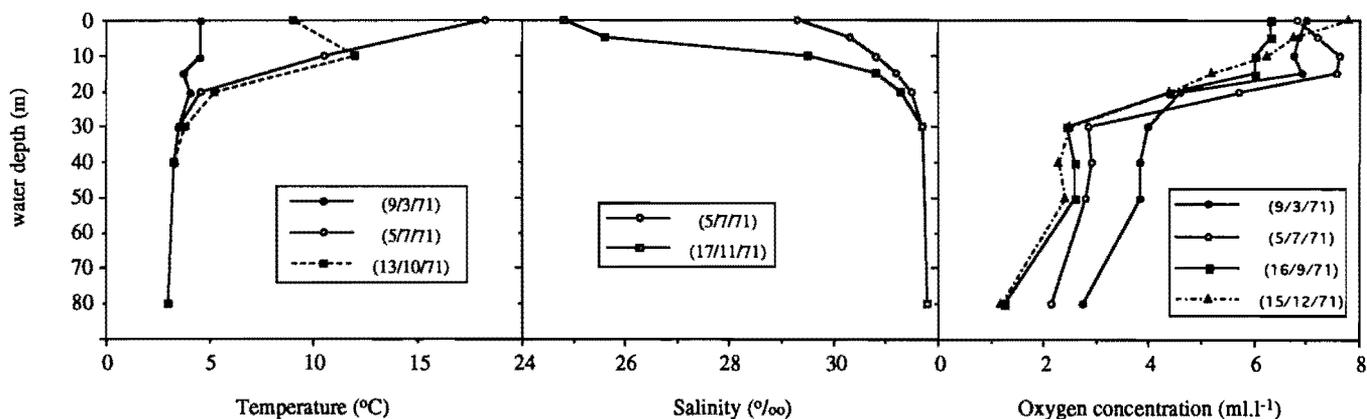


FIGURE 4. Oceanographic data from station F, Spjeldnesosen. Data after Aure (1972).

of the 'total' fauna) to only 14 specimens in sample 72-15 (representing 4% of the 'total' fauna). Counts of 'dead' specimens vary from 257 specimens in sample 72-13 to 337 specimens in sample 72-15; while 'total' counts range from 317 to 351 specimens. Thus, it is the 'dead' specimens which contribute most of the 'total' fauna at the time of sampling, and the 'dead' assemblages which bear greatest similarity to the 'total' assemblages in terms of their overall faunal composition (Fig. 6).

To illustrate some of the differences between the 'live' and 'dead' assemblages, the three most common taxa are ranked from the 'total' assemblages of these samples (Table 2). While differences do exist, these are generally less than 20%; however, there is a general tendency for agglutinating specimens to increase from the 'live' to the 'dead' assemblages. The major features of these assemblages are summarized in Figure 7; there is a close relationship between the 'dead' and 'total' assemblages. Of particular note in the 'dead' component are the increase in specimen concentrations to the deepest sample (2.2 to 50 specimens per cm^3) and the decreasing species dominance (58.5% to 28.8%) with increasing depth along the entire transect.

'Live' Assemblage Changes. The pattern of change for ten of the most common taxa is illustrated in Figure 8a. Those taxa exhibiting decreasing frequencies along the transect from samples 72-12 to 72-15 include *Eggerelloides scabrum*, *Elphidium williamsoni* and *Ammonia batavus*. For these taxa the decline is most marked between 10.0 m and 15.0 m water depth; all three are absent at 34.0 m.

While the above taxa are in decline, other species, including *Elphidium excavatum*, *Trochammina bullata*, *Bulimina marginata* and *Cibicides lobatulus*, are increasing and are most frequent at 15.0 m; again, all

four are absent at 34.0 m. Finally, three species occur at the deepest station and appear to characterize this water depth best; these taxa are *Adercotryma glomerata*, *Buccella frigida* and *Elphidium albiumbilicatum*.

It would therefore appear that a simple three-fold subdivision of the 'live' faunas is possible, although the most marked change appears to occur between a water depth of 15.0 m and 34.0 m.

'Dead' Assemblage Changes. The frequencies for the ten most common 'dead' taxa are illustrated in Figure 8b. The species which decline from samples 72-12 to 72-15 are the same as those in the 'live' assemblages. However, the initially high frequency of *E. scabrum* at 58.5% in sample 72-12 is greater than in the 'live' assemblage (41.6%) and this species clearly dominates the two shallowest samples of the transect.

The middle samples of the transect, notably sample 72-14, are characterized by increased frequencies of *T.*

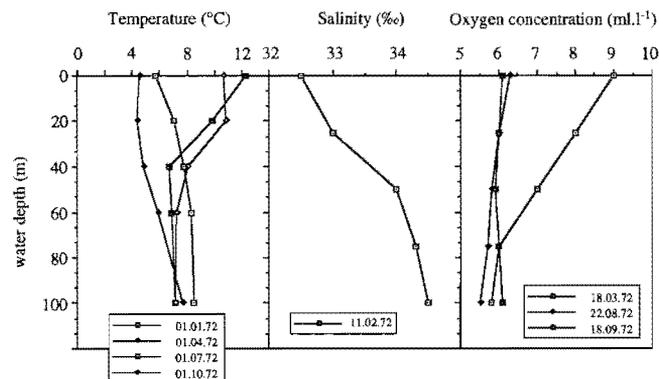


FIGURE 5. Oceanographic data from station III, Fensfjord. Data after Gade (1973).

TABLE 1. Syslakvåg assemblages—summary data.

station number	72-12	72-13	72-14	72-15	72-12	72-13	72-14	72-15	72-12	72-13	72-14	72-15
	LIVE %				DEAD %				TOTAL %			
species												
<i>Adercotryna glomerata</i>			2.63	35.71			3.23	28.78			3.15	29.06
<i>Ammonia batavus</i>	10.40	4.94			3.90	2.33	0.72		6.36	2.96	0.63	
<i>Ammoscalaria tuniana</i>	0.80				4.39	7.39	1.08		3.03	5.62	0.95	
<i>Astrononion gallowayi</i>				7.14			0.36	12.76			0.32	12.54
<i>Bolivina</i> spp.			2.63								0.32	
<i>Buccella frigida</i>		2.47	7.89	21.43		2.33	1.79	3.26		2.37	2.52	3.99
<i>Bulimina marginata</i>		1.23	7.89			0.78	2.87	0.89		0.89	3.47	0.85
<i>Cassidulina laevigata</i>							0.36	0.59			0.32	0.57
<i>Cassidulina reniforme</i>							0.72	0.30			0.63	0.28
<i>Cibicides lobatulus</i>		1.23	2.63				1.43	8.61		0.30	1.58	8.26
<i>Cribrostomoides crassimargo</i>							0.36	1.78			0.32	1.71
<i>Cribrostomoides jeffreysii</i>						0.39	0.72			0.30	0.63	
<i>Eggerelloides scabrum</i>	41.60	20.99	7.89		58.54	43.97	24.37		52.12	38.46	22.40	
<i>Elphidium albiumbilicatum</i>		6.17		14.29		3.89	0.72	24.33		4.44	0.63	23.93
<i>Elphidium excavatum</i>	2.40	17.28	18.42		4.88	12.45	12.54	0.59	3.94	13.61	13.25	0.57
<i>Elphidium hallandense</i>						2.33		6.82		1.78		6.55
<i>Elphidium macellum</i>		1.23			0.49	1.56	1.08		0.30	1.48	0.95	
<i>Elphidium williamsoni</i>	8.00	4.94			6.34	1.56			6.97	2.37		
<i>Elphidium</i> spp.	1.60	16.05	2.63		1.95	1.56	1.43		1.82	5.03	1.58	
<i>Gutulina lactea</i>		1.23				0.39	1.43			0.59	1.26	
<i>Gutulina</i> spp.		1.23								0.30		
<i>Hippocrepinella hirudinea</i>						0.39				0.30		
<i>Lagena striata</i>						0.39				0.30		
<i>Miliammina fusca</i>			13.16				2.51	0.30			3.79	0.28
<i>Miliolinella subrotunda</i>	16.80		2.63		3.41		0.36		8.48		0.63	
<i>Morulaepecta bulbosa</i>								0.30				0.28
<i>Nonion barlecanum</i>						0.39		0.30		0.30		0.28
<i>Nonion depressulus</i>	9.60				2.93	0.78			5.45	0.59		
<i>Patellina corrugata</i>		1.23								0.30		
<i>Quinqueloculina seminulum</i>	0.80		2.63		0.49	0.39	0.72		0.61	0.30	0.95	
<i>Reophax (Leptohalysis) catella</i>			2.63					0.30			0.32	0.28
<i>Reophax fusiformis</i>						0.39		1.78		0.30		1.71
<i>Reophax subfusiformis</i>		1.23				5.45	5.73	0.59		4.44	5.05	0.57
<i>Rosalina vilardeboana</i>	2.40				0.98	1.17			1.52	0.89		
<i>Rosalina</i> spp.		2.46								0.60		
<i>Stainforthia (Fursenkoina) fusiformis</i>				7.14			1.43	0.30			1.26	0.57
<i>Stainforthia (Fursenkoina) loeblichii</i>		1.23		7.14						0.30		0.28
<i>Textularia tenuissima</i>								0.30				0.28
<i>Textularia</i> sp.								0.30				0.28
<i>Trifarina fluens</i>				7.14				5.93				5.98
<i>Trochammina</i> spp.		1.23			0.49	0.78	0.36	0.30	0.30	0.89	0.32	0.28
<i>Trochamminaella bullata</i>	5.60	13.58	26.32		11.22	8.95	33.33		9.09	10.06	32.49	
<i>Valvulina conica</i>								0.30				0.28
<i>Valvulina fusca</i>							0.36				0.32	
Sample counts	125	81	38	14	205	257	279	337	330	338	317	351
Number of specimens per cm ³	2.06	2	0.3	2.07	3.37	6.35	2.18	49.93	5.43	8.35	2.47	52
Number of species	11	18	13	7	13	23	25	24	13	28	27	25
Species dominance (%)	41.6	20.99	26.32	35.71	58.54	43.97	33.33	28.78	52.12	38.46	32.49	29.06
Diversity (Fisher-Alpha)	3.4	6	5		3	6	6.5	6	2.8	7	6.8	6

bullata, *E. excavatum* and *B. marginata*. Both *T. bullata* and *E. excavatum* are absent at 34.0 m. The dominant species at 34.0 m are *A. glomerata* and *E. albiumbilicatum*, with *B. frigida* and *C. lobatulus* also reaching their greatest frequencies at this depth.

Thus, as for the 'live' taxa, a three-fold subdivision of the 'dead' assemblages along the Syslakvåg transect is suggested; again, it is the transition between 15.0 m and 34.0 m which is most marked.

'Total' Assemblage Changes. The changes within the 'total' assemblages (Fig. 8c) are largely a function of changes within the 'dead' assemblages; the high index of affinity values between 'dead' and 'total' assemblages from all samples along the transect confirm this (Fig. 6). The same three-fold subdivision of the 'total' assemblages is therefore suggested and, again, the transition between 15.0 m and 34.0 m is the most marked along the transect.

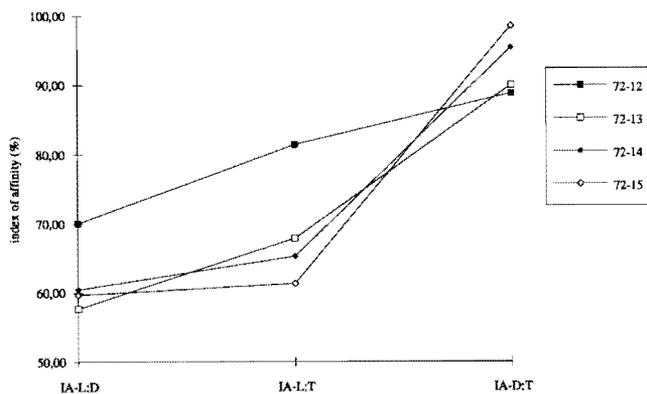


FIGURE 6. Index of affinity (%) data based on all common taxa, Syslakvåg. Comparisons are L:D = Live : Dead, L:T = Live : Total, D:T = Dead : Total.

FORAMINIFERAL ASSEMBLAGES FROM HÅVARDEN

A total of seven samples were analysed along a transect of increasing water depth from the shallow embayment to the southeast of Håvarden (Fig. 3). Water depths ranged from 1.5 m at station 72-9 to 32.0 m at station 72-10. The faunal composition of the assemblages ('live', 'dead' and 'total') is given in Table 3, together with a number of other faunal parameters; some of the latter are plotted against water depth in Figure 9. Of particular note are the general trends of increased specimen concentrations and number of spe-

TABLE 2. Ranked order of 3 dominant taxa in "total" assemblages from Syslakvåg, showing % frequency change from "live" to "dead."

sample number	species	'LIVE'	'DEAD'	% difference
72-12	<i>E. scabrum</i>	41.6	58.5	16.9
	<i>T. bullata</i>	5.6	11.2	5.6
	<i>M. subrotunda</i>	16.8	3.4	-13.4
72-13	<i>E. scabrum</i>	21	44	23
	<i>E. excavatum</i>	17.3	12.5	-4.8
	<i>T. bullata</i>	13.6	8.9	-4.7
72-14	<i>T. bullata</i>	26.3	33.3	7
	<i>E. scabrum</i>	7.9	24.4	16.5
	<i>E. excavatum</i>	18.4	12.5	-5.9
72-15	<i>A. glomeratum</i>	35.7	28.8	-6.9
	<i>E. albiumbilicatum</i>	14.3	24.3	10
	<i>A. gallowayi</i>	7.2	12.8	16.9

cies with increasing water depth. The various components of these assemblages are described below.

'Live' Assemblage Changes. The distribution of nine of the most common taxa along the transect is illustrated in Figure 10a. The dominant species of the shallowest sample, 72-9, at 1.5 m are *A. batavus*, *E. williamsoni* and *E. excavatum*. The very high species dominance of *A. batavus* (>56%) and the rather low number of species (10) in this sample are notable; as are the very low frequencies of this taxon elsewhere along the transect. However, the absence of *A. batavus* at the next station, 72-6, at 7.0 m is marked by increased frequencies of *T. bullata*, *E. scabrum* and *E. williamsoni*; the latter species dominating (42.8%) at this water depth.

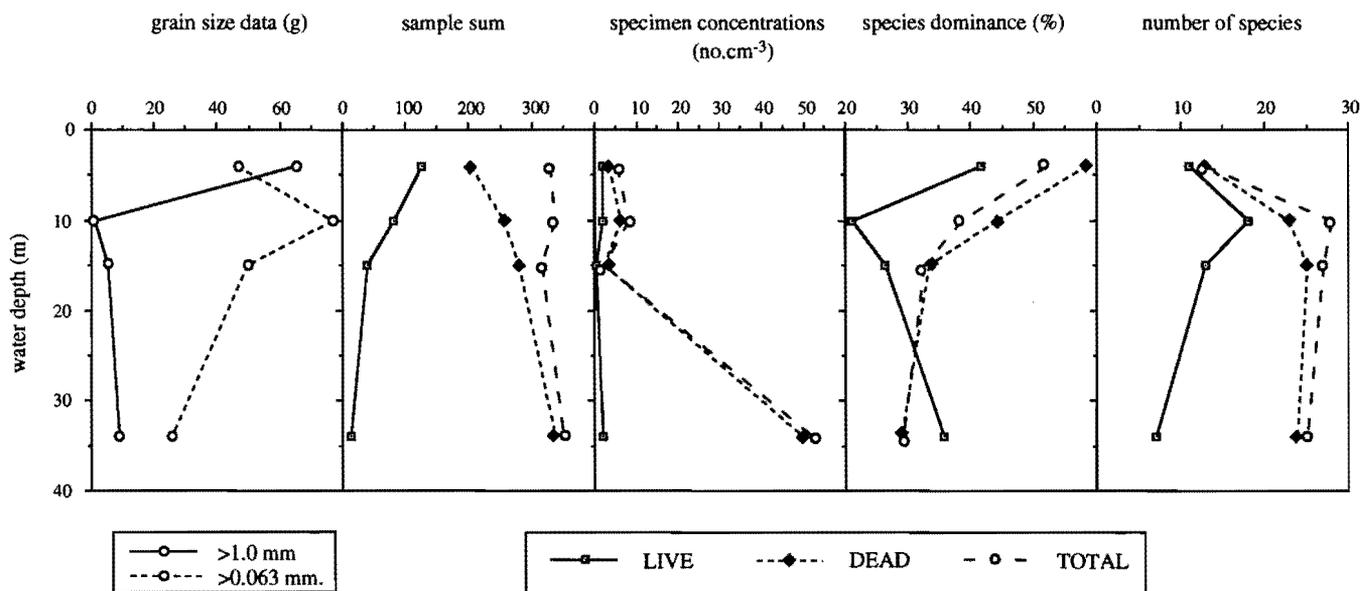


FIGURE 7. Summary of the main faunal parameters plotted against water depth from Syslakvåg.

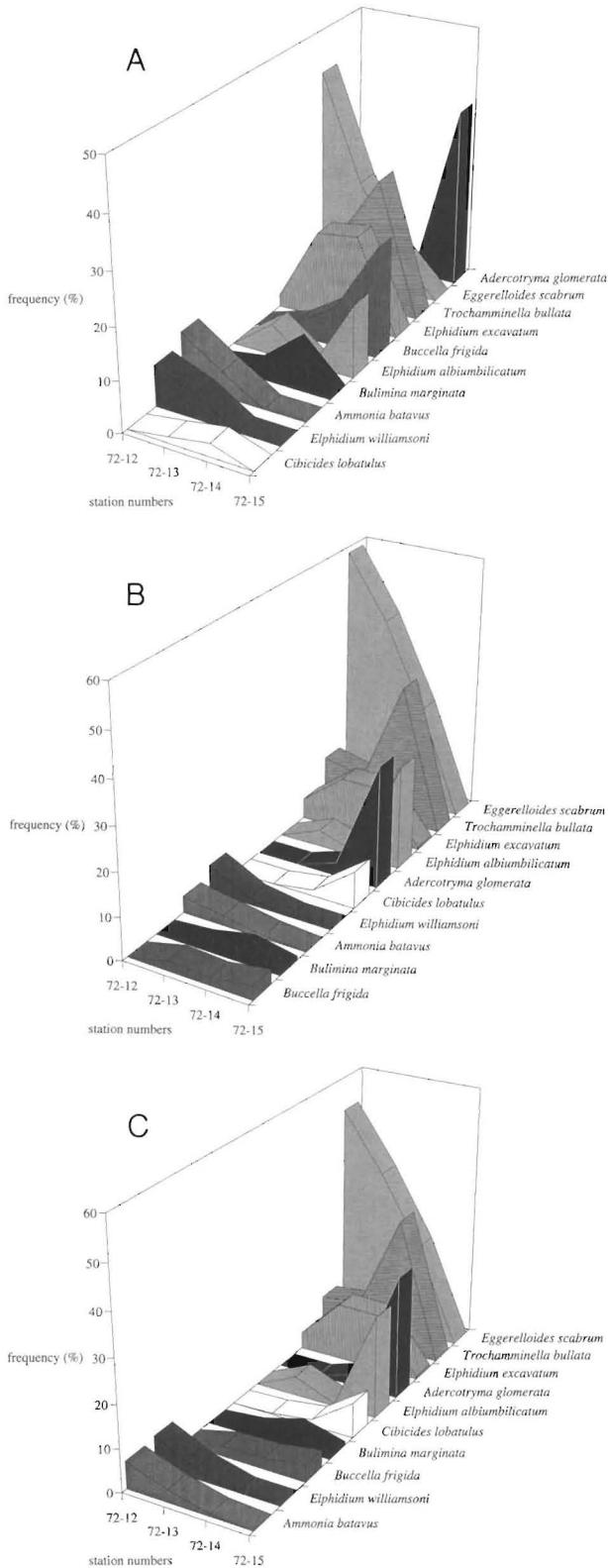


FIGURE 8. Summary frequency (%) diagrams of the 10 most common taxa from Syslakovåg. A. 'Live' specimens, B. 'Dead' specimens, C. 'Total' specimens.

The next sample, 72-5, at 10.0 m is characterized by a peak in *T. bullata* and a smaller peak in *Miliammina fusca*; both taxa decline notably with increasing water depth and are absent from the deeper water stations. This sample may not, however, accurately represent the 'live' assemblages from this water depth because the number of 'live' specimens counted only amount to 8; this factor clearly affects species diversity and probably explains why only 4 species were recorded. However, the number of species recorded from the 'dead' assemblages of the same sample is also at its lowest value along the transect, with only 8 species recorded from a sample count of 349 specimens. Equally, the 'total' species count number is at its lowest here, with only 10 species from a count of 357 specimens.

Species diversity increases greatly from sample 72-5 to 72-4, at 13.0 m; the dominant species here being *B. marginata* with a frequency of 34%. This increase is also seen in a number of other taxa, notably *C. lobatulus* and *C. laevigata*, and marks the most clearly defined change in the faunas along the transect. The remaining samples (72-3, 72-2 and 72-10) can be grouped together with 72-4 and are characterized by increasing frequencies of *C. lobatulus* and *C. laevigata*, both of which reach a maximum at 32.0 m; *B. marginata* reaches its maximum frequency in sample 72-3, at 15.0 m.

'Dead' Assemblage Changes. Sample counts of 'dead' specimens vary from 29 specimens in sample 72-9 to 455 specimens in sample 72-4, while specimen concentrations vary from 0.09 specimens cm^{-3} in sample 72-9 to > 145 specimens cm^{-3} in sample 72-10. The structure and composition of the 'dead' assemblages, while differing from the 'live' assemblages, maintain the previously well defined faunal transition at between 10.0–13.0 m. This two-fold subdivision of the faunal assemblages is clearly seen in Figure 10b.

The three shallower water stations (72-9, 72-6 and 72-5) are defined by high frequencies of *E. scabrum*, *M. fusca*, *T. bullata* and *A. batavus*. While these four taxa are also an important component of the 'live' assemblages, *E. williamsoni* is much reduced here and, as Figure 11 illustrates, the 'live' and 'dead' assemblages from these sample stations have low index of affinities to each other. For example, the frequency of *A. batavus* is reduced from 56% to 20% from the 'live' to 'dead' assemblage in 72-9; *E. williamsoni*, equally, decreases from >42% to only 5% in sample 72-6.

The four deeper water samples (72-4, 72-3, 72-2 and 72-10) bear a closer affinity to their 'live' assemblage counterparts, as the higher index of affinity values of

TABLE 3. Håvarden assemblages—summary data.

station number	72-9	72-6	72-5	72-4	72-3	72-2	72-10	72-9	72-6	72-5	72-4	72-3	72-2	72-10	72-9	72-6	72-5	72-4	72-3	72-2	72-10																	
	LIVE %																			DEAD %																		
species	TOTAL %																			TOTAL %																		
<i>Annonia batavus</i>	56.14			1.19	2.06		0.53	20.69	0.78			0.88	1.94	1.69	0.41	44.19	0.61				0.99	1.98	1.33	0.46														
<i>Ammonia</i>										0.39	2.01	0.22					0.31	1.96																				
<i>Astronotus galloisii</i>														1.22										0.69														
<i>Bolivina difformis</i>												0.44											0.28															
<i>Bolivina pseudoplicata</i>				0.79			2.11					1.10	0.65	0.42	1.22						0.99	0.40	0.33	1.61														
<i>Bolivina skagerakensis</i>							1.05							0.42	0.41								0.33	0.69														
<i>Bolivina spatulata</i>														0.42									0.33															
<i>Bolivina</i> spp.				0.40			0.53								1.22							0.14		0.92														
<i>Buccella frigida</i>				0.79	1.03		2.11					2.20	0.65	1.27	0.82							1.70	0.79	1.00	1.38													
<i>Bulimina marginata</i>	2.86			34.13	58.76	46.15	24.74	3.45	0.39			28.57	32.26	41.95	22.86	1.16	0.92				30.55	42.46	42.86	23.68														
<i>Cassidulina laevigata</i>				1.39	4.12	4.62	12.11		0.39			0.44	4.52	5.08	6.12			0.31			0.85	4.37	4.98	8.74														
<i>Cassidulina obtusa</i>				0.40		1.54	1.05							0.42	0.82						0.14		0.66	0.92														
<i>Cassidulina</i> sp.									0.39												0.31																	
<i>Cibicides berthelotii</i>							0.53														0.82			0.69														
<i>Cibicides lobatulus</i>	3.31			15.08	4.12	33.85	38.95	3.45				18.24	12.26	24.15	42.45	3.49						17.11	9.13	26.25	40.92													
<i>Cyclodina involvens</i>					1.03		1.05																0.40	0.46														
<i>Cyrtostomoides jeffreysii</i>			12.50						4.67	12.32	1.10										3.67	12.32	0.71															
<i>Eggereloides scabrum</i>	3.51	28.57		1.98	2.06	1.54		17.24	62.26	46.13	5.93	19.35	7.20			8.14	55.05	45.10			4.53	12.70	5.98															
<i>Ephidium albumbilicatum</i>				1.19		1.54						1.54	0.65			0.82						1.41	0.40	0.33	0.46													
<i>Ephidium excavatum</i>	12.28	4.29		11.11	1.03	3.08			0.78	0.29	16.48	0.65	1.69	0.41		8.14	1.53	0.28			14.57	0.79	1.99	0.23														
<i>Ephidium hallandense</i>				4.37		1.54						2.20										2.97		0.66														
<i>Ephidium muellum</i>	1.75	1.43		13.10					0.78		10.55	1.29	1.27	0.41		1.16	0.92				11.46	0.79	1.00	0.23														
<i>Ephidium moegastaceum</i>				0.40	2.06							3.87										0.14	3.17															
<i>Ephidium margaritaceum</i>							1.05									0.41								0.69														
<i>Ephidium ustulatum</i>				1.43																	0.31																	
<i>Ephidium wilkinsoni</i>	14.04	42.86	25.00	5.56	1.03			5.06			1.32	1.29				9.30	13.15	0.56			2.83	1.19																
<i>Ephidium</i> spp.				2.38				2.11			2.42	5.81	1.27	2.04							2.40	3.57	1.00	2.07														
<i>Fissurina danica</i>						1.54		0.53																0.23														
<i>Fissurina fasciata</i>																								0.33														
<i>Fissurina laevigata</i>												0.22		0.42							0.14			0.73														
<i>Fissurina</i> spp.												1.95		0.41								1.20		0.23														
<i>Globalina</i> sp.							0.53																	0.23														
<i>Guttulina austriaca</i>												0.65											0.40															
<i>Guttulina problema</i>												0.65											0.40															
<i>Guttulina</i> spp.														0.41										0.23														
<i>Hopliphragmoides</i> sp.					1.03								2.58										1.98															
<i>Hyalina balthica</i>							0.53									1.22								0.92														
<i>Lagena mollis</i>					1.03					3.44				0.42								3.36	0.40	0.33														
<i>Lagena</i> spp.													0.65			0.41						0.40		0.23														
<i>Miliammina fusca</i>	1.75	1.43	12.50	0.79				31.03	5.06			0.22				11.63	4.28	0.28			0.42																	
<i>Miliolinella subrotunda</i>						1.03						0.65		0.42									0.79	0.33														
<i>Nionin depressulus</i>		1.43			2.06		0.53					1.94									0.31		1.98	0.23														
<i>Nionin labradoricum</i>					1.03									0.42	0.82							0.40	0.33	0.46														
<i>Nionin</i> sp.															0.41									0.23														
<i>Nioninella tardida</i>					1.03		1.05					0.22			0.41							0.14	0.40	0.69														
<i>Oolina aculeata</i>														0.41										0.23														
<i>Oolina globosa</i>								3.45								1.16																						
<i>Oolina hexagona</i>							0.53				0.22			0.41								0.14		0.46														
<i>Oolina mela</i>						1.54					0.22			0.41								0.14		0.33														
<i>Oolina</i> sp.				0.40										0.42								0.14		0.53														
<i>Quinqueloculina agglutinata</i>	1.75															1.16																						
<i>Quinqueloculina oblonga</i>												0.65											0.40															
<i>Quinqueloculina sensibulum</i>	3.51				1.03				0.39			0.65				2.33	0.31					0.79																
<i>Recurvodes trochaneriforme</i>														0.42										0.33														
<i>Rosalina globularis</i>					2.06																		0.79															
<i>Rosalina progeri</i>					1.03		0.53						1.29		2.04								1.19	1.38														
<i>Rosalina vlardeboana</i>					1.03		0.53								0.41								0.40	0.46														
<i>Rosalina</i> spp.				2.38		3.08		3.45			2.42		4.65	1.22	1.16						2.40		4.31	0.69														
<i>Spiroloculina norvegica</i>												0.65											0.40															
<i>Spiroplectammina sorgholii</i>							5.26				0.22				4.49							0.14		4.83														
<i>Stainforthia (Fursenkoina) suliformis</i>				1.19	1.03		0.53				1.10	1.29			0.41							1.13	1.19	0.46														
<i>Stainforthia (Fursenkoina) isobialis</i>				0.40							0.22											0.28																
<i>Textularia bechi</i>					9.28							0.65	2.97										3.97	2.33														
<i>Trifarina angulosa</i>							1.05					0.65		0.41								0.40		0.69														
<i>Trifarina fluens</i>														0.85										0.66														
<i>Trochammina astrifica</i>									0.39													0.31																
<i>Trochammina</i> spp.							6.90	0.39	2.01							2.32	0.31	1.96																				
<i>Trochammina ballata</i>		15.71	50.00				10.34	17.90	30.09	1.10			0.85		3.49	17.43	30.53				0.71		0.66															
<i>Agglutinated</i> spp. (indeterminate)							0.53				3.72			0.42	2.86																							

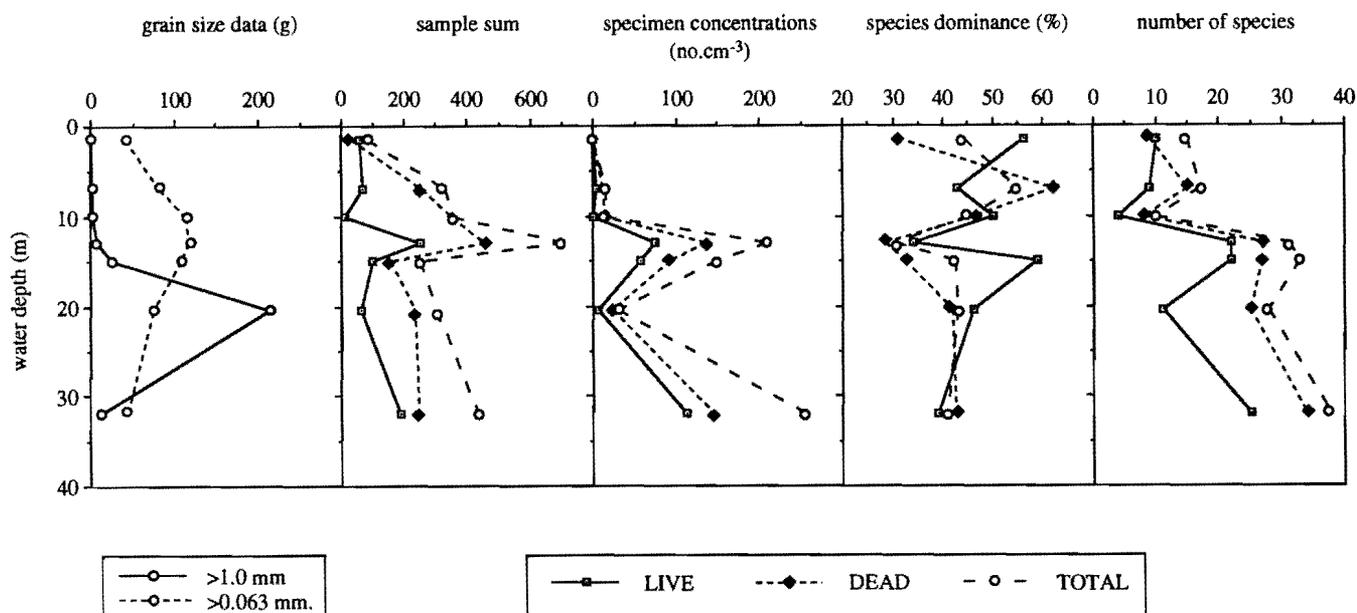


FIGURE 9. Summary of the main faunal parameters plotted against water depth from Håvarden.

occur in the 'dead' assemblages of these deeper samples than do in the 'live' assemblages.

'Total' Assemblage Changes. The overall pattern of change in the 'total' assemblages along the transect reflect the same two-fold subdivision of the faunas recognized from both the 'live' and 'dead' assemblages. The shallow water samples are defined by high frequencies of *E. scabrum*, *T. bullata*, *A. batavus*, *E. williamsoni* and *M. fusca*. The deeper water taxa are *B. marginata*, *C. lobatulus* and *C. laevigata*. Contributions of both 'live' and 'dead' components to the 'total' assemblage can be calculated from Table 3, while affinities between both 'live'-'total' and 'dead'-'total' are summarized in Figure 11. Of the latter, all but one of the 'dead' assemblage samples, 72-9, bear a closer affinity to the 'total' assemblages than do the 'live' assemblages from the same stations; this situation arises largely from the fact that the 'dead' specimen numbers contribute between 56% and 98% of the specimens to the 'total' assemblages, except in sample 72-9, where they contribute only 34%. It can be seen from Figure 11 that both 'live' and 'dead' assemblages are essentially the same as the 'total' assemblages from the four deeper stations, but more variable in the three shallower water stations. This transition in the faunas is equally well recorded by the increased number of species in the deeper stations; although when sample size is accounted for, as in the Fisher- α diversity measure, the differences are slightly less pronounced but still useful in defining the transition.

DISCUSSION

The interpretation of the factors governing the distribution of these faunas is somewhat limited by the low number of sample stations investigated. However, clearly defined changes within these assemblages are observed to correspond to described oceanographic features at both localities. A descriptive account of foraminiferal distribution in relation to oceanographic conditions is therefore possible, but we acknowledge the need for further investigation.

SYSLAKVÅG

At Syslakvåg the most marked change in the assemblages occurs between 15.0 m and 34.0 m, corresponding to the depth range at which strong seasonal variations in temperature and salinity give way to more stable conditions throughout the year at depth. We can therefore characterize the seasonally stable waters of Syslakvåg, which exhibit temperatures which vary little from ca. 3°C, salinities close to 32‰ and oxygen concentrations between approximately 2-4 ml·l⁻¹, by an assemblage dominated by *A. glomerata*, *B. frigida*, *E. albiumbilicatum* and *C. lobatulus*.

Similar species associations have been described from Sandebukta, a branch of the Oslo Fjord by Alve and Nagy (1986). *Adercotryma glomerata* is described as the second most abundant species in Sandebukta and is common in samples from depths greater than 9 m,

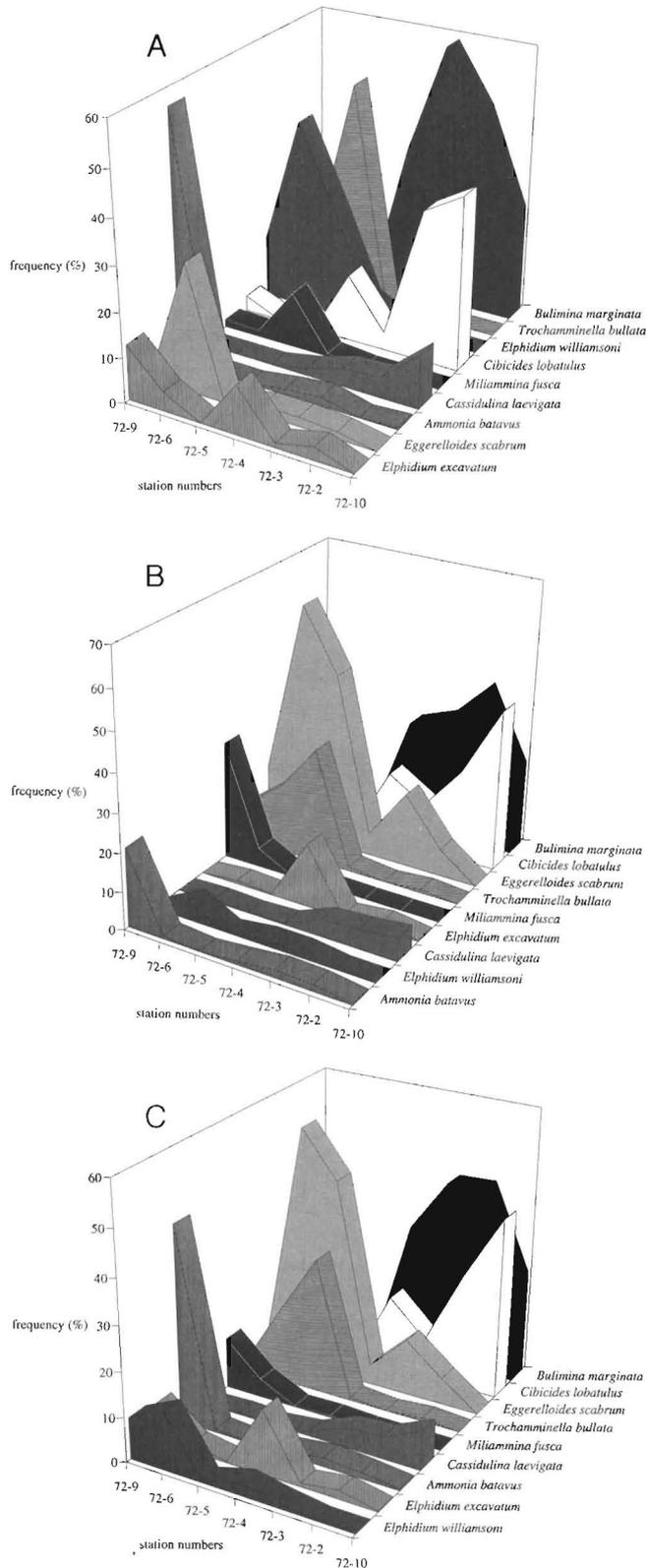


FIGURE 10. Summary frequency (%) diagrams of the 9 most common taxa from Håvarden. A. 'Live' specimens, B. 'Dead' specimens, C. 'Total' specimens.

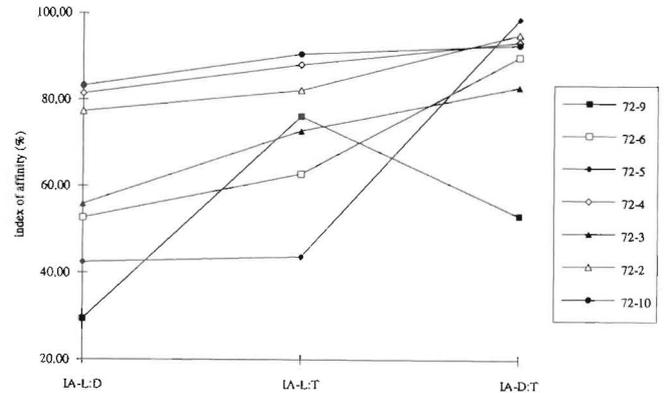


FIGURE 11. Index of affinity (%) data based on all common taxa, Håvarden. Comparisons are L:D = Live : Dead, L:T = Live : Total, D:T = Dead : Total.

although it is reported not to dominate any of the samples examined. The strong correlation of assemblages dominated by this species on the Nova Scotian margin to temperatures of between 1.8–3.0°C has been suggested by Williamson and others (1984) and discussed further by Alve and Nagy (1986), who quote ranges of salinity of 29.5‰–34.7‰ and temperatures of 3.9°C–6.8°C where it is abundant in Sandebukta. However, Thiede and others (1981) consider that “its distribution appears to be restricted mostly by the salinity of the water masses (stenohaline)”;

they also note that it is common in Arctic waters. The presence of *E. albumbilicatum* and *B. frigida* as the common accessory species, together with *A. glomerata*, is unexpected in view of the very low numbers of calcareous tests recorded from Sandebukta, particularly during August, and suggests that carbonate dissolution is not as marked here.

In attempting to summarize differences in wall type composition between ‘live’, ‘dead’ and ‘total’ assemblages (Fig. 12), dissolution of calcareous tests, both hyaline and porcelaneous, is suggested to occur and it appears to be most effective at the shallower water stations. This is in agreement with the observations of Alve and Nagy (1986), who recorded considerable reductions in the number of calcareous tests in the shallow waters of Sandebukta between April and June. Our data suggest that the contribution of carbonate tests to the overall wall structure composition may decrease by up to 30% from ‘live’ to ‘dead’ assemblages. However, since our data on the faunas has no seasonal component, any such conclusions regarding the dissolution of calcareous tests must be treated as tentative only.

Intermediate water depth samples at Syslavåg, be-

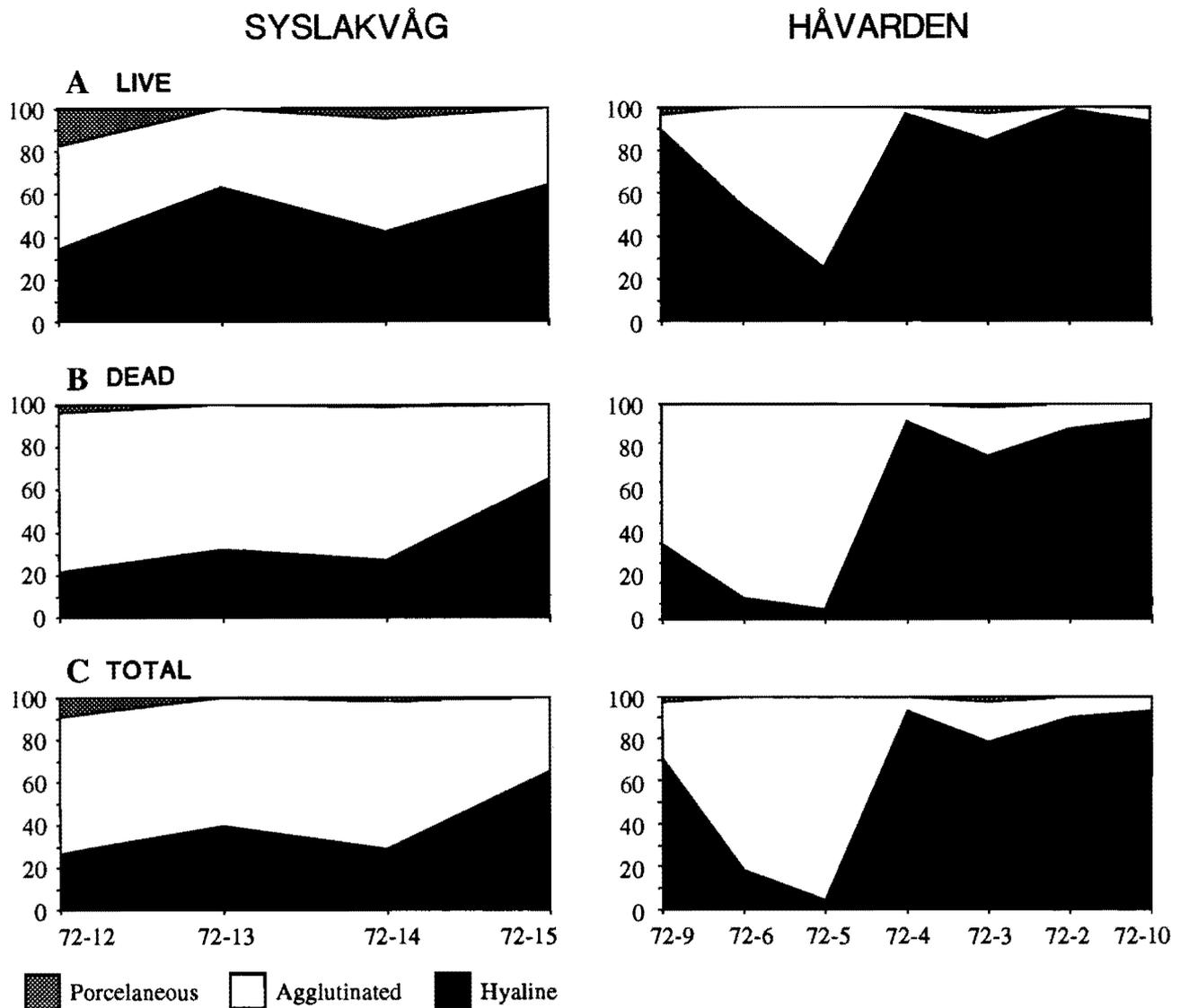


FIGURE 12. Composition (%) of the three main wall structure groups from Syslakvåg (72-12, 13, 14, 15) and Håvarden (72-9, 6, 5, 4, 3, 2, 10).

tween 10.0 m and 15.0 m are characterized by annual temperatures between ca. 4°C–12°C, salinities between 29‰–31.5‰, and oxygen concentrations from ca. 5–8 ml·l⁻¹, the assemblages are dominated by *T. bullata*, *E. excavatum* and *E. scabrum*.

The shallowest station at 4.0 m water depth experiences major seasonal temperature and salinity variations and the faunal response to these extreme conditions are reflected by a low number of species and high species dominance in the 'live' and 'dead' assemblages. Temperatures may vary between ca. 4°C and 20°C, salinities between 25‰ and 30‰, and oxygen concentrations between approximately 6 ml·l⁻¹–8 ml·l⁻¹. The dominant species are *E. scabrum*, together

with *A. batavus* and *E. williamsoni*. Murray (1991), from a compilation of N.W. European data on lagoons and estuaries, has summarized the ecological requirements of an association dominated by *E. scabrum* as very similar to the conditions described here.

HÅVARDEN

At Håvarden the assemblages can be subdivided into two groups, with a transition between 10–13 m. The limited oceanographic data make such a transition in the faunas difficult to explain except that the surficial waters of this inlet may experience greater fluctuations of temperature, and particularly salinity, than those recorded at Gade's station III from mid-fjord (Fig. 5).

In such a situation, hydrographic conditions may begin to approach those of the surficial waters of Spjeldnesosen, and we interpret the faunal similarities between the sites as partly reflecting these seasonally variable conditions. Thus, the high frequencies of *A. batavus*, *E. scabrum*, *E. williamsoni* and *T. bullata* at depths of less than 10 m from Håvarden characterize assemblages that are similar to those which occur in the upper 20–30 m at Syslakvåg.

The deeper water assemblages, below approximately 10 m, differ significantly from those described above and are interpreted as reflecting the greater stability of temperature, salinity and dissolved oxygen concentrations which they experience. These assemblages, characterized by high frequencies of *B. marginata*, *C. lobatulus* and *C. laevigata* are often considered more typical of the shelf; Sejrup and others (1981) have described not too dissimilar assemblages from the adjacent shelf areas, although at considerably greater water depths than 10–30 m.

In comparing the changes in test wall composition from the 'live', 'dead' and 'total' assemblages (Fig. 12), the faunal transition between 10–13 m (72-5 and 72-4) remains very well defined. Below this water depth the 'live' and 'dead' compositions are almost identical. However, the sample stations at or above 10 m appear to confirm the general pattern of carbonate dissolution in shallower water as discussed above. Sample station 72-9, at 1.5 m, records a decrease in carbonate tests from 93% in the 'live' assemblage to 34% in the 'dead' assemblage. Of the 93% carbonate tests in the 'live' assemblage *A. batavus* contributes >56%, and of the 34% carbonate tests in the 'dead' assemblage it contributes 20%. Alve and Nagy (1986) note the prolific occurrence of *A. batavus* and *E. excavatum* at certain times of the year in Sandebukta, with samples collected at ca. 10 m during April containing about 90% calcareous tests. Thus, it may be that the large differences between the 'live' and 'dead' assemblages in these shallow water stations arise due to seasonal "population explosions" of calcareous taxa, such as *A. batavus*, which are subsequently reduced in the 'dead' assemblages as a result of carbonate dissolution. But, without seasonally collected data, it is not possible to confirm these inferences. Scott and Medioli (1980) discuss at greater length the implications of counting 'living' versus 'total' assemblages throughout seasonal cycles.

TAXA WITH ARCTIC AFFINITIES

A number of species with modern or fossil distributions associated with Arctic environments are re-

corded at both localities, albeit with low percentage frequencies. These taxa occur both stained and unstained by the rose Bengal solution. Examples from Syslakvåg include both 'live' and 'dead' *Trifarina fluens* at sample station 72-15, 'dead' *Elphidium hallandense* at sample stations 72-13 and 72-15, and 'dead' *Cassidulina reniforme* at sample stations 72-14 and 72-15. The Håvarden stations include 'dead' *T. fluens* at 72-2, both 'live' and 'dead' *E. hallandense* at 72-2 and 72-4, but no *C. reniforme*. These are the taxa with the most obvious Arctic affinities, although other species, including *E. excavatum* forma *clavata*, *Astrononion gallowayi*, *Nonion labradoricum* and *A. glomerata*, also extend northwards into Arctic waters.

The question which we wish to address here is: do species such as *T. fluens*, *E. hallandense* and *C. reniforme* extend their southern limits of modern distribution from the Arctic to as far south as western Norway?

It might be argued that the 'live' records of *T. fluens* and *E. hallandense* at these localities are clearly evidence that they are autochthonous components of the faunas. However, work by Gooday (1984, 1986a, b) and more recently by Moodley (1990) on the "squatter" behaviour in soft-shelled foraminifera as they occupy empty tests emphasize the caution which must be applied to the interpretation of 'live' records. We have re-examined the 'live' specimens in question and find none of the diagnostic "squatter" foraminiferid characteristics described by Moodley (1990) present.

Furthermore, if we consider *C. reniforme*, Sejrup and others (1981) clearly demonstrate its relationship to their Norwegian continental slope (62°N–65°N) biofacies (BF3), which occurs between a water depth of ca. 700–1,200 m, with 'total' frequencies quoted between 7–30%. They argue that the erratic shelf records of this species, together with other Arctic taxa, are a function of reworking from pre-Holocene sediments. This interpretation is supported by Mackensen and others (1985), because no living specimens were found on the shelf. It is noted (D.B. Scott, written communication, March 1993) that *C. reniforme* is recorded as living in present day Canadian Atlantic estuaries. However, it must be born in mind that the equivalent climatic zone on the eastern Atlantic seaboard may be considerably further north than the present study area. Thus, the occurrence of 'dead' *C. reniforme* in the surface sediments of Syslakvåg may be explained either by the reworking of older sediments or by the fact that it tolerates the hydrographic conditions which prevail under the seasonally stratified waters of the Spjeldnesosen basin.

In view of the indirect evidence for carbonate dissolution at both localities, we favour the modern occurrence hypothesis to explain the presence of these species. However, at Håvarden in particular, the sample stations concerned (72-2 and 72-4) are both located below the water depth at which carbonate dissolution is inferred to take place (see Fig. 12). Whatever the real explanation may be, it is clear that further investigation into the occurrence of "cold" water taxa in these and similar environments is required. For example, stratigraphic investigations may reveal whether or not species such as *C. reniforme* have been present in basins such as Spjeldnesosen for the entire Holocene or whether they have migrated there when conditions of seasonal stratification, arising from the increased isolation of such basins in response to glacio-isostatic rebound, made conditions favourable.

COMPARISONS WITH FOSSIL INTERGLACIAL ASSEMBLAGES FROM WESTERN NORWAY

There are two main sites with foraminiferal faunas described from western Norway which warrant comparison with the assemblages described above. These are the last interglacial sediments of the sections described from Bø, Karmøy (Sejrup, 1987) and the sections at Fjøsanger, near Bergen (Mangerud and others, 1981). While it is possible to make such comparisons, the possibility of post-depositional alteration of these fossil faunas must be kept in mind. Both syndepositional carbonate dissolution, as discussed above, and the selective postdepositional destruction of agglutinated tests, as discussed from the Fjøsanger site and by Brodniewicz (1965), occur and therefore change the composition of the foraminiferal assemblages. Foraminiferal determinations from all of the following sites are based upon the $>125 \mu\text{m}$ fraction of the washed sediment residues.

The Avaldsnes Interglacial at Bø, Karmøy. Sections comprising marine sediments from the last interglacial (Eemian), known locally as the Avaldsnes Interglacial, are described from an abandoned clay pit on the eastern side of Karmøy Island, near Haugesund, south west Norway by Andersen and others (1983). Useful reviews of the locality and its regional geological setting are Mangerud and others (1981) and Andersen and others (1981). The foraminiferal faunas are described by Sejrup (1987), with the depositional environment of the Avaldsnes Interglacial interpreted as "high-energy", with a sea level 20–50 m higher than present. Sea water temperatures were similar to slightly warmer than those in the area today. The Avaldsnes Intergla-

cial is correlated to the Eemian Interglacial of N.W. Europe (Oxygen isotope stage 5e, ca. 125 ka BP) on the basis of pollen stratigraphic evidence (Andersen and others, 1983). Additional evidence from aminostratigraphy regarding the correlation of this site to the interglacial beds at Fjøsanger, also believed to correlate with the Eemian (Mangerud and others, 1981) has proven controversial. These problems are discussed by Miller and others (1983), Sejrup (1985) and Miller and Mangerud (1986). However, recent work by Kaufman and Sejrup (unpublished) on the aminostratigraphy of high molecular weight protein fractions from common taxa at both Bø and Fjøsanger suggest that these sites belong to the same interglacial, the Eemian.

The interglacial faunas at Bø are described from the Avaldsnes Sand and are assigned to the foraminiferal biozone FB6 (Sejrup, 1987). *Cibicides lobatulus* occurs throughout this formation, but the zone is named after the more characteristic species *Elphidium margaritaceum* and *B. marginata*. The assemblages include species such as *Elphidium crispum* and *Nonion depressulus*, which are reported not to have been recorded subsequently this far north (59°22'N). Increasing frequencies upwards through the section of species belonging to the genus *Elphidium* are interpreted as reflecting decreasing water depths, while the high degree of sorting in the sands is characteristic of high energy depositional environments. Of particular note in FB6 are the high number of species (ca. 30) and the large number of specimens per unit weight of dry sediment (25,000–50,000 · 100 g⁻¹).

High frequencies of *C. lobatulus* (>21% to >61%) in FB6 do not correspond to the data from Syslavåg, where this species attains a maximum frequency of 8% in the 'total' assemblage of sample 72-15. However, 'total' values of *C. lobatulus* from Håvarden, up to 41% at station 72-10, where it dominates an assemblage numbering 38 species, together with *B. marginata* and *C. laevigata*, may be analogous to those from FB6. Since the 'total' assemblages described above, from a depth >30m at Håvarden, are very similar to those of FB6, it is possible to suggest that conditions prevailing during the deposition of the Avaldsnes Sand were similar to those of the modern Fensfjord? This implies annual temperature ranges of ca. 4.5°C–10°C, salinities close to or slightly less than present normal marine values and dissolved oxygen concentrations of approximately 6 ml·l⁻¹ or more.

The Fjøsangerian Interglacial at Fjøsanger, near Bergen. Excavations at the Fjøsanger site, on the outskirts of Bergen, revealed a sedimentary sequence interpreted as representing accumulation through a com-

TABLE 4. Local foraminiferal assemblage biozones from Fjøsanger (modified from Mangerud and others, 1981).

Local Foraminiferal Assemblage Biozone	Diagnostic Taxon	Ranked order of 3 Dominant species	Number of Species	Number of specimens per 100g
F6	<i>E.albiumbilicatum</i>	<i>E.albiumbilicatum</i> (45%) <i>C.lobatulus</i> (30%) <i>B.marginata</i> (5%)	20	<1,000
F5	<i>C.laevigata</i> <i>B.marginata</i>	<i>C.lobatulus</i> (35%) <i>C.laevigata</i> (25%) <i>B.marginata</i> (15%)	32	ca. 25,000
F4	<i>B.marginata</i> <i>C.obtusa</i>	<i>B.marginata</i> (45%) <i>C.obtusa</i> (20%) <i>C.lobatulus</i> (15%)	29	ca. 5,000
F3	<i>T.angulosa</i> <i>C.lobatulus</i>	<i>C.lobatulus</i> (50%) <i>C.obtusa</i> (15%) <i>T.angulosa</i> (10%)	25	ca. 22,000

plete interglacial cycle, known locally as the Fjøsangerian Interglacial. The site, near present day sea level, lies at the head of Nordåsvatn, a small semi-enclosed fjord basin which is separated from the deeper Byfjorden to the north by a bedrock watershed at 25 m above present day sea level. It is in the context of changing relative sea levels and their resultant effect upon oceanographic conditions within Nordåsvatn that Mangerud and others (1981) interpreted the foraminiferal assemblages at the site. The basis for correlation with the Eemian Interglacial of N.W. Europe (Mangerud and others, 1981) relies upon pollen stratigraphy and aminostratigraphy (Miller and others, 1983).

Local foraminiferal assemblage biozones which represent interglacial conditions from the site are summarized in Table 4. The first incursions of Atlantic water are recognized in zone F3, named the *T. angulose*-*C. lobatulus* zone, on the basis of earlier work by Sejrup and others (1980). Zone F4, named the *B. marginata*-*C. lobatulus* zone, is interpreted as representing continued circulation through the Bergen valley system and water depths between 20–100 m are quoted. Zone F5, named the *C. laevigata*-*B. marginata* zone, contains the maximum frequencies (11%–20%) of the only

agglutinated species recorded, *Textularia bocki*. Based on earlier work by Höglund (1947) from the Gullmar Fjord, an open channel through the Bergen valley and water depths of 40–50 m were proposed. Zone F6, named the *E. albiumbilicatum* zone, suggests that hydrographic conditions changed considerably from the underlying zone F5 as a result of lowered relative sea level below that of the Bergen valley rock threshold. The presence of “species which today are most common in arctic waters”, such as *E. excavatum*, *E. bartletti* and *A. gallowayi*, provided Mangerud and others (1981) with a dilemma concerning the palaeoenvironmental interpretation of water temperature. However, based on Risdal’s (1964) work on some of the shallow water faunas of the Oslo Fjord, which also contain some of these Arctic elements, they concluded that water depths were somewhere between 15–25 m higher and that water temperatures were similar to present day values.

Applying the distributional data from Syslavåg and Håvarden to the interpretation of these faunas leads us to the following conclusions; these are largely in agreement with those of Mangerud and others (1981). Firstly, the foraminiferal assemblages of zones F3, F4

and F5 are most closely related to those described at depths >10 m from Håvarden. This applies particularly to the high percentage frequencies of *C. lobatulus* and *B. marginata*, although the near absence of *Trifarina angulosa* and *Cassidulina obtusa* in the assemblages described above indicate some significant differences, as do the absence of any agglutinated taxa other than *T. bocki*. The general trends through zones F4 and F5 of increasing *C. lobatulus* and *C. laevigata*, together with declining *B. marginata*, suggest water depths increasing to >30 m or possibly increased bottom current velocities. Applying present day Håvarden conditions to those during zones F4 and F5, then at a depth of ca. 30 m, temperatures might have ranged from 4°C–10°C, salinity might be somewhat reduced from normal marine values, and dissolved oxygen concentrations >6 ml·l⁻¹.

Secondly, the assemblages described from zone F6 are clearly related to those described from the deeper waters of the Syslakvåg transect, with the exception that all agglutinated taxa other than the robust *T. bocki* are missing. *Elphidium albiumbilicatum* reaches a maximum 24% in the 'total' assemblage of sample station 72-15, compared to over 41% within zone F6, but if the former is recalculated without the inclusion of agglutinated taxa (35%) in the sample sum (351) then a value of about 37% is obtained. Thus, the Syslakvåg stations appear to provide closely comparable assemblages to those from zone F6 at Fjøsanger, particularly when the possibility of selective post-depositional destruction of agglutinated tests is considered. In their conclusions regarding the depositional conditions acting during the accumulation of zone F6, Mangerud and others (1981) suggest water depths of 15–25 m higher than present, that is below the current elevation of the Bergen valley bedrock threshold. Our understanding of the Syslakvåg system suggests that their interpretation is correct, that water depths were probably in excess of 20 m, with mean annual temperatures at this depth close to, and varying little from, 3°C, salinity about 31‰–32‰, and dissolved oxygen concentrations variable but probably less than 4 ml·l⁻¹.

SPECIES NORTHERN LIMITS

Elphidium macellum is recorded as living at both localities from the present study and these are the most northerly N.W. European 'live' records that we are aware of. In view of the persistent taxonomic confusion of this species with *E. crispum* (see discussion by Austin, 1991), we advise caution in the future interpretation of fossil assemblages from these latitudes as be-

ing warmer than present. For example, the suggestion that the Eemian Interglacial of western Norway was warmer than present (Sejrup and Larsen, 1991) is probably valid, but the presence of *E. macellum* in deposits of this age, as discussed by Mangerud and others (1981) and Sejrup (1987), can no longer be considered supporting evidence. This also applies to *N. depressulus* and *Haynesina germanica*, both of which have been recorded together as *N. depressulus* in Tables 1 and 3, but are illustrated separately on Plate 2, figures 2 and 3.

SUMMARY AND CONCLUSIONS

(1) Well defined species and assemblage responses to oceanographic conditions are demonstrated. Seasonally stratified waters are identified as the major controlling factor upon distribution, to the extent that generally accepted species' northern and southern limits of distribution become less significant than they are in shelf environments.

(2) At Syslakvåg, seasonally stable waters below 15–20 m are characterized by assemblages dominated by *A. glomerata*, *B. frigida*, *E. albiumbilicatum* and *C. lobatulus*. Shallow water sample stations experience greater seasonal variation in temperature and salinity and the assemblages are dominated by *E. scabrum*, *E. williamsoni* and *A. batavus*.

(3) At Håvarden, the increased influence of "open" marine waters is reflected in the assemblages, particularly below a depth of 10 m. The assemblages of these deeper stations are dominated by *B. marginata*, *C. lobatulus* and *C. laevigata*; while the shallow water stations are dominated by *A. batavus*, *T. bullata*, *E. williamsoni* and *E. scabrum*.

(4) Carbonate dissolution in shallower water is inferred to occur from the observed differences in the wall structure composition of 'live' and 'dead' assemblages.

(5) Selective post-depositional destruction of agglutinated tests is inferred from the composition of last interglacial fossil assemblages from Fjøsanger, western Norway. When calcareous frequencies from the modern assemblages are calculated without the addition of agglutinated taxa to the sample sum, then closer faunal affinities to the fossil assemblages are obtained.

(6) The presence of taxa with Arctic affinities are due to modern occurrences and not due to the reworking of older Quaternary sediments, as on the adjacent continental shelf. Their presence probably reflects the rather extreme environmental conditions of temperature, salinity and dissolved oxygen concentration which have been discussed above.

(7) The 'live' northern limits of a number of species have been extended by this study; these include *E. macellus*, *N. depressulus* and *H. germanica*. The implications of these new finds are discussed in the light of previous palaeoecological reconstructions regarding the relative warmth of the last interglacial from western Norway.

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APPENDIX 1. Species list

Adercotryma glomerata (Brady, 1878)
Ammonia batavus (Hofker, 1951)
Ammoscalaria runiana (Heron-Allen and Earland, 1916)
Astrononion gallowayi Loeblich and Tappan, 1953
Bolivina difformis (Williamson, 1858)
Bolivina pseudoplicata Heron-Allen and Earland, 1930
Bolivina skagerrakensis Qvale and Nigam, 1985
Bolivina spathulata (Williamson, 1858)
Buccella frigida (Cushman, 1992)
Bulimina marginata d'Orbigny, 1826
Cassidulina laevigata d'Orbigny, 1826
Cassidulina obtusa Williamson, 1858
Cassidulina reniforme Nørvang, 1945
Cibicides bertheloti (d'Orbigny, 1839)
Cibicides lobatulus (Walker and Jacob, 1798)
Cribrostomoides crassimargo (Norman, 1892)
Cribrostomoides jeffreysii (Williamson, 1858)
Cyclogyra (Cornuspira) involvens (Reuss, 1850)
Eggerelloides scabrum (Williamson, 1858)
Elphidium albiumbilicatum (Weiss, 1954)
Elphidium williamsoni Haynes, 1973
Elphidium excavatum (Terquem) forma *clavata* Cushman, 1930
Elphidium excavatum (Terquem) forma *selseyensis* (Heron-Allen and Earland, 1911)
Elphidium hallandense Brotzen, 1943
Elphidium macellum (Fichtel and Moll, 1798)
Elphidium magellanicum Heron-Allen and Earland, 1932
Elphidium margaritaceum (Cushman, 1930)
Elphidium ustulatum Todd, 1957
Fissurina danica (Madsen, 1895)
Fissurina laevigata Reuss, 1850
Guttulina austriaca d'Orbigny, 1846
Guttulina lactea (Walker and Jacob, 1798)
Guttulina problema (d'Orbigny, 1826)
Hippocrepinella hirudinea Heron-Allen and Earland, 1932
Hyalinea balthica (Schroeter, 1783)
Lagena mollis (Cushman, 1944)
Lagena striata (d'Orbigny, 1839)
Miliammina fusca (Brady, 1870)
Miliolinella subrotunda (Montagu, 1803)
Morulaepecta bulbosa Höglund, 1947
Nonion barleeianum (Williamson, 1858)
Nonion depressulus (Walker and Jacob, 1798)
Nonion labradoricum (Dawson, 1860)
Nonionella turgida (Williamson, 1858)
Oolina acuticosta (Reuss, 1862)
Oolina globosa (Montagu, 1803)
Oolina hexagona (Williamson, 1848)
Oolina melo d'Orbigny, 1839
Patellina corrugata Williamson, 1858
Quinqueloculina agglutinata Cushman, 1917
Quinqueloculina oblonga (Montagu, 1893)
Quinqueloculina seminulum (Linné, 1758)
Recurvoides trochamminiiforme Höglund, 1947
Reophax (Leptohalysis) catella Höglund, 1947
Reophax fusiformis (Williamson, 1858)
Reophax subfusiformis Earland, 1933
Rosalina globularis d'Orbigny, 1826
Rosalina praegeri (Heron-Allen and Earland, 1913)
Rosalina vilardeboana d'Orbigny, 1839
Spiroloculina norvegica Cushman and Todd, 1944

Spiroplectammina wrightii (Silvestri, 1903)
Stainforthia (Fursenkoina) fusiformis (Williamson, 1858)
Stainforthia (Fursenkoina) loeblichii (Feyling-Hanssen, 1954)
Textularia bocki Höglund, 1947
Textularia tenuissima Earland, 1933
Trifarina angulosa (Williamson, 1858)
Trifarina fluens (Todd, 1947)
Trochammina astrifica (Rhumbler, 1938)
Trochamminella bullata Höglund, 1947
Valvulina conica Parker and Jones, 1865
Valvulina fusca (Williamson, 1858)

PLATE 1

1 *Reophax fusiformis* (Williamson), side view, ×75. **2,3** *Haplophragmoides* cf. *wilberti* Anderson, **2** side view, ×127. **3** apertural view, ×145. **4** *Haplophragmoides* sp., dorsal view, ×175. **5** *Eggerelloides scabrum* (Williamson), side view, ×67. **6** *Milliammina fusca* (Brady), side view, ×173. **7** *Miliolinella* sp., side view, ×108. **8** *Cassidulina laevigata* d'Orbigny, side view, ×130. **9** *Stainforthia (Fursenkoina) fusiformis* (Williamson), side view, ×157. **10** *Bulimina gibba* Fornasini, side view, ×176. **11** *Bulimina marginata* d'Orbigny, side view, ×129. **12** *Trifarina angulosa* (Williamson), side view, ×88.

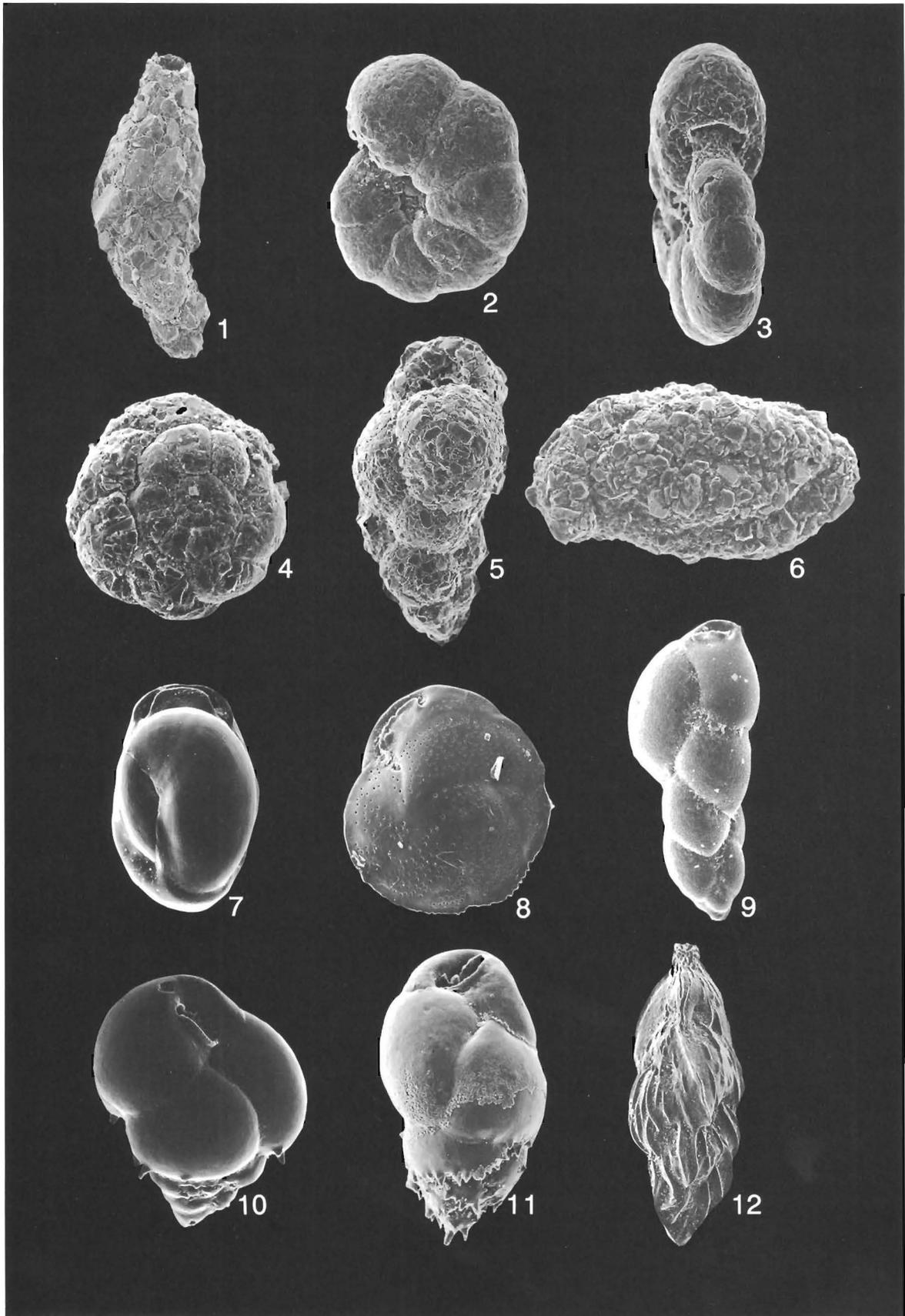
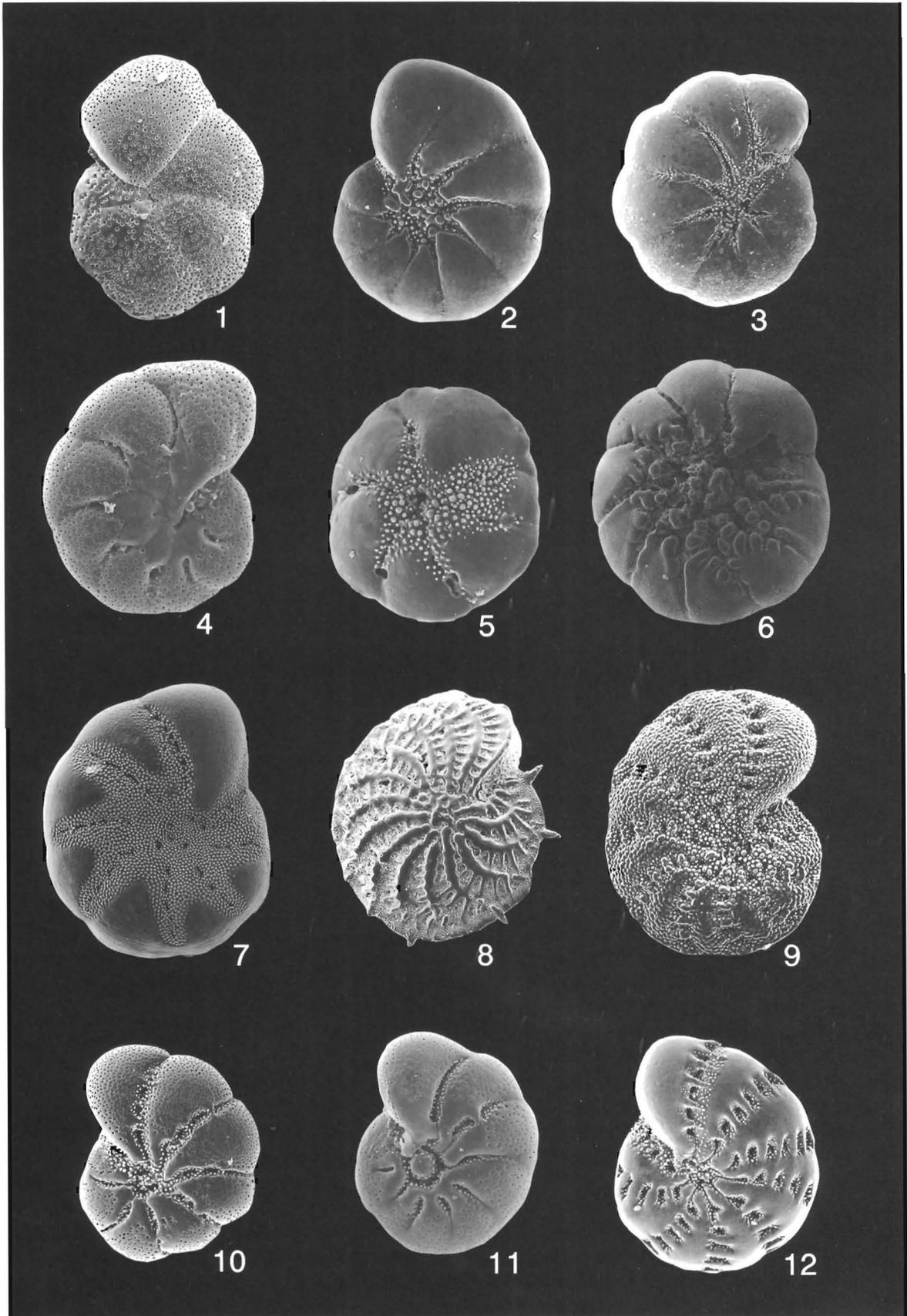


PLATE 2

1 *Cibicides lobatulus* (Walker and Jacob), ventral view, ×52. 2 *Nonion depressulus* (Walker and Jacob), side view, ×144. 3 *Haynesina germanica* (Ehrenberg), side view, ×74. 4 *Astrononion gallowayi* Loeblich and Tappan, side view, ×130. 5 *Buccella frigida* (Cushman), ventral view, ×175. 6 *Ammonia batavus* (Hofker), ventral view, ×67. 7 *Elphidium albiumbilicatum* (Weiss), side view, ×88. 8 *Elphidium macellum* (Fichtel and Moll), side view, ×59. 9 *Elphidium margaritaceum* (Cushman), side view, ×89. 10 *Elphidium excavatum* (Terquem) forma *selseyensis* (Heron-Allen and Earland), side view, ×113. 11 *Elphidium excavatum* (Terquem) forma *clavata* Cushman, side view, ×145. 12 *Elphidium williamsoni* Haynes, side view, ×115.



FORAMINIFERAL BIOFACIES AND PALEOENVIRONMENTS IN A PLIOCENE MEGACHANNEL OF THE GLACIOMARINE YAKATAGA FORMATION, GULF OF ALASKA

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ABSTRACT

Foraminifera are common in the glaciomarine Yakataga Formation of the eastern Gulf of Alaska and can provide key insights into the depositional history of Late Cenozoic glaciomarine paleoenvironments in the northeast Pacific Ocean. Lithologic evidence of tide-water glaciation consists of two main intervals of diamictites and sediments containing ice-rafted debris. The first is in the basal Yakataga Formation and is of latest Miocene age, while the second consists of 2-4 km of late Pliocene-early Pleistocene glaciomarine sediment in the upper Yakataga Formation. A distinctive feature of this latter interval is megachannels up to 400 meters deep and several kilometers wide. Megachannels cut into, and are filled with, a variety of lithofacies, including massive and stratified diamictites, thinly interbedded turbidite sandstones and mudstones, massive to laminated mudstones and crudely stratified conglomerates. These megachannels have been identified as possible paleofjords by some investigators but may also represent glacially influenced sea valleys, similar to the modern Yakutat Sea Valley or Bering Trough. A study of foraminiferal biofacies and sediments provide a paleoenvironmental framework for evaluation of the origin of the megachannels. Channel-fill successions

begin with conglomerates overlain by fine-grained turbidites and mudstones. The turbidites pass upwards into massive and stratified diamictites deposited predominantly by sediment gravity flow processes. The turbidites and mudstones contain faunas characterized by *Epistominella pacifica*, agglutinated taxa and contain planktic foraminifera. These faunas represent upper bathyal water depths (150-500 m). Some diamictites contain sparse faunas dominated by *Elphidium excavatum clavatum* and represent neritic water depths. Near the margins of megachannels, vigorous downslope gravity processes are reflected by gravel beds and upper bathyal biofacies containing greater numbers of displaced shallow water taxa (particularly *Elphidium excavatum clavatum*), including rare innermost shelf taxa (e.g., *Elphidiella oregonense*). The distribution of foraminiferal biofacies suggests water depths for channel-fills consistent with the amount of channel incision (100's of m) and does not suggest restricted or silled conditions as seen in many modern fjords. Thus, the megachannels most closely resemble the glacially-influenced sea valleys found on the modern Gulf of Alaska continental margin.

INTRODUCTION

The northeastern Gulf of Alaska is an area of active temperate glaciation and has been so since the late Miocene (Eyles and others, 1991; Lagoe and others,

1993). The Yakataga Formation is a product of this glacial history. It is composed of glaciomarine (e.g., diamictites) and marine (e.g., mudstones, sandstones) lithologies. In places the Yakataga Formation is up to 7 km thick (Zellers and Lagoe, in press) and thus rep-

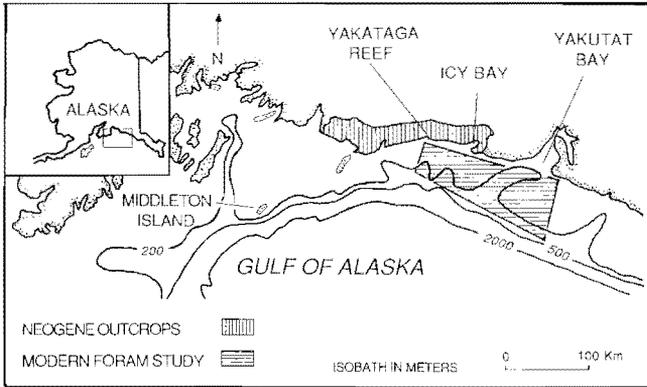


FIGURE 1. Locality map for the northeastern Gulf of Alaska showing the distribution of prominent fjords and sea valleys. Note the location of Yakutat Bay and Yakutat Sea Valley just seaward of it. Also shown is the location of the geologic map for Neogene outcrops of Figure 5 (modified after Carlson and others, 1977). Modern foraminiferal study area is for data from Echols and Armentrout (1980).

resents the thickest record of late Cenozoic glaciomarine deposition in the northern hemisphere (Plafker and Addicott, 1976). Recently, several aspects of this record have been documented, including sedimentology (e.g., Eyles and others, 1991; Eyles and Lagoe, 1990; Eyles, 1987, 1988; Eyles and Lagoe, 1989); micropaleontology (e.g., Lagoe, 1983; Lagoe and others, 1989; Zellers, 1989, 1990); ichnology (e.g., Eyles and others, 1992) and paleoclimatic history (e.g., Lagoe and others, 1993; Lagoe, in press). This paper investigates the depositional significance of distinctive megachannels which are common in the upper part of the Yakataga Formation exposed in the coastal ranges of the northeastern Gulf of Alaska (Fig. 1).

The Yakataga Formation overlies the marine, Oligo-Miocene Poul Creek Formation (Fig. 2) and can be informally subdivided into three stratigraphic units; 1) a lowermost interval containing significant amounts of glaciomarine sediment (diamictites), 2) a middle marine unit of sandstone, mudstone and conglomerate, and 3) an upper unit dominated by glaciomarine diamictite and subordinate turbidites. The megachannels described here are found in the uppermost stratigraphic unit and frequently occur as a succession of stacked, cross-cutting channel fills. Individual megachannels show up to 400 m of incision (Fig. 3) and are a few km across. Little detailed work has been done on these megachannels, but Armentrout and others (1979) have suggested that the megachannels represent paleofjords. We intend to test this suggestion against an alternate hypothesis that the megachannels were formed as gla-

EPOCH	FORMATION	INFORMAL UNITS
PLEISTOCENE	YAKATAGA	UPPER GLACIOMARINE UNIT
PLIOCENE		NORMAL MARINE UNIT
		LOWER GLACIOMARINE UNIT
MIOCENE	POUL CREEK	"UPPER POUL CREEK FM." UNIT PC OF LAGOE (1983)
		REGIONAL HIATUS
		"ORGANIC SHALE" UNIT PB OF LAGOE (1983)
		"LOWER POUL CREEK FM." UNIT PA OF LAGOE (1983)
OLIGOCENE		

FIGURE 2. Stratigraphy of Neogene and Quaternary sediments of the Yakataga District, Gulf of Alaska (after Lagoe and others, 1993).

cially-influenced sea valleys, similar to the modern Yakutat Sea Valley and Bering Trough (Fig. 1).

The specific objectives of this paper are as follows: to describe the sediments, foraminiferal biofacies and paleoenvironments within a megachannel exposed in the central Robinson Mountains, Yakataga District; likewise, characterize the sediments into which the megachannel is cut; and to evaluate whether the megachannel most resembles a fjord or a sea valley.

FJORDS AND SEA VALLEYS

Fjords are narrow, glacially-overdeepened valleys, excavated below sea-level by fast flowing valley glaciers (Hughes, 1987). The typical modern fjord is cut into crystalline basement rock and is floored by relatively thin sediments deposited during ice retreat; older sediments are rarely preserved because they are removed during glacial advances and bulldozed to the continental slope (Andrews, 1990). Broader, more shallow features of similar origin have been termed fjards (Fairbridge, 1968). Both of these features are commonly silled at their seaward ends of former terminal moraines. Thus fjords and fjards often act oceanographically as silled basins. Glacially influenced sea valleys are incisions into the continental margin, formed at least partially by the action of tidewater glaciers, but lacking the oceanographic restriction of most fjords. Two features in the eastern Gulf of Alaska illustrate the differences between these geomorphic forms; Yakutat Bay and Yakutat Sea Valley (Fig. 1).

Yakatut Bay contains a classic fjord in its landward reach (Russell Fjord), while its more broad seaward

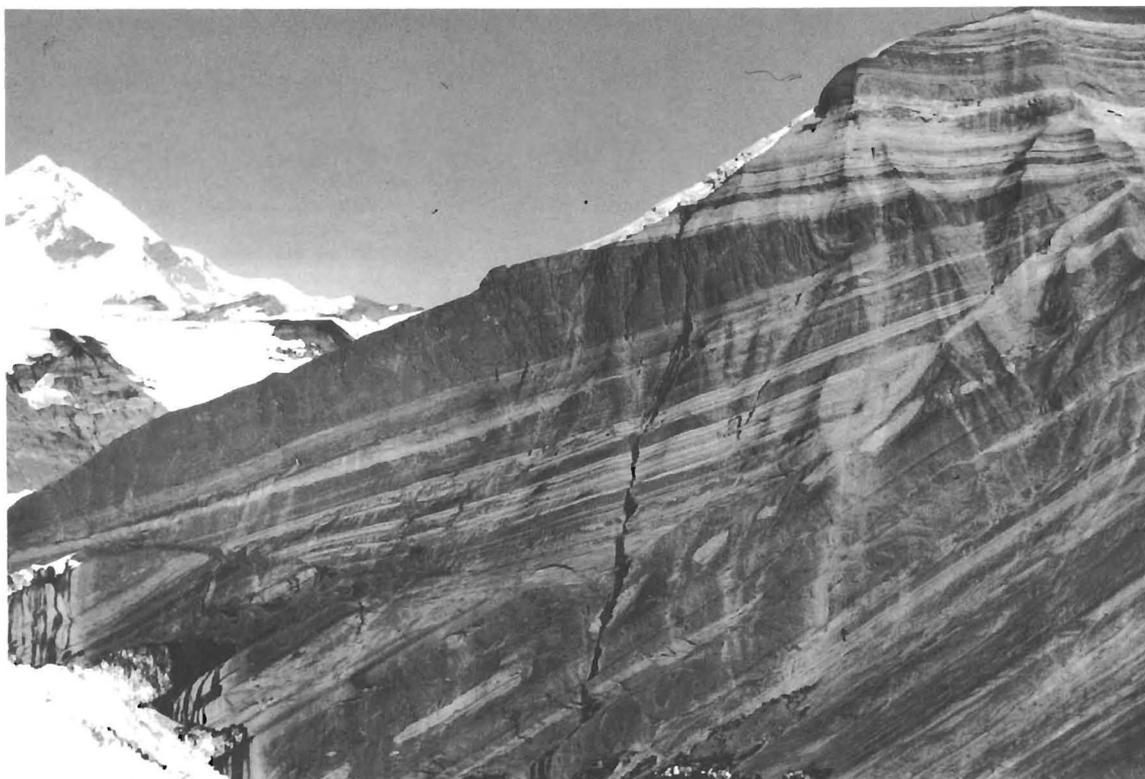


FIGURE 3. Photograph of megachannel in the upper Yakataga Formation of Icy Bay. Channel is located on the back limb of a prominent fold. Approximate relief associated with the channel is 400 m.

extent can be classified as a fjord (Armentrout, 1983a). The seaward boundary of the bay is marked by a prominent sill, a former moraine (Fig. 4A–C; Wright, 1972; Echols and Armentrout, 1980). Yakutat Sea Valley is a 300 m deep incision into the continental shelf just seaward of Yakutat Bay. A summary of the oceanographic, sedimentologic and micropaleontologic characteristics of these features illustrates their essential differences.

From an oceanographic standpoint, the water filling Yakutat Sea Valley is a representative cross section of the water column in the eastern Gulf of Alaska (Royer, 1972; Echols and Armentrout, 1980; Reed and Schumacher, 1986). This is illustrated here using salinity as a defining characteristic of water masses (Fig. 4B). The depth range of the sea valley (down to about 300 m) falls within the mixed, surface layer and upper part of the permanent halocline (intermediate water). The oceanography of Yakutat Bay is considerably different. In places (e.g., Disenchantment Bay) the depths within the Yakutat Bay system are nearly as deep as Yakutat Sea Valley (285 meters; Wright, 1972). However, because of the baymouth moraine forming a sill

at 50–75 m, only water from above that depth enters the bay system (Fig. 4; Reeburgh and others, 1976). The deeper waters of Yakutat Bay thus have characteristics of the surface water layer on the continental shelf. In both the sea valley and the bay/fjord system, bottom waters are well oxygenated (Reeburgh and others, 1976; Armentrout, 1983a).

Modern sediments in the two features are also quite different. Tidewater ice margins in the eastern Gulf of Alaska are currently restricted to the landward reaches of most fjords. There is no significant glaciomarine influence on the open continental shelf. Sediments in Yakutat Bay reflect this difference (Fig. 4A), being dominated by mud with variable amounts of gravel (Wright, 1972; Armentrout, 1980). The mud reflects the enormous amounts of glacial flour carried by local temperate glacial systems (e.g., Turner and Hubbard Glaciers), while the gravel component is distributed by ice-rafting and resedimentation of the coarse-grained terminal moraine. Holocene sedimentation rates in such environments are extremely high, approaching a few meters/year in many cases (Carlson and Molnia, 1978; Molnia, 1979, 1983). In contrast, the floor of Yakutat

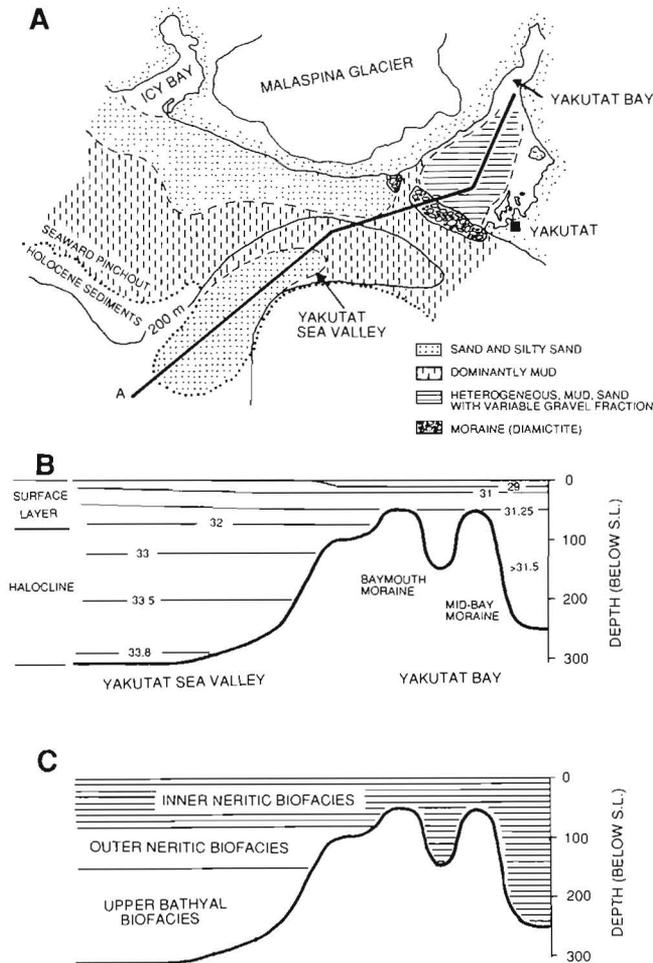


FIGURE 4. Modern oceanographic, sediment and benthic foraminiferal biofacies relationships in Yakutat Bay and Yakutat Sea Valley. **A**, Dominant modern sediment types (based on information in Armentrout, 1980; Carlson and others, 1977). Heavy line marked "A" shows trend of cross sections illustrated in B and C below. **B**, Oceanographic cross section of Yakutat Bay and Yakutat Sea Valley using salinity as a defining characteristic of water masses. Note that because of the sill formed by the baymouth moraine, only surface water can enter Yakutat Bay. Because of this, note the contrast between deeper waters on either side of the sill (after information in Echols and Armentrout, 1980; Royer, 1972; Reeburgh and others, 1976). **C**, General depth distribution of benthic foraminiferal biofacies (described in text). Note that inner neritic faunas dominate all depths in Yakutat Bay. The distribution of biofacies mimics the distribution of water masses shown in B above (based on information in Echols and Armentrout, 1980; Lagoe and others, 1989).

Sea Valley is covered by silty sand (Armentrout, 1980; Carlson and others, 1977), without an apparent coarse-grained glaciomarine component. During glacial times, when tidewater ice margins extend onto the open continental shelf, the sea valley would undoubtedly be influenced more by glaciomarine deposition.

TABLE 1. Benthic foraminiferal counting groups used in compiling Table 2.

Benthic counting groups
<i>Bathysiphon</i> sp.
<i>Buccella frigida</i> (Cushman)
<i>Buccella tenerrima</i> (Brady)
<i>Cassidulina californica</i> Cushman and Hughes
<i>Cassidulina minuta</i> Cushman
sharp margined cassidulinids
Several species are included here which are difficult to distinguish when preservation is not good. These include <i>C. limbata</i> Cushman and Hughes, <i>C. teretis</i> Tappan and <i>C. norcrossi</i> Cushman. <i>C. limbata</i> and <i>C. norcrossi</i> , as well as <i>C. californica</i> and <i>C. minuta</i> are assigned by many authors to the genus <i>Islandiella</i> .
<i>Cibicides</i> spp.
Includes <i>Cibicides lobatulus</i> (Walker and Jacob), <i>Cibicides</i> cf. <i>C. mckannai</i> Galloway and Wissler, and <i>Cibicides</i> sp. A (of Lagoe, 1983).
<i>Cyclammina</i> spp.
<i>Elphidiella hannai</i> (Cushman and Grant)
<i>Elphidiella oregonense</i> (Cushman and Grant)
<i>Elphidium bartletti</i> Cushman
<i>Elphidium excavatum clavatum</i> Cushman
<i>Elphidium</i> spp.
<i>Epistominella pacifica</i> (Cushman)
<i>Glandulina laevigata</i> d'Orbigny
<i>Haplophragmoides</i> spp.
Several species are represented, some may be <i>Cribrostomoides</i> but preservation does not allow their differentiation.
<i>Nonionella miocenica</i> Cushman
<i>Pullenia salisburyi</i> Stewart and Stewart
<i>Quinqueloculina</i> spp.
<i>Uvigerina juncea</i> Cushman and Todd
Planktic counting groups
<i>Globigerina bulloides</i> d'Orbigny
<i>Globigerina quinqueloba</i> Natland
<i>Globigerinita glutinata</i> (Egger)
<i>Neogloboquadrina pachyderma</i> (Ehrenberg)
Indeterminate planktic spp.

Benthic foraminiferal biofacies in the modern Gulf of Alaska strongly reflect the environmental gradient correlated to depth (Bergen and O'Neil, 1979; Echols and Armentrout, 1980; Lagoe and others, 1989). Within Yakutat Sea Valley, this normal progression of faunas is exhibited (Fig. 4C). Within Yakutat Bay, the faunas are more uniform and reflect the nature of biofacies at the sill depth (Fig. 4C), predominantly inner neritic (Echols and Armentrout, 1980). Thus, the distribution of benthic foraminiferal biofacies mimics the distribution of water masses.

These contrasts between modern fjords and sea valleys in the eastern Gulf of Alaska will be used to evaluate the paleoenvironmental significance of megachannels in the Yakataga Formation.

METHODS

Sections in the study area were logged on a meter scale using techniques described in Eyles and others

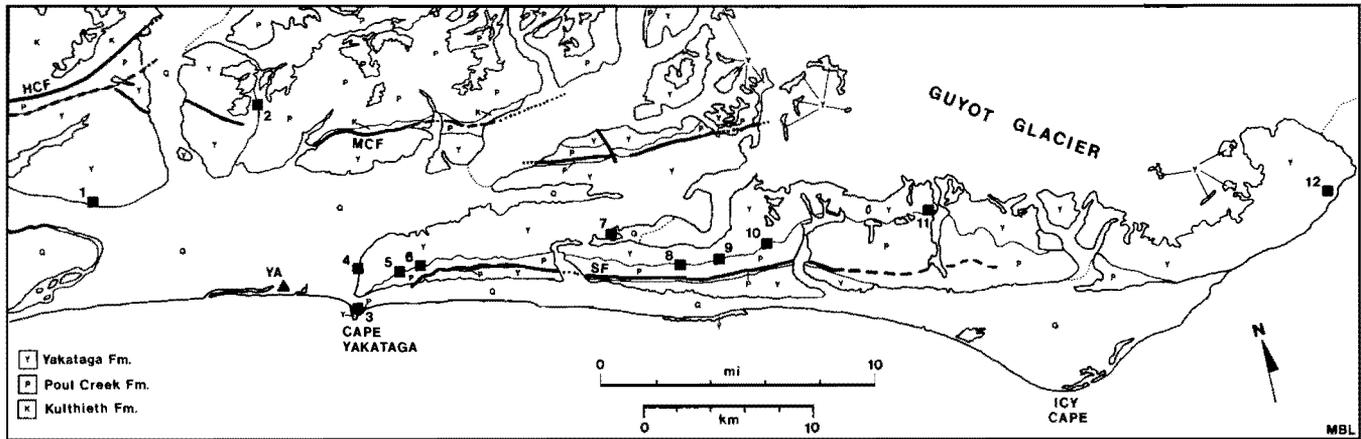


FIGURE 5. Geologic map of the western Robinson Mountains showing sections studied in our regional work on the Yakataga Formation. Armentrout's Channel is located at section 7. See Figure 1 for location of map. Other sections studied in references cited in text: 1)—Kulthieth Mountain; 2)—Duktoth Mountain; 3)—Yakataga Reef; 4)—White River #1 well; 5)—Peak 2170; 6)—Twomile Creek; 7)—Steamboat Rock; 8)—Shokum Creek; 9)—Lawrence Creek/Munday Peak; 10)—Poul Creek; 11)—Lare Glacier; 12)—Icy Bay. Abbreviations: MCF—Miller Creek Fault; SF—Sullivan Fault; YA—Yakataga Airstrip. Heavy dark lines on map represent faults.

(1985). Particular care was taken to note evidence for glaciomarine influence (e.g., dropstones, striated/faceted clasts in diamictites). Sections were sampled for microfossils as they were measured.

Micropaleontological samples were disaggregated by boiling in a solution of Quaternary O for 30–60 minutes. Samples were wet sieved at 63 microns, dried and then dry sieved at 150 microns. Three hundred specimens were randomly picked from the >150 micron fraction of the dried residues, abundance permitting. Foraminifera were identified into counting groups (Table 1) which have been previously found to be useful for paleoenvironmental analysis (Lagoe and others, 1989; Zellers, 1990; Zellers and Lagoe, in press). The taxonomy of these faunas is discussed in more detail in Lagoe (1983), Lagoe and others (1989) and Zellers (1989).

ARMENTROUT'S CHANNEL

LOCATION, GEOMETRY AND GEOLOGIC SETTING

The megachannel studied here is located in the central Robinson Mountains, Yakataga District near the White River Glacier (Fig. 5). This feature was first studied by Armentrout and others (1979) and Armentrout (1983b). It is informally referred to here as "Armentrout's Channel." The megachannel is located in the upper glaciomarine unit of the onshore Yakataga Formation (Fig. 2). This interval is of late Pliocene age based on planktic foraminifera and regional correlations (Zellers, 1989, 1990; Lagoe and others, 1993).

Outcrop relationships show that only the eastern side

of the megachannel is preserved (Fig. 6). Measured sections within and outside Armentrout's Channel illustrate its basic geometry (Fig. 7). The main megachannel is itself truncated by another megachannel, of which only the lower part is preserved. This superposition of channeling is common at several scales within the upper part of the onshore Yakataga Formation (Eyles and others, 1991). Armentrout's channel exhibits approximately 330 m of preserved incision, while the megachannel which truncates part of it shows over 150 m of relief (Fig. 7). The full width of Armentrout's channel is not preserved, but must have been at least a few km. The long axes of megachannels lie subparallel to the structural grain of folds in the Gulf of Alaska. Thus, channel orientations are structurally controlled as a result of compressive forces generated by a component of plate margin convergence (Eyles and others, in prep.).

The megachannel contains a diverse sediment fill, including glaciomarine and marine lithologies (Fig. 7). Seventy-two samples were collected for micropaleontological analysis. These have been examined for the presence of microfossils and the contents of 38 of these samples are used in this study. Both the sedimentology and micropaleontology are analysed in light of the two hypotheses for the megachannel's origin—fjord or sea valley.

SEDIMENTOLOGY

Both massive and stratified diamictites are present in the sections measured in Armentrout's Channel (Fig.



FIGURE 6. Photograph of Armentrout's Channel showing incision of eastern margin of channel and sediment fill of turbidites and diamictite.

7). Massive diamictites consist of muddy fine-grained sandstones with scattered clasts and occasional deformed stringers and pockets of sandstone. These facies probably formed by a combination of "rain-out" and resedimentation processes.

Stratified diamictite facies consist of interbedded diamictites with variable matrix texture and clast content and contain common deformed sandstone stringers and rafts. These facies are typical of resedimented, subaqueous debris flows. Deformed diamictite facies occur in the section logged outside of the channel and contain numerous, highly contorted and folded rafts of sandstone, mudstone and diamictite in a muddy sandstone matrix. These facies also represent debris flow deposits.

The lower portion of the section within Armentrout's Channel is dominated by thinly interbedded sandstones and mudstones, interpreted as turbidites (Fig. 7). Sandstone beds range from a few centimeters to a few meters in thickness and are mostly massive and sharp-based. Intervening mudstone beds are massive or bioturbated with common megafossils and occasional dropstones. Bioturbated mudstones contain ichnofacies typical of areas subject to repeated turbi-

dite activity (Eyles and others, 1992). Similar fine grained turbidite deposits are recorded in the section outside the megachannel (Fig. 7).

Several massive to crudely stratified conglomerate beds occur interbedded with turbidite deposits towards the base and lateral margin of the megachannel (Fig. 7). Marginal conglomerate beds grade into fine-grained turbidites of the central channel fill over a distance of tens of meters. This suggests a local source of clasts, probably from the channel margins.

In summary, the sediments preserved within Armentrout's Channel were deposited primarily by sediment gravity flow processes, indicating an environment affected by relatively high sedimentation rates and substrate relief. It is important to note that sediments into which the megachannel is cut show very similar characteristics and may also represent the infill of a megachannel, the margins of which are not exposed in outcrop.

MICROPALAEONTOLOGY

The distribution of foraminifera (benthic counting groups described in Table 1 and planktic foraminifera)

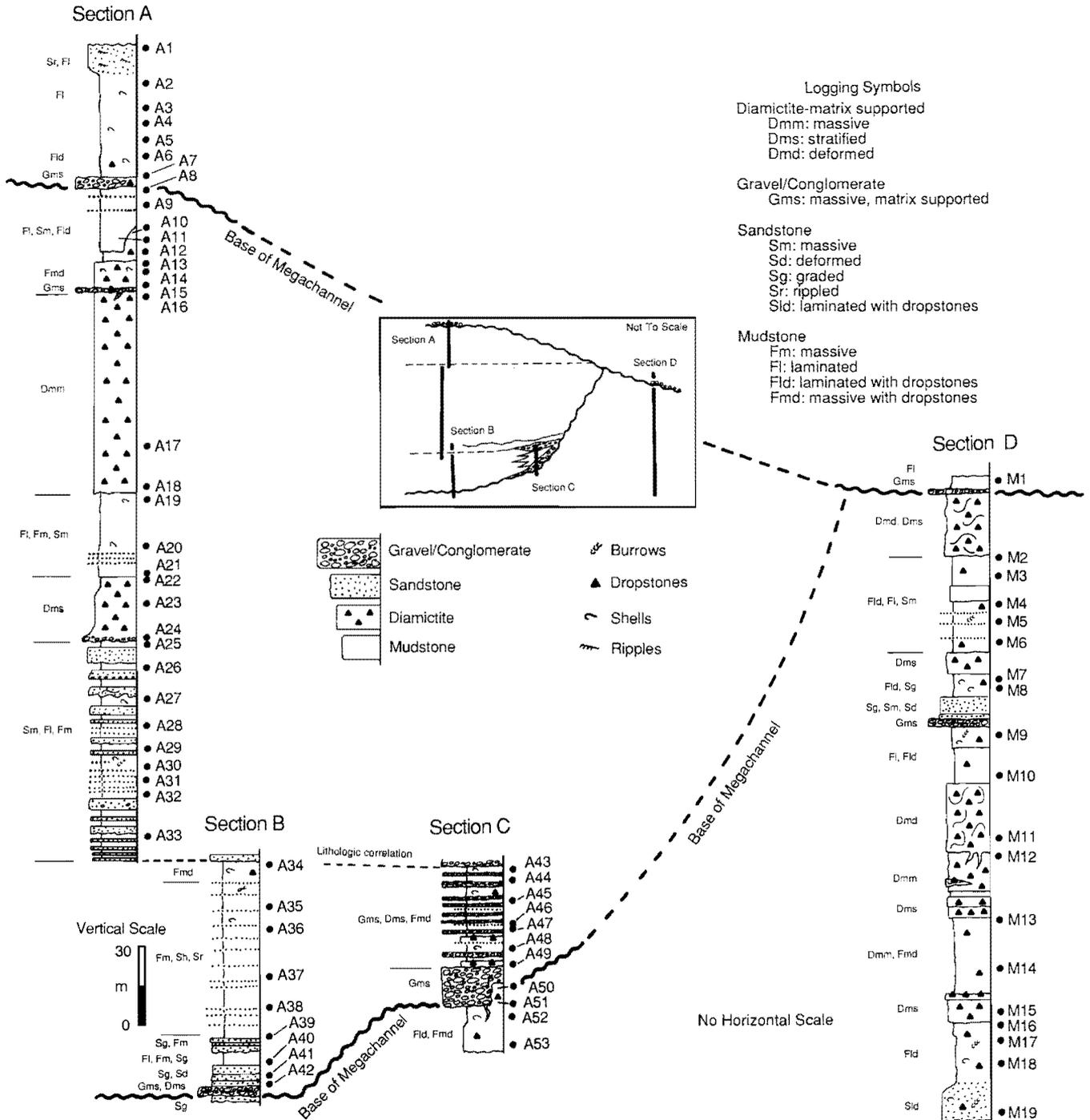


FIGURE 7. Measured sections within (A, B, C) and outside (D) Armentrout's Channel. Location of micropaleontology samples shown by solid dots.

is shown in Table 2. The benthic counting groups are arranged on Table 2 in a rough paleobathymetric order, shallow on the left, deeper on the right. Planktic foraminifera are rare or absent in most samples studied. Only in sample A4 are they common.

Several paleoenvironmentally significant benthic foraminiferal biofacies have been recognized by previous work on the Yakataga faunas (e.g., Lagoe, 1983; Lagoe and others, 1989; Zellers, 1989, 1990). Interpretation of the Yakataga biofacies is based on the distribution

TABLE 2. Distribution of foraminifera in samples from the vicinity of Armentrout's Channel. Actual counts of planktic foraminifera are shown. Relative abundance of benthic foraminifera is described in the following terms: V = very rare (1 specimen/sample), R = rare (2-9 specimens/sample), F = few (10-32 specimens/sample), C = common (33-100 specimens/sample), A = abundant (>100 specimens/sample), ? = uncertain identification (poor preservation).

SAMPLES	Barren Samples = B	Elphidiella oregonense	Elphidiella hannah	Elphidium excavatum clavatum	Elphidium bartletti	Elphidium spp.	Buccella frigida	Buccella tenerrima	Quinqueloculina spp.	Cibicides spp.	Haplophragmoides spp.	Cassidulina minuta	sharp margined cassidulinids	Glandulina laevigata	Nonionella miocenica	Cassidulina californica	Uvigerina juncea	Pullenia salisburyi	Epistominella pacifica	Cyclamina spp.	Bathysiphon sp.	Globigerina bulloides	Globigerina quinqueloba	Globigerinita glutinata	Neogloboquadrina pachyderma-left	Neogloboquadrina pachyderma-right	Indeterminate planktic spp.	Total planktic specimens	
A1			?	C	R	F	R		R	V				F					?									0	
A3				A	R	R			V	R	A	R		F	F								5						7
A4				A	F	F	R	R	R	R	C	V		F	F		V						58	1	1	3	2	9	72
A5				C	R	F		R		V	A		V	R	F								1						1
A6				R		R					A					V													0
A8				F	R	F		R								V													0
A10				F				V				V																	0
A13				A		R						V	V	R									2						2
A14				A	R	F	R				C			F															0
A16				C		F				R					V								2						2
A17				R																									0
A18				R																									0
A19				V																							2		2
A20				C			R			F	C	R	C	F	R								7				1		8
A22				F					V																				0
A24				F									V																0
A27				F	R	R	V			R	C	V	V	V	R														0
A29				C		R	R		V	R	F		C	R	R								4						4
A31				C		R	V	V		R	C		F		V								4				1		5
A32				C		R					F	R																	0
A33				V	F																								0
A35				C			V				A		R																1
A37	B																												
A39				C	R	V	R		R		C	V	F			R							4	1		2			7
A40	B																												
A45			R	A	R	F	R	R			C	R	R										1						1
A46				R							R																		0
A49				R		V	V				R																		0
A51				C		R	R				R	F	C		R														0
A52				C		R					C	V	R		V														0
M1				R		R	R	R		R	F	R		V	F														0
M6				C	F	F	R					F		V															0
M7				F	R	R	R				R	R			R									1					1
M11	B																												
M13	B																												
M14				F				V																					0
M15				F		R	R			R	R	R	R		R														0
M18				R			R			V	R	R			V														0

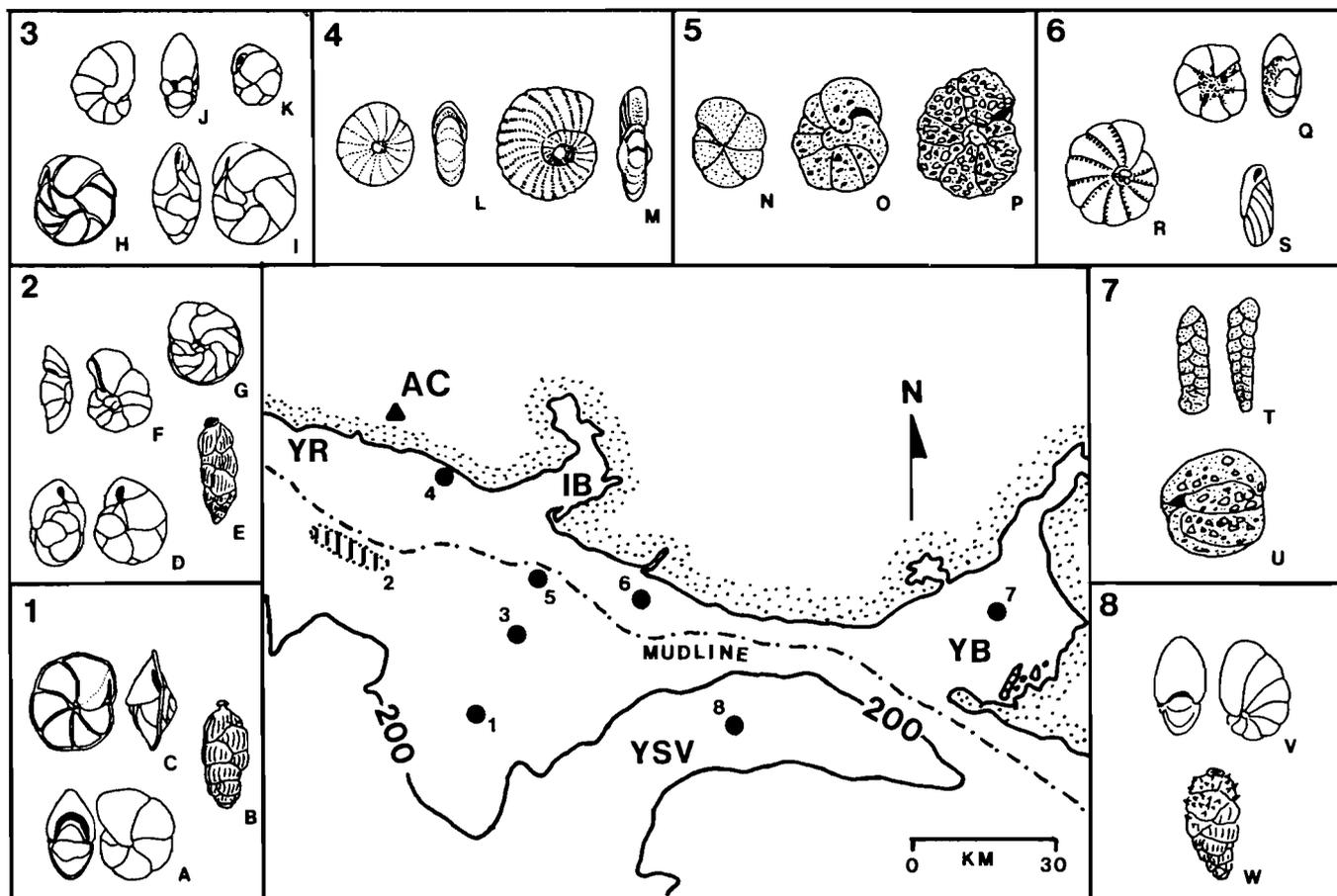


FIGURE 8. Characteristic benthic foraminifera from the modern Yakataga continental margin. The 200 m isobath approximates the shelf-edge. Geographic abbreviations: YB—Yakutat Bay; YSV—Yakutat Sea Valley; IB—ICY Bay; YR—Yakataga Reef; AC—Armentrouts Channel. Mudline is approximate boundary between inner shelf sandy substrates and outer shelf muddy substrates. Location of characteristic faunas shown by numbered solid circles. 1) Upper bathyal biofacies: A) *Pullenia salisburyi*, B) *Uvigerina juncea* (striate), C) *Epistominella pacifica*; 2) Biofacies characteristic of sediment starved areas (bedrock outcrop shown by vertical lines): D) *Cassidulina californica*, E) *Trifarina angulosa*, F) *Cibicides lobatulus*, G) *Cassidulina limbata*; 3) Outer neritic biofacies: H) *Cassidulina norcrossi* s.l., I) *Cassidulina* cf. *C. teretis*, J) *Nonionella miocenica*, K) *Cassidulina minuta*; 4) Innermost neritic biofacies: L) *Elphidiella hannai*, M) *Elphidiella oregonense*; 5) Mudline biofacies: N) *Haplophragmoides* sp., O) *Recurvoides turbinatus*, P) *Cribrostomoides* sp.; 6) Inner neritic biofacies: Q) *Buccella frigida*, R) *Elphidium excavatum clavatum*, S) *Buliminella elegantissima*; 7) Fjord biofacies: T) *Spiroplectammina* sp., U) *Adercotryma glomerata*; 8) Sea valley biofacies (Upper bathyal, sandy substrates): V) *Nonionellina labradorica*, W) *Uvigerina juncea* (hispidocostate). Sketches represent characteristic taxa only and not entire assemblages. Based on data from Echols and Armentrout (1980), analyzed in Lagoe and others (1989) and Zellers (1989). Figure modified from Eyles and others (1991).

of benthic foraminifera in the modern Gulf of Alaska (Smith, 1963, 1973; Todd and Low, 1967; Bergen and O'Neil, 1979; Echols and Armentrout, 1980; Quintero and others, 1980). Quantitative analysis (cluster and factor analysis) of the Echols and Armentrout (1980) data is particularly useful for interpreting Yakataga biofacies (see Lagoe and others, 1989; Zellers, 1989, 1990; Zellers and others, 1992). Distinctive assemblages are found to occupy different parts of the Yakataga continental margin (Fig. 8), varying systematically with depth, substrate, sedimentation rate, water masses and current energy. Those modern biofacies im-

portant in this study are summarized below (see Lagoe and others, 1989; Zellers, 1989, for details on definition of biofacies). A more complete summary of all biofacies present on the Yakataga continental margin is given in Figure 8. Taxa listed below are most abundant in the particular biofacies indicated, but may occur in lesser abundance in other biofacies, commonly due to *post-mortem* transport. It should be noted however that during the current interglacial (relatively high sea level), downslope, *post-mortem* transport of faunas is quite limited (Lagoe and others, 1989; Lagoe and others, 1992).

Innermost Neritic (high energy, a few 10's m water depth)

Elphidiella hannai

Elphidiella oregonense

Trichohyalus ornatissima

Inner Neritic (sandy substrates, photic zone, 20–90 m)

Buccella frigida

Buccella tenerrima

Buliminella elegantissima

Elphidium excavatum clavatum

Elphidium bartletti

Quinqueloculina spp.

Transition between Inner and Outer Neritic (mudline)

Diverse agglutinated assemblage (see Zellers, 1989, 1990)

Outer Neritic (muddy substrates, 90–150 m)

Cassidulina minuta

sharp margined cassidulinids (see Table 1)

Glandulina laevigata

Nonionella miocenica (also occurs in inner neritic)

Uvigerina juncea (transitional to upper bathyal)

Upper Bathyal (muddy substrates, 150–500 m)

Bathysiphon sp.

Cyclammina spp.

Pullenia salisburyi

Epistominella pacifica

Uvigerina peregrina

Most of these modern taxa are recognized in samples from the Yakataga Formation of this study.

PALEOENVIRONMENTAL INTERPRETATION

The foraminiferal data from Armentrout's Channel provide several insights into the paleoenvironments of the channel fill. A study of the checklist (Table 2) indicates that, in terms of the biofacies mentioned above, much faunal mixing is represented in the samples. Most samples containing upper bathyal species also contain common neritic taxa. This is consistent with the dynamic depositional regime in proximity to active tide-water ice margins (Eyles and others, 1985; Lagoe and others, 1992). Resedimentation is common and one result of that is common downslope transport of shallower taxa into deeper environments. Paleoenvironmental interpretations in this study deal with this problem of faunal mixing in two ways. First, individual samples are examined for taxa representing the deepest biofacies in that sample. This deeper component is interpreted as representing the best estimate of the depositional depth for that sample. This estimated depth

represents a minimum, as the upper depth limits of characteristic taxa are used (Ingle, 1980). Secondly, samples are examined within their sedimentologic context and with respect to surrounding micropaleontological samples. Within a consistent lithofacies some individual water depth estimates may vary because some samples may consist almost entirely of displaced taxa. In such situations surrounding samples may dictate a deeper interpretation than indicated by the fauna of an individual sample.

Taking the processes described above into account, the benthic foraminiferal data can be interpreted in terms of paleobathymetry (Fig. 9). Paleobathymetric fluctuations within the sections studied are evident.

We shall begin by describing trends within Armentrout's Channel. The lowermost fill of Armentrout's Channel, interpreted sedimentologically as turbidites, contains upper bathyal benthic foraminiferal biofacies (samples A29 and A39). These samples contain few to common *Epistominella pacifica* and scattered bathyal agglutinated taxa (*Cyclammina* sp., *Bathysiphon* sp.). Deposition at 150–500 m water depth is indicated, consistent with the sedimentological interpretation of turbidites for this interval.

Diamictites within the channel contain sparse faunas that seem to indicate inner neritic water depths (samples A16 to A18, A22, A24), though care must be taken in interpreting sparse faunas. These faunas are dominated by *Elphidium excavatum clavatum*.

Good faunas near the top of the channel succession, below the truncation surface (which occurs between samples A7 and A8 on Fig. 7) indicate a shoaling neritic environment. Samples A13 and A14 contain outer neritic taxa such as *Cassidulina* spp., *Glandulina laevigata*, and *Haplophragmoides* spp., while the overlying samples (A8, A10) contain only inner neritic taxa, *Elphidium* spp. and *Buccella tenerrima*. Above the truncation surface neritic faunas abruptly grade into upper bathyal biofacies, samples A4 and A5 containing *Epistominella pacifica* and A4 containing common planktic foraminifera. These are, in turn, overlain (samples A1, A2) by neritic assemblages (Fig. 9).

Samples from section C, near the margin of the megachannel (particularly sample A45, Fig. 7) indicate vigorous downslope transport of neritic fauna. Here, innermost neritic *Elphidiella oregonense*, along with abundant inner neritic *Elphidium excavatum clavatum*, have been transported into upper bathyal environments. Lithologically the interval is characterized by common gravel beds which were deposited by sediment gravity flows (Fig. 7). This attests to the steep-sided nature of the megachannel and narrowly bor-

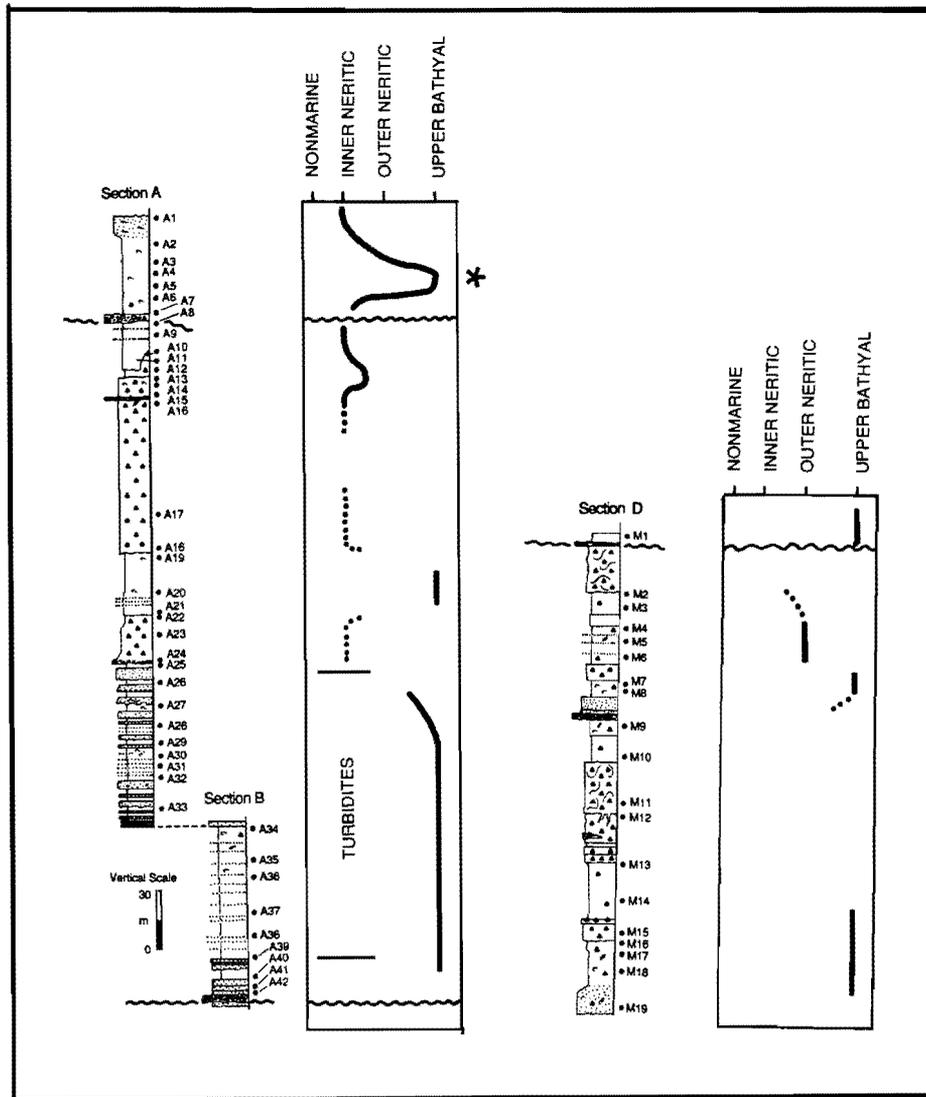


FIGURE 9. Paleobathymetric interpretation of sections within (A, B) and outside (D) Armentrout's Channel. Water depth estimates based on benthic foraminiferal biofacies. See Figure 7 for orientation of sections. Starred horizon indicates only sample in which planktic foraminifera were common (A4).

dering neritic zones which are characteristic of both fjords and sea valleys in the eastern Gulf of Alaska.

Several water depth fluctuations on the order of 100 m or so are apparent within Armentrout's Channel. It will be important to note that the basal fill of the megachannel was deposited at upper bathyal water depths.

Section D, outside Armentrout's Channel, contains fewer samples with good foraminiferal faunas than the sections within the megachannel. Most of the section (samples M1, M7, M15, M18) appears to have been deposited at upper bathyal water depths (Fig. 9), with some neritic conditions suggested by faunas from diamictites and other glacially influenced units (e.g.,

sample M14). In general, the types of sediments and their interpreted paleoenvironments are very similar to those found within the megachannel.

FJORD OR SEA VALLEY?

Discrimination of fjord and sea valley depositional settings is not easy and requires consideration of a combination of geomorphological, sedimentological and paleoenvironmental data. The most telling micropaleontological evidence regarding the origin of Armentrout's Channel is the reconstructed paleoenvironment of the basal channel-fill sediments. The bas-

al sediments are turbidites deposited at upper bathyal water depths (150–500 m), consistent with the relief of the megachannel (at least 330 m). This suggests that a normal environmental gradient (i.e., succession of water masses) was present in the megachannel and it did not contain a sill. In a silled basin, such as a typical fjord, we would expect to see faunas indicative of sill depths (most likely neritic) even in the deepest part of the channel. This is the case in modern Yakutat Bay (Fig. 4). The presence of bathyal faunas in the basal part of Armentrout's Channel suggests that this feature had unrestricted water circulation and formed with oceanographic characteristics comparable to modern sea valleys in the Gulf of Alaska.

The megachannels described here from the upper Yakataga Formation are part of a thick progradational continental margin succession that records rapid outbuilding of a slope by mass flow processes (Eyles and others, 1991). Megachannels may comprise part of an upper slope channel system similar to that present on the modern Gulf of Alaska continental slope (e.g., Stephenson and Embley, 1987). Channel formation in these settings occurs either as a result of erosion by debris and meltwater derived from ice margins extending out onto the shelf or as a result of large scale downslope failure of rapidly deposited sediment (Eyles and others, in prep.).

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RECENT AND LATE QUATERNARY DISTRIBUTION OF *ELPHIDIUM EXCAVATUM* F. *CLAVATUM* IN ARCTIC SEAS

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ABSTRACT

The distribution of living and total (dead + living) specimens of *Elphidium excavatum* f. *clavatum* was mapped in arctic seas, including the Barents Sea, Kara Sea and Svalbard fjords. Its distribution pattern is related to cold waters (< 1°C), turbid waters close to the terminus of glaciers, and shallow settings and low saline waters in high sediment accumulation areas. Consequently, *E. excavatum* f. *clavatum* is a sensitive indicator of a marked melt water event between 13,000 and 14,000 years B.P. which occurred on the Svalbard-Barents Sea margin. With an increase of temperature

(10,000 years B.P.), *E. excavatum* f. *clavatum* migrated both northwards and eastward and into the fjords of Svalbard.

Reworking of *E. excavatum* f. *clavatum* from glaciomarine shelf sediments most probably explain its scattered distribution in the surface sediments from the shelf underlying temperature normal saline waters, high flux on the slope during the Holocene, and high percent frequencies on the continental slope during the last deglaciation.

INTRODUCTION

Elphidium excavatum f. *clavatum* is the most frequent shallow marine benthic foraminiferal species from late Quaternary glaciomarine deposits from high northern latitudes. It typically dominates the foraminiferal assemblages in glaciomarine sediments proximal to retreating glaciers (Vilks, 1981; Osterman, 1984). Consequently the present day distribution of *E. excavatum* f. *clavatum* in the Arctic is important for understanding its stratigraphical occurrence in the late Quaternary.

E. excavatum is shown to have various forms (or subspecies) (Feyling-Hanssen, 1972; Wilkinson, 1979; Miller and others, 1982). Some of these are recorded in the investigated material, but *Elphidium excavatum* (Terquem) forma *clavatum* Cushman, is by far the most dominant.

The distribution of both dead and living specimens of *E. excavatum* f. *clavatum* was analyzed in surface sediments from the Barents Sea, the Kara Sea and three fjords of Svalbard (Figs. 1, 3, 6A, Tables 1, 2). The Barents Sea is a shallow, epicontinental ocean, spanning various climatic, oceanographic and bathymetric environments. The Kara Sea is a shallow sea sheltered from the open ocean. It is influenced by input from large Siberian rivers which result in fluctuating and reduced salinities and high sediment accumulation in near coastal sites. The eastern and northern Barents Sea and the Kara Sea are dominated by cold Arctic water which is covered by sea ice during winter (Fig. 2). The southwestern Barents Sea is dominated by temperate Atlantic water. The Svalbard fjords are also covered by sea ice during winter and have a glaciomarine regime. In light of the modern distribution of *E. excavatum* f. *clavatum*, we discuss its stratigraphic occurrence in differing glaciomarine and marine continental shelf environments from the Last Glacial Maximum (LGM) to the present.

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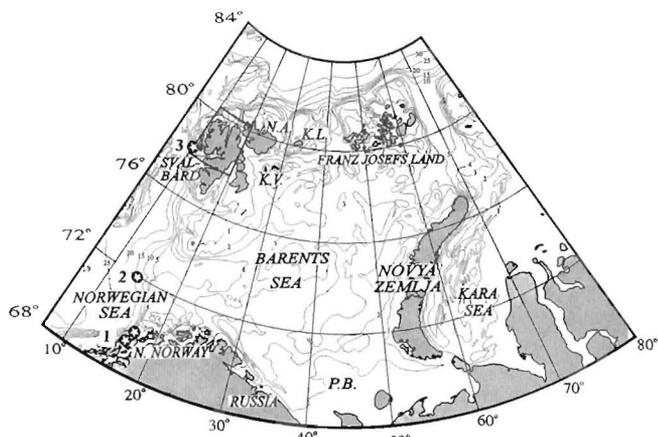


FIGURE 1. Location map showing the Barents Sea and adjoining seas. Bathymetry is given in 10^2 m. KV = Kvitøya, KL = Kong Karls Land, NA = Nordaustlandet, PB = Pechora Basin. Asterisks denote the core locations on the Svalbard-Barents Sea margin, 1 = shelf off northern Norway, 2 = core T-88-2 on the continental slope off the Barents Sea, and 3 = core NP-90-12 on the Svalbard margin. Framed area on Svalbard is shown in detail in Figure 6a.

MATERIAL AND METHODS

Modern benthic foraminifera were studied in the 0.1–1 mm size fraction of approximately 500 surface sediment samples from the Barents Sea and Kara Sea and 31 samples from three fjords on Svalbard (see Figs. 3 and 6A for sample locations). Living foraminifera were identified by the rose Bengal staining method (Lutze, 1964; Bernhard, 1988). The samples from the Svalbard fjords and most of the samples from the western Barents Sea were obtained by using a box-corer. The rest of the Barents Sea and Kara Sea samples are partly core-tops and partly grab samples. In addition, stratigraphic sequences from gravity cores, one off northern Norway (37 samples) and the other off western Svalbard (19 samples), were analyzed (Fig. 1). Preparation of the samples mainly followed the methods given by Feyling-Hanssen (1958) and Meldgaard and Knudsen (1979). However, in about half of the samples flotation was carried out using a mixture of di-chlor benzol and bromoform, while on the other half we used tetra chlor, both liquids were diluted with alcohol to a specific gravity of 1.8. Owing to the fragile nature of the agglutinating foraminifera (they disintegrate easily), they were omitted from the data sets.

RECENT DISTRIBUTIONS

BARENTS SEA AND KARA SEA

The database (Table 1) is a compilation from several sources (Østby and Nagy, 1981; Stenløkk, 1984; Stoll,

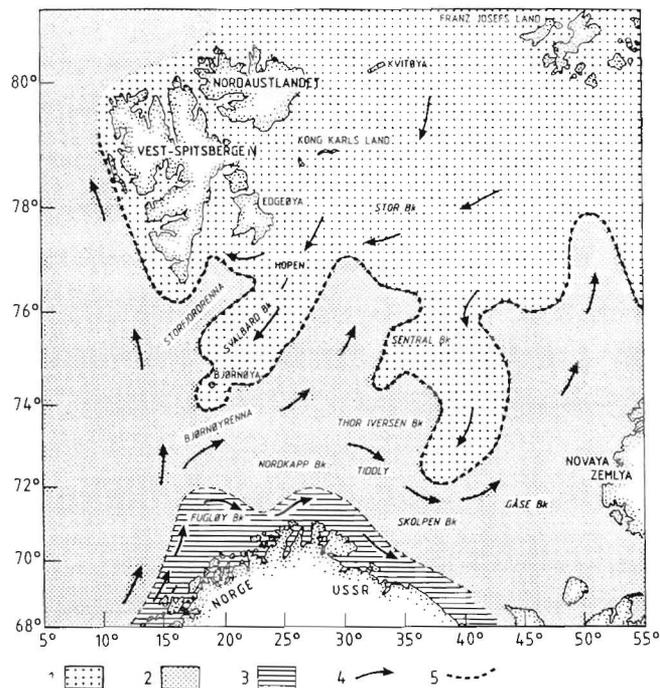


FIGURE 2. Surface water in the Barents Sea and adjoining Seas modified from Loeng (1983). 1 = Arctic water, 2 = Atlantic water, 3 = coastal water, 4 = surface currents, 5 = average position of the sea ice limit.

1967; Digas, 1969) and our own data. Most of the database is from samples taken by box corer and grab, but 108 samples from Østby and Nagy (1981), Stenløkk (1984) and Stoll (1967) and 40 Russian samples from the southeastern Barents Sea, are core tops. Water depth for the sample locations (Fig. 3) range from 500 to <100 m, however the bulk of the samples are from between 100 and 300 m.

By performing Q-mode factor analysis on all the samples (Imbrie and Kipp, 1971), the calcareous benthic foraminiferal fauna was divided into five different factors. The most widely distributed factor is dominated by *E. excavatum* f. *clavatum*. This factor covers most of the Kara Sea and the areas north of 77°N and east of Svalbard. *E. excavatum* f. *clavatum* is associated mainly with *Elphidium subarcticum*, *Buccella frigida* and *Nonion labradoricum*. The other four calcareous factors identified in this region are dominated respectively by *Nonion barleeanum*, *Cibicides lobatulus*, *Cassidulina reniforme* and *Epistominella nipponica*. *E. excavatum* f. *clavatum* is nearly absent in these other factors. (A paper presenting all the assemblages is in preparation by Steinsund and others.)

In the eastern and northern Barents Sea calcium carbonate dissolution has removed a large part of the

calcareous foraminifera (Steinsund and Hald, in press), leaving a mainly arenaceous assemblage dominated by various species of *Reophax*.

Elphidium excavatum f. *clavatum* is the most common species in calcareous foraminiferal assemblages over the northern and eastern Barents Sea and in the Kara Sea. It attains its highest percentages in the area of Franz Josef's Land and Svalbard, around the northern part of Novaya Zemlya, as well as along the coast of Western Siberia (Fig. 3). A maximum value of 74% (of the total calcareous benthic foraminiferal fauna) is found northwest of Novaya Zemlya. In the central eastern Barents Sea some ten samples contain more than 50% of *E. excavatum* f. *clavatum*. Most of the samples collected in the temperate waters from the western and southwestern Barents Sea do not contain any *Elphidium excavatum* f. *clavatum* at all.

A plot of *E. excavatum* f. *clavatum* versus bottom temperature (Fig. 4) shows that most *E. excavatum* f. *clavatum* are found at temperatures between 1°C and -1.8°C. *E. excavatum* f. *clavatum* is nearly absent at temperatures higher than 2.5°C while the abundance of *E. excavatum* f. *clavatum* is greatest at salinities around 33‰ (Fig. 5). High values of *E. excavatum* f. *clavatum* occur in areas with fluctuating and reduced salinities, especially in the southeastern Barents Sea and the Kara Sea. However, it is difficult to estimate the influence of lowered temperature and salinity independently, as most of the stations from low salinity areas also have low temperature.

SVALBARD FJORDS

The distribution of *E. excavatum* f. *clavatum* was also studied in surface sediments in the Svalbard fjords (Fig. 6, Table 2), including profiles in Isfjorden-Billefjorden (Fig. 6B), Nordfjorden-Isfjorden (Fig. 6C), Liefdefjorden-Woodfjorden (Fig. 6D), and Wijdefjorden (Fig. 6E). Water depths range between 65 and 430 m, but most of the stations are between 100 and 200 m. The content of foraminifera is normally below 100 individuals per gram bulk dry sediment. The number of living foraminifera (vs. total living + dead fauna) varies between 70 to <10%, but in most of the samples it is between 20–40%. The highest frequencies of living foraminifera are found in the inner parts of the fjords.

Both living and total specimens of *E. excavatum* f. *clavatum* are frequent in the inner (landward) parts of the fjords where this species dominates together with *Cassidulina reniforme*. In the inner part of Liefdefjorden *E. excavatum* f. *clavatum* accounts for nearly 60% of the living fauna. Its frequency decreases abruptly

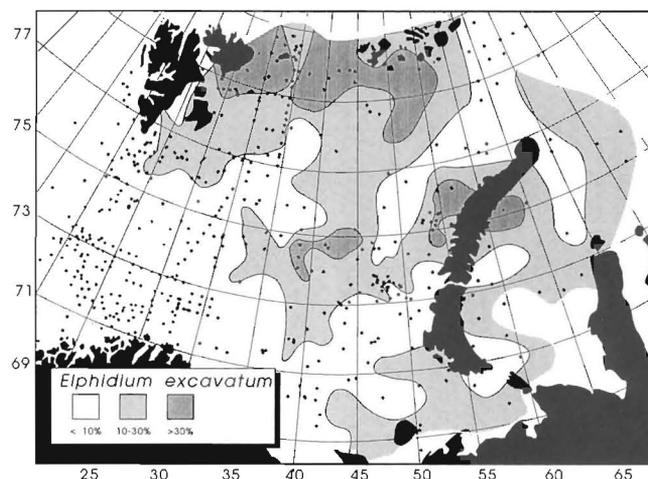


FIGURE 3. Recent distribution of living + dead *Elphidium excavatum* f. *clavatum* in the Barents and Kara Sea (percent values vs. total benthic foraminiferal fauna). Black dots indicate surface sediment sample stations.

seaward, especially in the Isfjorden-Billefjorden and Liefdefjorden-Woodfjorden profiles (Figs. 6B, 6D). In these outer areas *E. excavatum* f. *clavatum* constitutes around 10% or less and it is found in three different assemblages: The first assemblage is dominated by *Cibicides lobatulus*, typically found at the more shallow stations with coarse sediments and a low content of living foraminifera. The second assemblage is dominated by *Nonion labradoricum* and the third assemblage has a high content of agglutinating species (*Adercotryma glomerata*, *Reorvoides turbinatus* and *Reophax atlantica*). In all these assemblages *E. excavatum* f. *clavatum* is replaced by a more diverse fauna in a seaward direction. (A paper presenting the complete foraminiferal assemblages in these fjords is in preparation by Hald and Korsun.)

E. excavatum f. *clavatum* dominates the innermost parts of the fjords close to local calving glaciers. On-site water observations during sediment sampling on cruises in August 1990 and 1991 typically showed highly turbid waters, bottom salinities between 34.3 and 34.6‰ and bottom temperatures between 0.5 and -1.7°C. Slightly reduced salinities compared to normal marine waters (35‰) seems characteristic throughout all the investigated fjords. On the other hand, cold and negative temperatures are restricted to the inner basins of the Isfjorden-Billefjorden and Liefdefjorden-Woodfjorden profiles. These basins are limited by shallow thresholds and cold bottom water probably produced during local winter freezing and formation of sea ice. Salinity variations should also be expected in these environments but can only be detected by con-

TABLE 1. Location (latitude N, and longitude E) and percent values vs. total benthic foraminiferal fauna for the recent distribution of *Elphidium excavatum* f. *clavatum* in the Barents and Kara Sea (cf. Fig. 3).

Longitude	Latitude	% tot.	Longitude	Latitude	% tot.
70 24.00	76 44.50	0.00	23 40.00	71 55.00	0.96
74 39.00	78 03.40	0.00	13 30.00	74 35.00	0.00
87 32.00	81 04.00	0.00	19 20.00	72 45.00	0.11
87 39.00	81 30.50	0.00	13 45.00	71 55.00	0.00
84 54.00	81 30.50	0.00	15 00.00	73 55.00	0.00
82 15.00	81 30.60	0.00	11 00.00	73 55.00	0.00
79 52.00	81 34.80	0.00	09 00.00	75 50.00	0.10
75 20.00	81 37.00	1.88	13 30.00	76 30.00	4.98
73 00.00	81 36.00	0.00	38 35.00	75 54.00	4.00
70 46.00	81 42.30	0.00	40 08.00	74 03.00	10.71
67 32.00	81 35.50	0.61	16 10.00	72 50.00	0.00
67 08.00	81 02.20	0.00	16 30.00	74 00.00	0.60
69 34.00	80 58.10	9.62	18 20.00	70 50.00	0.10
82 05.00	81 08.00	0.00	17 00.00	69 50.00	2.03
83 58.00	81 07.00	0.00	29 56.00	74 35.00	4.93
83 59.00	80 35.80	0.00	32 37.00	74 33.00	9.76
84 01.00	80 00.50	0.00	32 50.00	75 47.00	0.00
84 02.00	79 35.50	0.00	31 19.00	75 49.50	8.86
82 13.00	80 41.10	0.00	33 06.00	75 54.00	0.00
74 32.00	80 36.80	0.00	34 38.00	75 00.00	7.94
71 43.00	80 39.90	0.00	34 44.00	74 30.50	14.01
69 10.00	80 42.90	0.00	36 20.00	74 59.00	31.76
66 48.00	80 45.10	0.00	36 30.00	75 54.00	0.56
64 15.00	80 00.00	0.00	38 33.00	75 14.00	18.82
66 55.00	80 00.00	0.00	38 35.00	74 47.00	10.81
69 47.00	80 00.00	0.00	38 34.00	74 25.00	0.00
72 11.00	80 00.00	0.00	38 36.00	74 06.00	28.79
74 36.00	80 00.00	0.00	41 25.00	74 03.00	13.75
69 27.00	79 35.00	0.00	41 25.00	74 51.00	38.89
66 57.00	79 35.20	0.00	71 15.00	78 53.00	28.30
64 06.00	79 06.20	0.00	14 26.00	72 13.00	0.53
74 09.00	79 05.00	0.00	40 00.00	68 10.00	0.66
66 39.00	78 50.70	0.00	32 00.00	70 05.00	1.18
63 38.00	78 33.00	0.00	49 02.60	76 58.00	9.02
54 15.00	75 25.00	5.19	44 41.50	75 20.00	26.13
51 10.00	76 40.00	0.00	38 21.50	72 55.20	19.39
46 00.00	71 25.00	13.89	44 35.00	79 38.70	0.00
58 00.00	69 45.00	20.83	44 35.00	79 57.80	57.58
41 45.00	72 50.00	2.70	43 44.00	80 00.00	39.44
53 00.00	73 55.00	2.74	45 40.00	80 42.50	6.47
50 20.00	69 30.00	31.37	46 18.40	80 43.30	9.88
33 00.00	71 20.00	1.61	46 25.50	80 38.20	35.71
32 50.00	73 25.00	0.00	47 59.00	80 35.20	25.53
25 20.00	76 05.00	6.91	47 48.00	80 37.10	20.90
33 00.00	77 15.00	0.00	47 43.00	80 41.07	64.91
31 30.00	77 25.00	2.56	41 56.90	79 58.80	37.38
44 15.00	70 55.00	0.63	46 26.20	78 59.60	24.87
37 10.00	70 25.00	0.00	50 33.80	79 07.30	35.84
51 10.00	72 50.00	0.00	55 22.52	79 51.95	32.46
16 00.00	76 20.00	1.00	46 53.30	78 47.90	28.57
35 30.00	78 10.00	0.00	48 15.30	78 42.50	42.97
33 30.00	76 40.00	0.00	39 43.23	79 22.87	24.66
32 10.00	74 45.00	25.48	35 14.37	79 35.90	33.33
40 30.00	70 20.00	2.08	35 12.35	79 49.27	8.11
16 40.00	74 05.00	0.40	37 03.50	79 47.80	37.01
14 20.00	75 35.00	0.00	38 30.00	72 00.00	0.00
17 00.00	72 35.00	0.98	38 59.50	71 59.40	5.56
15 30.00	75 15.00	0.71	36 15.30	71 30.30	0.00
18 30.00	70 25.00	0.19	36 30.60	70 39.40	0.00
30 00.00	74 40.00	6.03	36 30.00	71 35.00	13.00
33 00.00	69 55.00	2.03	21 07.90	74 02.90	0.52
24 30.00	71 10.00	0.10	49 31.00	73 35.00	11.20

TABLE 1. Continued.

Longitude	Latitude	% tot.	Longitude	Latitude	% tot.
24 15.00	74 21.40	2.05	50 35.00	74 32.00	8.33
22 05.00	74 22.70	5.10	56 48.00	76 17.00	37.91
22 28.50	74 59.30	4.95	46 37.00	74 56.00	0.00
17 48.10	75 04.90	4.04	47 22.00	74 45.00	5.13
20 02.40	75 32.30	6.32	41 25.00	70 17.00	48.35
18 23.40	75 34.10	7.25	56 52.00	75 28.00	7.89
19 18.10	75 37.70	4.04	53 40.00	75 41.00	10.02
24 32.50	75 59.20	8.74	53 39.00	75 41.00	10.19
23 11.90	76 26.90	18.18	52 35.00	75 24.00	31.91
22 35.00	76 26.40	20.21	52 45.00	75 29.00	40.00
21 58.80	76 23.80	12.31	54 05.00	75 17.00	25.24
17 39.90	75 40.20	8.04	53 40.00	75 09.00	39.64
20 12.70	76 04.80	6.52	54 37.00	75 37.00	16.10
20 14.10	76 32.80	19.79	53 38.00	75 24.00	23.38
18 53.00	76 06.20	11.28	54 33.00	75 36.00	0.00
17 47.80	76 25.70	15.15	54 50.00	75 37.00	13.38
17 26.00	76 06.00	20.32	46 59.48	72 07.13	0.19
17 06.70	75 55.40	20.30	46 40.58	72 01.50	1.04
16 24.00	75 52.80	9.30	50 27.97	73 12.53	3.05
18 10.00	76 43.70	29.69	45 32.00	74 44.00	6.05
20 08.20	76 52.20	29.03	37 30.00	70 50.00	1.99
21 27.10	76 29.80	12.31	40 30.00	71 15.00	2.07
39 55.00	70 40.05	0.00	43 55.00	73 00.00	9.10
40 10.00	72 20.00	16.33	46 50.00	74 45.00	12.97
21 08.70	71 57.10	0.00	41 45.00	74 45.00	8.00
13 00.00	75 46.00	0.00	44 55.00	70 58.00	6.67
26 32.00	74 09.00	17.44	39 00.00	70 20.00	0.00
55 12.00	74 28.00	16.84	35 15.00	70 25.00	0.00
53 14.60	74 48.40	25.00	34 20.00	70 25.00	0.00
52 53.00	74 27.00	4.44	52 25.37	73 28.75	15.33
49 16.00	74 55.40	21.43	50 00.00	73 15.00	11.06
45 15.20	73 28.00	0.85	47 30.90	73 30.40	0.00
50 16.70	72 38.10	0.00	36 10.53	71 34.40	5.05
49 15.60	72 47.30	0.00	37 05.23	70 39.28	0.00
46 58.40	73 12.10	8.28	43 24.28	73 05.32	5.23
45 25.80	72 17.10	7.89	44 11.12	73 10.98	4.00
41 37.40	69 31.20	6.84	43 04.47	73 10.87	8.16
43 46.40	72 33.70	9.09	41 28.95	71 26.28	0.34
45 00.00	74 26.50	14.29	40 25.30	70 22.00	0.00
46 35.30	73 42.00	11.76	41 28.00	70 38.00	14.02
44 18.00	73 42.00	8.85	26 07.50	74 33.10	2.69
57 16.20	75 29.20	48.73	26 11.20	75 24.53	2.03
62 08.80	77 01.30	14.29	28 47.50	75 20.57	7.68
43 42.50	71 49.50	7.04	26 19.33	76 00.40	5.96
49 12.00	73 22.00	0.00	46 20.00	72 00.00	2.02
46 41.00	73 58.00	0.00	37 16.30	68 48.50	1.32
48 46.00	73 43.00	10.36	50 13.70	68 44.90	51.85
49 25.00	73 38.00	6.58	50 14.20	69 21.00	53.90
47 05.00	73 49.00	1.97	61 40.90	69 48.00	33.67
47 47.00	73 44.00	3.23	67 50.40	74 01.00	9.09
47 50.00	73 43.00	9.32	78 07.40	72 52.50	40.00
47 02.00	73 45.00	4.23	77 12.90	75 09.00	16.56
48 11.00	73 37.00	8.07	75 20.40	76 00.60	11.49
48 09.00	73 36.00	2.82	69 56.10	76 24.80	7.60
48 02.00	73 36.00	0.00	64 52.00	75 17.00	14.38
48 08.00	73 35.00	5.05	62 06.70	75 17.50	36.44
48 13.00	73 55.00	13.22	59 28.70	74 21.30	0.86
47 33.00	73 38.00	12.90	57 31.60	73 26.60	10.50
47 42.00	73 45.00	2.84	56 43.20	73 03.60	21.34
48 21.00	73 16.00	2.01	59 32.80	72 36.50	70.76
48 02.00	73 30.00	0.69	56 50.30	72 21.00	18.52
48 20.00	73 46.00	0.00	55 50.80	71 35.40	1.63
46 48.00	73 57.00	6.08	59 04.00	71 41.60	6.56
47 01.00	73 56.00	8.08	56 37.00	71 08.50	0.00
49 33.00	73 36.00	5.79	34 30.22	77 20.23	0.00

ARCTIC DISTRIBUTION OF *ELPHIDIUM EXCAVATUM* F. *CLAVATUM*

TABLE I. Continued.

Longitude	Latitude	% tot.	Longitude	Latitude	% tot.
58 30.40	70 15.90	31.07	34 30.59	77 15.61	0.00
55 22.40	70 27.20	7.88	34 31.00	77 00.15	12.50
52 59.20	70 43.20	11.94	29 01.00	74 33.00	14.10
50 10.30	71 47.40	19.05	24 13.00	73 52.00	0.00
50 30.00	70 39.90	11.03	30 00.00	73 41.00	11.11
47 14.90	70 22.60	0.00	29 46.00	73 57.00	8.31
41 51.40	69 51.90	3.74	30 13.00	74 20.00	4.52
01 00.00	71 30.00	12.04	25 04.00	74 42.00	0.00
59 52.00	71 00.00	16.30	26 16.00	73 28.00	0.00
65 30.00	72 30.00	41.64	26 30.00	73 08.00	0.74
58 50.00	73 15.50	0.00	16 44.70	73 04.70	0.00
86 00.00	80 00.00	0.00	15 37.90	73 01.00	0.33
74 54.00	78 13.00	0.00	30 24.70	71 24.80	0.31
78 31.00	75 58.00	0.00	31 58.60	71 23.50	0.00
80 48.00	75 13.00	0.00	32 05.80	70 06.30	0.00
67 38.00	72 43.80	18.99	38 59.50	71 55.40	0.00
63 10.30	72 39.60	27.91	48 13.00	75 58.00	0.00
30 01.62	77 00.38	7.41	51 10.00	76 41.00	0.00
26 36.09	77 02.67	7.55	55 00.00	76 16.50	74.31
28 01.65	77 01.46	5.17	61 10.00	77 07.00	0.00
25 26.80	78 01.06	20.88	62 31.10	77 17.60	0.00
24 21.67	78 00.90	15.34	59 40.00	77 20.00	0.00
23 39.89	78 42.37	28.67	55 57.00	77 37.00	0.00
24 26.63	78 44.75	23.36	42 06.10	77 37.40	0.00
25 23.54	78 47.06	6.27	39 48.00	78 04.00	0.00
26 09.83	78 51.42	15.26	31 11.00	77 12.00	0.00
30 00.30	78 49.31	15.10	22 27.00	76 27.70	10.56
30 02.58	78 44.28	5.26	20 16.00	76 14.00	6.86
29 58.56	78 28.86	16.67	16 27.10	75 52.50	13.59
30 01.99	78 09.21	25.49	15 20.00	75 00.00	4.32
32 57.91	78 00.15	0.00	16 15.60	75 06.50	5.19
34 26.30	78 00.15	0.00	16 21.10	75 07.10	1.73
34 29.18	78 12.66	9.26	19 02.00	74 44.70	3.80
34 32.44	78 23.08	0.00	19 26.80	74 43.40	3.13
34 25.19	78 34.78	0.00	19 40.50	74 46.30	2.40
34 30.67	78 48.25	0.00	17 38.00	74 29.00	2.08
34 33.16	79 00.64	0.00	17 00.00	74 28.00	13.88
33 22.05	79 00.60	23.08	15 05.30	73 20.40	0.35
32 14.39	79 02.06	11.45	15 50.50	73 20.20	0.00
30 59.67	79 00.16	23.40	18 00.00	73 20.00	0.76
23 30.60	79 10.97	36.68	15 43.00	73 02.90	0.00
23 39.42	79 09.10	44.35	16 17.20	73 06.80	0.00
23 41.00	79 06.28	31.89	26 06.60	70 55.10	0.00
23 40.49	79 00.39	36.07	21 32.00	70 55.50	0.00
29 58.92	79 24.33	49.82	26 44.00	71 40.50	0.00
30 01.17	80 10.78	61.05	17 21.70	72 09.50	0.00
30 14.26	80 40.53	23.81	19 28.40	72 02.20	0.00
32 04.13	80 30.03	12.90	22 41.00	71 20.50	0.00
33 03.25	80 48.48	41.67	15 27.33	72 17.45	0.00
33 19.78	80 48.68	36.36	18 22.20	71 30.00	0.00
34 50.83	80 34.69	47.62	19 47.50	71 33.80	0.00
34 03.61	80 31.52	52.14	21 02.20	71 28.50	0.00
33 56.81	80 25.03	48.35	20 12.00	71 23.50	0.00
34 45.46	80 21.73	34.20	27 09.80	72 04.40	0.00
34 00.35	80 12.97	31.54	24 23.88	71 47.07	0.00
34 26.38	80 08.35	40.48	25 11.70	71 51.00	0.00
34 29.00	79 50.09	44.12	17 22.10	71 43.10	0.00
34 29.44	79 30.45	34.41	16 23.10	72 01.10	0.00
34 33.21	79 20.14	63.37	23 52.00	71 33.10	0.00
33 29.91	79 30.09	58.91	20 28.00	71 46.50	0.00
30 35.42	79 29.18	18.85	18 36.80	71 59.40	0.00
26 58.14	79 29.42	38.20	19 02.10	71 49.50	0.00
31 17.18	79 59.89	10.06	18 52.10	71 17.40	0.00
34 29.53	77 40.51	0.00	17 20.00	71 57.90	0.00
18 26.50	71 44.60	0.00	17 32.00	72 30.00	0.00

TABLE I. Continued.

Longitude	Latitude	% tot.	Longitude	Latitude	% tot.
21 32.00	71 15.40	0.00	18 48.00	72 30.00	0.00
24 59.00	72 12.95	0.00	19 26.10	72 29.90	0.00
25 07.50	72 03.28	0.00	19 59.60	72 40.00	0.00
22 18.00	71 29.00	0.00	19 59.00	72 50.00	0.00
19 02.00	71 33.50	0.00	20 00.00	73 00.00	0.00
25 14.13	71 38.03	0.00	18 44.00	73 00.00	0.00
17 50.30	72 06.00	0.00	18 07.80	72 59.90	0.00
24 18.08	71 57.05	0.00	17 38.60	72 20.50	0.00
23 34.30	71 25.50	0.00	18 00.00	72 00.00	0.00
22 19.10	71 04.90	0.00	26 08.05	73 03.03	0.00
21 49.97	71 21.58	0.00	26 48.00	73 39.00	0.00
20 40.80	71 37.10	0.00	27 31.00	74 15.00	5.38
23 17.50	71 52.90	0.00	21 57.40	72 00.10	0.00
22 00.00	71 46.00	0.00	21 57.90	72 29.90	0.00
22 43.08	71 37.50	0.00	21 59.30	72 44.60	0.00
22 11.93	71 22.24	0.00	22 00.00	72 59.80	0.08
23 33.80	71 44.10	0.00	21 58.10	73 15.00	0.00
22 43.84	71 43.73	0.00	21 10.00	73 15.00	0.00
27 29.90	72 12.00	0.00	20 17.80	73 14.90	0.06
28 42.00	72 15.00	0.00	19 23.90	73 14.90	0.00
27 30.01	72 14.97	0.00	18 31.90	73 14.70	0.00
27 30.00	72 13.00	0.00	17 49.50	73 14.90	0.26
28 07.21	72 14.96	0.00	16 47.80	73 15.00	0.19
27 29.65	72 22.35	0.00	15 56.90	73 14.90	0.47
28 41.00	72 15.00	0.00	14 53.80	73 15.00	0.00
31 29.90	72 15.00	0.00	14 01.50	73 26.30	0.00
28 29.63	71 13.01	0.00	17 00.10	72 40.00	0.00
28 29.55	72 45.00	0.00	16 11.20	72 39.80	0.00
30 30.20	72 45.00	0.00	15 17.60	72 39.90	0.00
27 29.37	71 29.83	0.00	14 35.80	72 40.00	0.11
27 29.96	72 29.00	0.00	13 47.40	72 39.80	0.00
27 29.86	72 20.31	0.00	14 30.20	72 46.00	0.38
27 30.00	72 30.00	0.00	15 14.10	72 53.00	0.05
72 15.00	28 41.00	0.00	16 00.40	73 00.00	0.37
27 29.30	72 19.50	0.00	17 00.50	73 10.10	0.03
28 11.15	72 15.00	0.00	21 59.39	72 29.77	0.00
27 29.74	72 14.04	0.00	22 43.53	72 30.11	0.00
28 30.00	72 15.00	0.00	23 27.47	72 30.30	0.08
27 30.05	71 48.08	0.00	24 56.40	72 30.02	0.00
27 29.90	72 00.00	0.00	25 40.13	72 29.90	0.00
28 30.00	72 30.00	0.00	26 33.24	72 30.01	0.05
30 29.98	72 29.93	0.00	27 19.93	72 30.01	0.06
30 29.61	72 15.00	0.00	27 20.24	72 59.98	0.00
29 29.96	72 29.96	0.00	26 29.17	73 00.00	0.00
29 29.85	72 45.00	0.00	25 38.90	73 00.04	0.00
29 30.00	72 15.00	0.00	24 49.99	73 00.00	0.00
15 15.80	78 20.60	9.89	24 00.35	73 00.16	0.00
13 48.50	78 09.40	9.93	22 53.32	72 59.90	0.00
11 24.00	77 57.50	10.91	22 00.45	73 00.04	0.00
11 18.00	77 33.00	2.61	26 27.00	72 21.00	0.29
12 00.00	77 32.50	10.47	27 10.00	73 57.00	1.22
12 44.80	77 22.70	2.37	27 52.00	74 33.00	4.88
12 34.30	77 10.20	8.33	28 14.00	74 51.00	6.73
13 24.00	77 03.20	5.91	28 35.00	75 09.00	7.85
14 54.90	76 50.50	2.99	28 56.00	75 27.00	1.28
15 59.20	75 57.70	11.57	29 17.00	75 45.00	10.62
15 54.00	75 41.20	8.26	29 39.00	76 03.00	8.84
15 06.00	75 30.00	5.35	31 00.00	76 22.00	9.23
16 41.20	75 07.00	1.92	31 00.00	76 39.00	8.06
17 32.20	74 49.90	2.12	31 00.00	76 56.00	0.94
17 28.10	74 41.10	0.00	29 51.00	76 56.00	3.95
17 25.70	74 11.00	1.35	28 42.00	76 56.00	1.42
17 30.70	73 02.70	0.00	28 00.00	76 30.00	0.00
17 32.00	72 42.90	0.00	27 20.00	76 25.00	5.33
22 40.00	76 40.00	12.26	19 05.00	76 16.00	9.43

TABLE 1. Continued.

Longitude	Latitude	% tot.	Longitude	Latitude	% tot.
18 09.00	76 48.00	1.96	18 05.00	76 08.00	13.44
18 12.00	76 28.00	6.67	17 55.00	75 45.00	43.14
17 40.00	76 21.00	7.43	17 25.00	75 45.00	2.18

tinuous measurements over a longer period than was possible in this study.

The frequencies of living and total specimens of *E. excavatum f. clavatum* correlate well. However, in the inner parts of the fjords, especially in Liefdefjorden, the percentage of living *E. excavatum f. clavatum* (vs. total living fauna) is larger than percentage of *E. excavatum* of the total fauna (Fig. 6D). This may indicate that *E. excavatum f. clavatum* preferentially lives and reproduces during summer (and melting) and/or that reproduction of co-occurring species (of which *C. reniforme* is dominant) is more spread throughout the year. In the outer parts of the fjords where sediment accumulation is lower, the relation between living and total may be opposite; that is total percentages dominates. This is especially distinct in the *Cibicides lobatulus* assemblage, where the content of living foraminifera is very low. This relation is probably due to reworking of *E. excavatum f. clavatum*.

TABLE 2. Station and percent total and percent living vs. total benthic foraminiferal fauna for the recent distribution of *Elphidium excavatum f. clavatum* in the Svalbard fjords, Isfjorden-Billefjorden (Fig. 6b), Nordfjorden-Isfjorden (Fig. 6c), Liefdefjorden-Woodfjorden (Fig. 6d) and Wijdefjorden (Fig. 6e).

Station	% tot.	% liv.	Station	% tot.	% liv.
Isfjorden-Billefjorden			Liefdefjorden-Woodfjorden		
90-70	11.5	0	91-64	11.7	—
90-71	10.9	2.17	91-65	0.4	1.1
90-72	10.9	4.0	91-66	6.9	10.0
90-73	25.0	—	91-74	9.2	—
90-74c	0	0	91-73	19.8	19.1
90-81	5.51	—	91-72	36.6	59.0
90-80	9.5	8.8			
90-79	22.1	—			
90-78	35.1	34.7			
Nordfjorden-Isfjorden			Wiedjefjorden		
90-75	16.9	12.8	91-51	8.2	—
90-76	38.7	36.4	91-52	2.0	—
90-77	10.7	7.92	91-53	1.0	—
			91-54	4.0	1.7
			91-55	14.1	10.6
			91-56	18.4	—
			91-57	22.4	—
			91-58	20.9	3.6
			91-59	19.1	4.5
			91-60	11.8	7.0
			91-61	36.4	49.6
			91-63	46.6	46.1

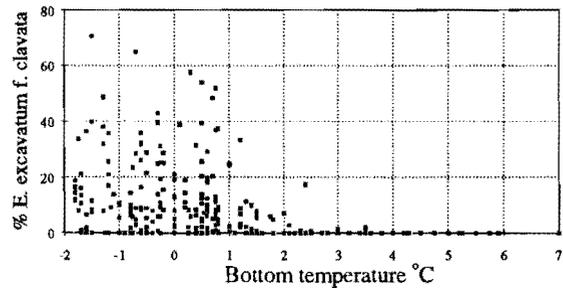


FIGURE 4. Percent of *Elphidium excavatum f. clavatum* vs. summer bottom water temperature (°C) in the Barents and Kara Sea.

From the data presented above it is concluded that recent *E. excavatum f. clavatum* in the Svalbard fjords prefer near-glacial (melting) conditions, cold and turbid waters with slightly reduced salinities.

LATE WEICHSELIAN-HOLOCENE DISTRIBUTION ON THE SVALBARD-BARENTS SEA MARGIN

Two sites were chosen to study the stratigraphic distribution of *E. excavatum f. clavatum*. One is the near coastal continental shelf off northern Norway (300–500 m ocean depth) (Fig. 1, site 1) and the other is close to the shelf edge (684 m depth) off Isfjorden, Svalbard (Fig. 1, site 3). The late Quaternary stratigraphy of these sites, spans a time interval from the Last Glacial Maximum (LGM) to the present.

SHELF OFF NORTHERN NORWAY

The continental shelf off northern Norway (site 1, Fig. 1) has been studied in great detail by Vorren and others (1983a, b, 1984), Hald and Vorren (1984, 1987a, b), and Thomsen and Vorren (1986). Figure 7 shows eight foraminiferal assemblage-zones that are defined in the upper Quaternary strata off northern Norway (Hald and Vorren, 1984, 1987a).

During the LGM, assemblage-zones 8 and 7 are found in basal tills deposited by glaciers that reached the shelf edge during the early late Weichselian (Vorren and others, 1983a). The foraminiferal assemblage is glacially reworked from marine/glaciomarine sediments and contains mixed elements from older Quaternary interglacials and interstadials (Hald and Vorren, 1987a). *E. excavatum f. clavatum* comprises between 13.1% and 47.2% of the total benthic foraminiferal assemblage. The average for assemblage-zones 8 and 7 is 19.9% (Fig. 7).

During the very early phase of the deglaciation of the northern Norwegian shelf, a laminated and almost

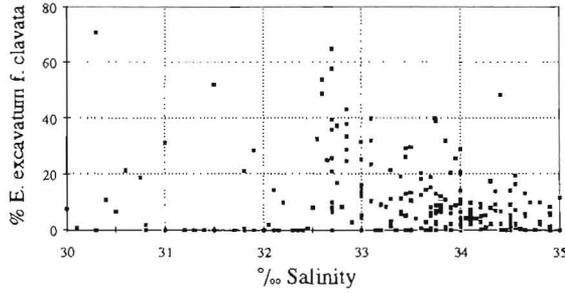


FIGURE 5. Percent of living + dead *Elphidium excavatum* f. *clavatum* vs. summer bottom salinity (‰) in the Barents and Kara Sea.

clast-free clay (unit tF in Fig. 7) was deposited in a low energy regime (Vorren and others, 1983b, 1984). Biogenic production was low and the sea surface was seasonally covered by sea ice. Some foraminifera from this period (assemblage-zones 6 and 5) show indications of a reworked origin. The foraminiferal content is very low (frequently less than 1 specimen per gram, though it increases from zone 6 to 5) and *E. excavatum* f. *clavatum* comprises on average 10% of the fauna in the zones. The upper part of zone 5 occurs in a bioturbated clay which has a characteristically high content of planktic foraminifera. This probably reflects open, but cold shelf water.

In assemblage-zone 4 (between 14,000 and 13,000 years B.P.) there is an increase in *E. excavatum* f. *clavatum* reaching a peak of 59.4% at approximately 13,400 years B.P. This zone has been interpreted to indicate near-glacial conditions partly based on sedimentological evidence and partly based on the foraminiferal fauna (Vorren and others, 1984; Hald and Vorren, 1987a). During the last 500 years of this period, the bottom waters were depleted in oxygen, reaching an oxygen minimum at about 13,300 years B.P. (Hald and Vorren, 1987a, b). This depletion is identified by a benthic $\delta^{13}C$ minimum corresponding to a maximum of *Bolivina spissa* (Hald and Vorren, 1987a, b). *B. spissa* is a benthic foraminifer known to abound in low-oxygen bottom water environments (Uchio, 1960; Bandy, 1963; Bandy and Rodolfo, 1964; Smith, 1964; Douglas, 1979). The macro-fossil assemblage also in-

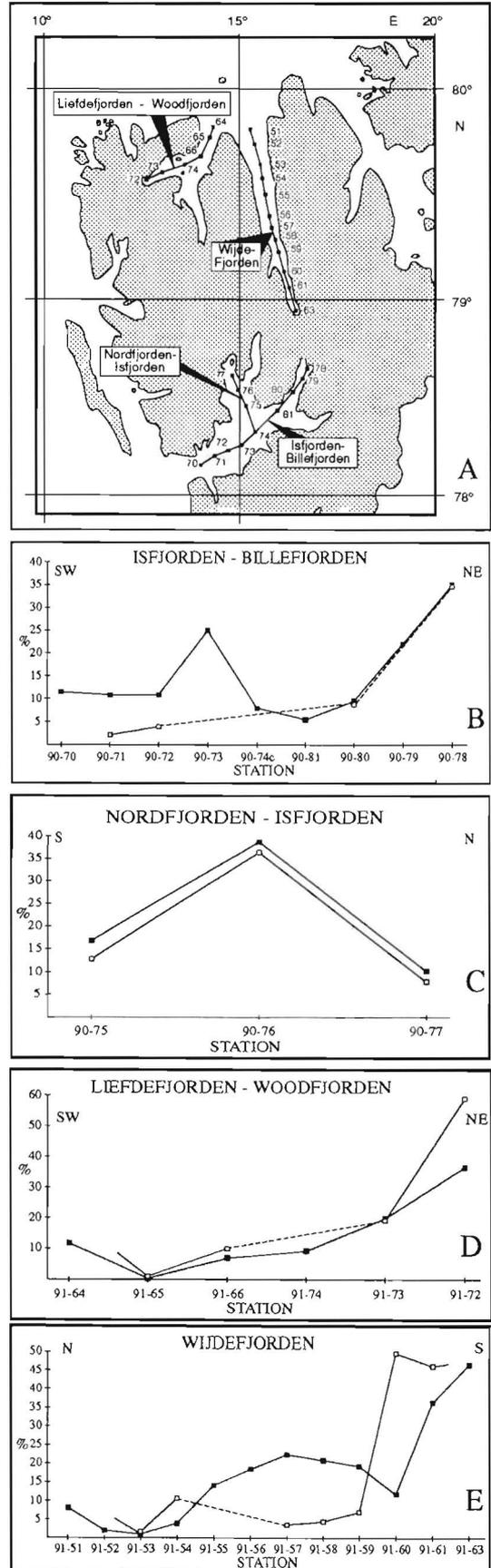


FIGURE 6. Percent of living + dead *Elphidium excavatum* f. *clavatum* in surface sediment samples in fjords from Svalbard. Open boxes = percent living vs. total living benthic foraminiferal fauna. Filled boxes = percent living + dead vs. total living + dead benthic foraminiferal fauna. A) Location of the station profiles, B) Isfjorden-Billefjorden profile, C) Nordfjorden-Isfjorden profile, D) Liefdefjorden-Woodfjorden profile, E) Wijdefjorden profile.

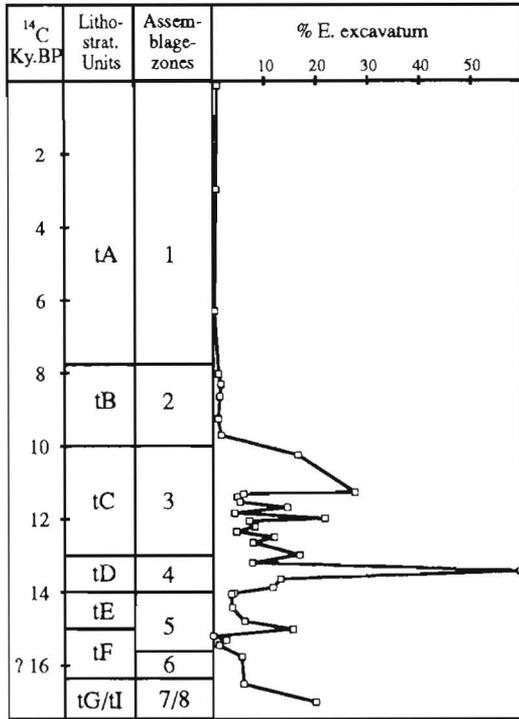


FIGURE 7. Composite Late Weichselian-Holocene stratigraphic distribution of *Elphidium excavatum* f. *clavatum* on the continental margin off northern Norway. For location see Figure 1.

dicates that the environment was suffering from an oxygen deficiency (Thomsen and Vorren, 1986). Reduced ventilation of the bottom water was probably the result of either sea ice or a stable surface layer of meltwater, preventing vertical mixing.

The boundary between zones 3 (13,000–10,000 years B.P.) and 4 is transitional. Zone 3 reflects a general amelioration of the climate, indicated by the introduction of new species and an increase in number of foraminifera per gram sediment (Hald and Vorren, 1987a). The content of *E. excavatum* f. *clavatum* varies between <1 to >30% (average 10.7%). It increases in the upper part of the zone, which corresponds to the Younger Dryas cooling period.

The Holocene/Pleistocene boundary represents a marked environmental change on the continental shelf off northern Norway (Vorren and others, 1984; Hald and Vorren, 1984). Cold glaciomarine waters are replaced by warmer, more saline Atlantic waters of the Norwegian Current. This boundary coincides with a drastic decline of *E. excavatum* f. *clavatum*. The species constitutes approximately 1% or less of the fauna. It is not found living in the area today (Hald and Steinund, 1992). Its Holocene distribution is considered to

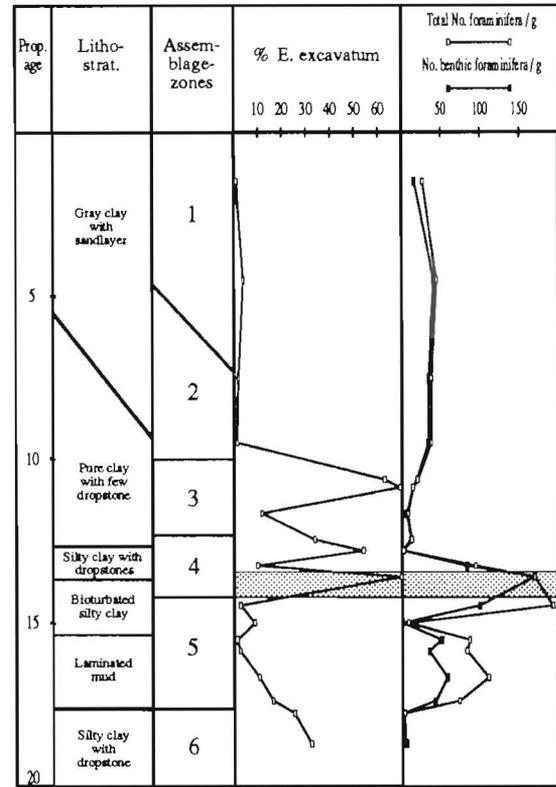


FIGURE 8. Late Weichselian-Holocene stratigraphic distribution of *Elphidium excavatum* f. *clavatum*, number of foraminifera per gram, and benthic foraminifera per gram in core NP-90-12 on the continental margin off Svalbard. Shaded area marks the first marked melt-water event interpreted from the oxygen isotopes (Dokken and Hald, in prep.). For location see Figure 1.

be due to reworking from underlying glaciomarine sediments.

THE SVALBARD MARGIN

One gravity core (NP 90-12) (Fig. 8), from the outer Svalbard margin (site 3, Fig. 1) is under investigation (Dokken and Hald, in prep.). The chronology of the core was established by oxygen isotope stratigraphy and correlation to well-established isotope events in other AMS-dated $\delta^{18}O$ -records. The core extends back to the mid-isotope stage 2 (18,000–19,000 years B.P.), has a well preserved stratigraphic record throughout the last glacial maximum, the deglaciation and the Holocene.

Interpolation of the ages between three $\delta^{18}O$ -fix points gives the following: 1) 9,500 years; termination Ib (Mix and Ruddiman, 1985), 2) 13,600 years B.P.; first great meltwater event in the Norwegian Sea (Sarnthein and others, 1992), and 3) 14,800 years B.P.; last $\delta^{18}O$ -maximum in the LGM before the onset of the meltwater

event (Winn and others, 1991). The sedimentation rate observed differs from less than 5 cm/1,000 years in the Holocene to more than 30 cm/1,000 years in the deglaciation and LGM. The benthic foraminiferal fauna is divided into six assemblage-zones (Fig. 8).

Assemblage-zone 6 was deposited in a glaciomarine diamicton which has a high content of ice-rafted debris (IRD) and low planktic $\delta^{18}\text{O}$ -values (4.6–4.7‰). This assemblage has low numbers of foraminifera per gram and planktic foraminifera are nearly absent. *Elphidium excavatum* f. *clavatum* (25%) and *Cassidulina reniforme* (41%) dominate. The lower part of this assemblage has not been penetrated. Assuming a linear sedimentation rate, the upper part of this zone has an age of approximately 17,500 years B.P.

Assemblage-zone 5 was deposited during the LGM (between 17,500 and 13,600 years) and has a relatively large number of foraminifera per gram. This zone is characterized by certain levels which are dominated by *Cassidulina teretis* (20–66%) whereas other levels are dominated by *Cassidulina reniforme* (20–60%). *E. excavatum* f. *clavatum* accounts for less than 10% of the benthic fauna in this zone. All levels have a large component of planktic foraminifera (>50%), mainly sinistral *Neogloboquadrina pachyderma*. The lower part of this zone consists of a laminated sediment with low IRD content while the upper part is deposited in a strongly bioturbated sediment with increasing IRD content.

Assemblage-zone 4 (between 13,600 and 12,500 years) is characterized by a dramatic rise of *Elphidium excavatum* f. *clavatum* which reaches 70%. This peak coincides with the meltwater event recorded in the $\delta^{18}\text{O}$ -data. This assemblage represents the earliest phase of deglaciation which had a relatively high input of IRD and lower content of *Cibicides lobatulus* and *Nonion labradoricum* (<20%). *Cassidulina reniforme* is less frequent than in assemblage-zones 3 and 5 and planktic foraminifera are almost absent.

Assemblage 3, deposited in a late phase of the deglaciation (about 12,500 to 10,000 years B.P.), is dominated by *E. excavatum* (11–68%) and *Cassidulina reniforme* (25–80%) and has low foraminiferal content. *Cassidulina teretis* is nearly absent, and the amount of IRD is rapidly decreasing.

In Assemblage 2, *E. excavatum* and *C. reniforme* (in part) are replaced by *C. teretis* and *Nonion barleeanum*. The faunal change also coincides with a lowering in $\delta^{18}\text{O}$ -values interpreted as Termination Ib. The lower boundary of assemblage-zone 2 probably corresponds to the Pleistocene/Holocene boundary.

Assemblage 1 corresponds to the modern fauna in

the area which shows a dominance of *N. barleeanum*, a decrease of *C. teretis*, an increase of planktic foraminifera, a slight increase in the total number of foraminifera, and an increase in faunal diversity.

REWORKING TO THE DEEP SEA

The present distribution of *Elphidium excavatum* f. *clavatum* shows that it is a shallow water species. However, it is observed in deep Norwegian Sea surface sediments, but only as dead specimens, and is thus interpreted to be reworked from older glaciomarine sediments (Mackensen and others, 1985; Mackensen, 1987). *E. excavatum* f. *clavatum* is also recorded, often with high frequencies, in late Quaternary studies in the Norwegian Sea (Phleger and others, 1953; Høltedahl, 1959; Jansen and others, 1983). Thus it has been suggested that *E. excavatum* f. *clavatum* may have lived in the deep glacial Norwegian Sea.

In order to elucidate this problem the quantitative distribution of *Elphidium excavatum* f. *clavatum*, including flux, (number of specimens/cm²/1,000 year), number per gram bulk sediment, and percent of total benthic foraminifera fauna, was studied in a well-dated sediment core (T-88-2) from the continental slope off the southern Barents Sea at 1,495 m depth (Fig. 1, site 2, Fig. 9). *Elphidium excavatum* f. *clavatum* is the dominant species in a diamicton deposited prior to 12,600 years B.P. with relative frequencies between 40 and 55%. In an upper unit, a hemipelagic mud deposited from 12,600 to the present, relative frequencies are low, mainly less than 5% (Fig. 9). However, the number per gram and flux of *Elphidium excavatum* f. *clavatum* show almost an opposite trend, that is, very low values in the glaciomarine diamicton followed by high values in the hemipelagic mud. Thus the dominance of *Elphidium excavatum* f. *clavatum* in the diamicton is not due to high production or accumulation, but rather to a general absence and low frequencies of other foraminifera in this sediment.

In conclusion, during the Holocene and at present, *Elphidium excavatum* f. *clavatum* is probably reworked down slope by sediment gravity flows. This process is active on the Barents slope today. From a quantitative point of view, reworking may also explain the distribution of *E. excavatum* f. *clavatum* in the diamicton. If so, the results show that reworking is quantitatively more important today and during the Holocene than during deposition of the diamicton. This suggests different modes of reworking. Possibly ice rafting was more important during glacials and gravity flow transport during the Holocene and at the present.

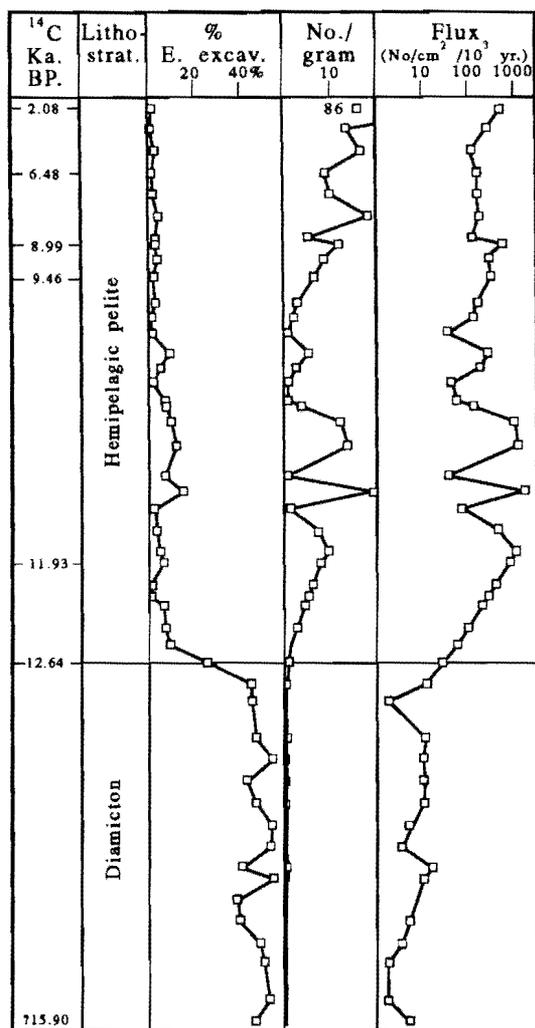


FIGURE 9. Late Weichselian-Holocene stratigraphic distribution of *Elphidium excavatum* f. *clavatum*, including percentage values, numbers per gram, and flux, core T-88-2, on the continental slope off western Barents Sea. For location see Figure 1.

DISCUSSION AND CONCLUSIONS

RECENT DISTRIBUTION

Four main factors, individually or in combination, can explain the Recent arctic distribution pattern of *E. excavatum* f. *clavatum*: a) fluctuating salinity and low saline waters, b) turbid waters, c) cold and seasonally ice covered water, and d) reworking.

Fluctuating salinity and low saline waters are found in the southeastern Barents Sea and the Kara Sea, which are influenced by the large Pechora, Ob and Jenisej rivers. Fluctuating or low salinity in very shallow waters, at middle and lower latitudes, are considered to be an important controlling factor for various *Elphidium* species, including *E. excavatum* f. *clavatum*, for

example, the Baltic Sea (Lutze, 1965; Hermelin, 1987), the North Sea (Murray, 1973), tidal flats off the Netherlands (van Voorthuysen, 1951; Haake, 1962), Hudson Bay, the Gulf of St. Lawrence and the James River (Ellison and Nichols, 1975). However, the southeastern Barents Sea and Kara Sea have in addition to low salinity both high sedimentation rates, indicative of turbid waters, and also fairly cold bottom water temperatures. According to L. Polyak (unpublished data) average Holocene sedimentation rates in the southeastern Barents Sea are very high, exceeding 100 cm/1,000 years in the central Pechora Basin. Thus, in this area all of the three main factors may contribute to the high frequencies of *E. excavatum* f. *clavatum*.

The arctic distribution of *E. excavatum* f. *clavatum* differs from its low/middle latitude distribution in its associated species. At middle/low latitudes, as well as along the river-influenced Siberian coast, the dominant associated species are other elphidiids whereas the main associated species in the Arctic are *C. reniforme*, *B. frigida*, *N. labradoricum* and *E. subarcticum*.

The cold water affinity of *E. excavatum* has been noted in several studies (e.g., Phleger, 1952; Parker, 1952; Loeblich and Tappen, 1953; Nagy, 1965; Feyling-Hanssen, 1972). But in these early works it is difficult to distinguish temperature from the other main limiting factors. Cold and seasonally ice-covered water may be the most important factor in the northern Barents Sea which is influenced by Arctic water with salinities above 34‰ and with sedimentation rates mostly less than 30 cm/1,000 years (Elverhøi and others, 1989). A tongue of *E. excavatum* >30% between 37 and 45°N and reaching south to 71°N corresponds to a southward current of cold Arctic water (cf. Fig. 2).

The third factor, turbidity, most probably favors *E. excavatum*. Its high frequencies in turbid waters close to the termini of glaciers at Svalbard fjords support this conclusion. *E. excavatum* is mainly an infaunal species. Haake (1962) and Hunt and Corliss (1993) observed live *E. excavatum* f. *clavatum* 6 cm and 10 cm below sea bed, respectively. In current investigations of the $\delta^{13}\text{C}$ in tests of nine benthic foraminiferal species in the Barents Sea and Kara Sea, *E. excavatum* f. *clavatum* has the largest negative $\delta^{13}\text{C}$ value indicating that this species has the deepest infaunal habitat (Poole and others, in prep.). Lutze (1965) suggested that by withdrawing protoplasm from its outer chambers, *E. excavatum* could survive in unfavorable environments for shorter periods. This may explain its affinity to both turbid and polluted waters (Schafer, 1970, 1973). Due to the dominance of live versus total specimens of *E. excavatum* f. *clavatum* we suggest that

it has a preferred summer reproduction, when the waters are more turbid than during winter. However, stained samples for a full season cycle should be studied in order to confirm this.

The Holocene and recent distribution of *E. excavatum* f. *clavatum* in the temperate waters of the western Barents Sea is attributed to reworking of underlying glaciomarine sediments. Indeed, the bank areas are often dominated by a thin Holocene lag deposit (Vorren and others, 1978; Hald and Vorren, 1984; Hald and Steinsund, 1992) in which reworked fossils are common.

STRATIGRAPHICAL DISTRIBUTION

Many of the conclusions regarding the habitat of *E. excavatum* are made from interpretation of its stratigraphical occurrence. Vilks (1981) found that foraminiferal assemblages dominated by *E. excavatum* f. *clavatum* were typical of cold and diluted waters, associated with the melting of the ice-sheets of northwestern Europe and North America. Osterman (1984), using stratigraphic evidence, further concluded that a low diversity *E. excavatum*-dominated assemblage was typical of near glacial environments. With increasing distance from the glacier, this assemblage graded into a more diverse fauna. These conclusions are supported by the present results from the fjords of Svalbard.

The two investigated stratigraphic sequences (Figs. 7, 8) show that *E. excavatum* f. *clavatum* is present throughout the Late Weichselian. During the LGM it occurs with moderate to low percent values. In the core off Svalbard *Elphidium excavatum* f. *clavatum* co-occurs inversely with a rich planktic fauna indicative of open oceanic waters. The sharp increase between 14,000 and 13,000 years B.P. is recorded simultaneously both off northern Norway and Svalbard and correlates to a marked light oxygen isotopic peak. This peak is interpreted as the first major melt water pulse from the Barents and Fennoscandian ice sheets (Jones and Keigwin, 1988; Sarnthein and others, 1992). Therefore it is concluded that *E. excavatum* f. *clavatum* is a sensitive indicator of the onset of the last deglaciation in this area. During the later part of the deglaciation *E. excavatum* f. *clavatum* is still important, although in number per gram it is less frequent (Fig. 8). The peak at the assemblage-zone 3/4 boundary in the core off Svalbard is tentatively correlated to the glacial advance in Isfjorden, Svalbard at c. 12,400–12,300 years B.P. (Svendsen, in prep.). More difficult to explain is a second maximum recorded in both cores during the Younger Dryas climatic cooling period. Both

locations were distant from glacier termini at that time and no marked meltwater pulses are recorded. One possible explanation could be increased dominance of cold, sea ice-covered Arctic water.

E. excavatum f. *clavatum* almost disappears in the western Barents Sea at the Holocene/Pleistocene boundary as cold Arctic water and melt water are replaced by temperate Atlantic water with temperatures similar to the present. At this time *E. excavatum* f. *clavatum* retreated into the fjords of Svalbard and to the northern and eastern Barents Sea and the Kara Sea. The Holocene appearance in the temperate waters of the Svalbard-Barents Sea margin is due to reworking from underlying glaciomarine sediments.

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DISTURBED FORAMINIFERAL STRATIGRAPHIES— A CAUTIONARY “TAIL”

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ABSTRACT

Three mechanisms which act to disturb foraminiferal biostratigraphy are discussed. These are downcore sediment smearing during the coring process, sediment reworking and associated redeposition, and bioturbation. All three mechanisms, when viewed in cores which span the Lateglacial-early Holocene unconformity of

the Hebridean Shelf, N.W. Scotland, make otherwise sharp faunal boundaries appear gradational. Associated with the disturbances, so-called species group “tails” are recognized. Careful sub-sampling of sediment cores is recommended and the merits of combined percent frequency and concentration data discussed.

INTRODUCTION

The recognition of disturbed foraminiferal assemblages is of increasing importance in palaeoecological studies which rely more and more often on quantitative data and geochemical measurements based upon foraminiferal tests. Stable isotope measurements, AMS ¹⁴C dating, amino acid geochemistry and a number of numerical methods all rely on the assumption that the foraminifera analysed represent coherent, *in situ* assemblages.

Identifying disturbed foraminiferal assemblages can be difficult and even where these are recognized the interpretations are often contentious (Austin and McCarroll, 1992). In this note the problems associated with recognizing disturbed foraminiferal stratigraphies from two case studies are discussed.

DOWNCORE SEDIMENT SMEARING

Amongst the coring devices employed by the British Geological Survey (B.G.S.) to sample the U.K. continental shelf and upper slope, the electric vibrocorer has proven extremely useful (Fannin, 1989). Details of the system are outlined by Weaver and Schultheiss (1990). However, one of the problems associated with this coring device, and probably more acute than other coring methods, is that it produces a disturbed outer

zone adjacent to the core barrel, around which sediments are “smeared” downwards. This disturbed zone is only rarely greater than 0.5 cm thick. Figure 1 illustrates this outer disturbed zone from a cross-section of a vibrocore. It also illustrates the separate problem of bioturbation which is often associated with shallow marine environments.

To examine the effects of this disturbed outer zone and to emphasize the need for careful sub-sampling, a parallel set of samples from the inner and outer parts of vibrocore 57/-09/60 from a water depth of 156 m from the St. Kilda Basin, N.W. Scotland were analysed for their foraminiferal content. Sub-samples were removed from the inner part and the outer 1 cm of the split core sections. The core section under question (Fig. 2) exhibits a major lithological change at a core depth of approximately 24 cm, with coarse shelly sands overlying silty clays with small stones. Regional geological studies (Austin, 1991; Peacock and others, 1992) reveal very similar sequences elsewhere in the basin and suggest that the overlying sands are of Holocene age, while the underlying sediments are glacial marine in origin and are probably of Lateglacial age. The summary foraminiferal diagram (Fig. 3) clearly illustrates the differences between the inner and outer sub-samples, with the downcore changes in the assemblages from the inner samples corresponding most closely to the lithological break.



FIGURE 1. Photograph of horizontally split core section; vibrocore 51/07/199 from the central Celtic Sea. Scale intervals are 1 cm.

High planktic : benthic ratios and relatively high percentage frequencies of *Spiroplectamina wrightii* and *Cassidulina laevigata* are characteristic features of Holocene assemblages from the region, while high frequencies of *Elphidium excavatum* are characteristic of the underlying glacial marine sediments (Austin, 1991). The common occurrence of the Holocene taxa above the unconformity in both inner and outer samples are as expected from the regional biostratigraphy (Peacock and others, 1992). Equally, the presence of typical glacial marine assemblages in the inner samples beneath the unconformity are as expected. However, outer samples from beneath the unconformity contain assemblages with a mixture of both Holocene and glacial marine assemblages and this is interpreted as the product of smearing downwards around the inside of the core barrel. The overall effect of including these contaminated sediments would be to "smooth" this faunal transition and make the change-over more gradational. This is the "downwards tail" which is observed in percent frequency diagrams where sidewall contamination has occurred.

The species *E. excavatum* forma *clavata* from the same vibrocore exhibits another interesting feature

which has been discussed by Glass (1969) with reference to the reworking and redeposition of microtektites in deep sea sediments. Here we see an "upwards tail" in the percent frequency data which is most marked in the inner samples. This is because the concentration of *E. excavatum* in the inner samples is not reduced by downward smearing of assemblages rich in Holocene assemblages, but poor in *E. excavatum*, as are the outer samples. The presence of this form of *E. excavatum* in Holocene assemblages is most probably a function of reworking and redeposition of pre-Holocene sediments. Such reworking is highly likely in view of the high current velocities and tidal streams associated with the Holocene transgression of the shelf (Austin, 1991).

BIOTURBATION

The photograph of Figure 1 exhibits another common feature of shallow marine environments: bioturbation. The effects of bioturbation from the deep sea are well documented (Berger and Heath, 1968; Glass, 1969; Ruddiman and Glover, 1972; Guinasso and Schink, 1975; Loubere, 1989; Wheatcroft, 1992) and



FIGURE 2. Photograph of the upper 0.6 m of a split core section; vibrocore 57/-09/60, St. Kilda Basin, N.W. Scotland. Scale bars represent 5 cm intervals.

have been modelled to explain, among other features, the stratigraphic redistribution of so-called “instantaneous events” such as volcanic ash horizons. The following example examines the effects of bioturbation across the Lateglacial–Holocene boundary in a B.G.S. vibrocore (57/-09/89) from a water depth of 156 m in the St. Kilda Basin. The relative merits of percentage

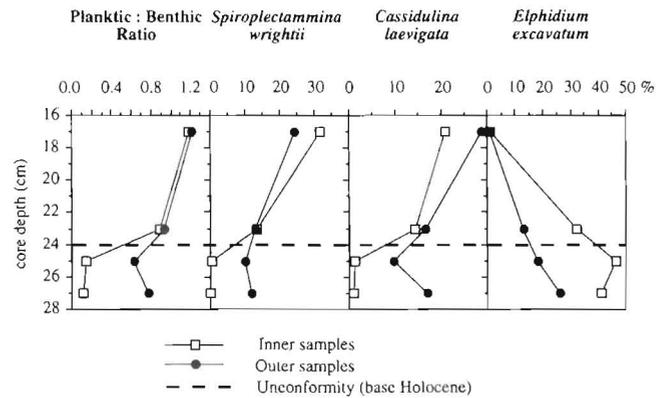


FIGURE 3. Parallel sub-samples from the inner and outer parts of vibrocore 57/-09/60 (data from Austin, 1991).

frequency versus concentration data are discussed, particularly in view of the numerical methods of zonation which were applied to these data.

The sequence consists of a well dated Lateglacial–Holocene transition (Austin, 1991; Peacock and others, 1992). For the purposes of this example, we are concerned only with the upper 2 m of the core, which spans approximately the past 11,000 years. Numerical methods of biostratigraphic zonation (Gordon and Birks, 1972; Birks and Gordon, 1985), applying three independent techniques to percentage frequency data for fourteen of the most common taxa, produced the zonation scheme illustrated in Figure 4. The main lithological transition in the upper part of this core occurs at 0.7 m, with coarse shelly sands overlying fine grained silty clays with drop-stones. Discreet, sand-filled burrows extend downwards from 0.7 m to 1.2 m; sub-samples from this depth range unavoidably include some of this coarse grained sandy sediment.

The numerical zonation methods suggest the following sub-division of the upper part of the core. Zone 7, from the upper 0.7 m of the core, represents the Holocene, with a corrected AMS ¹⁴C age of 5,555 ± 90 BP from *Tinoclea ovata* at 0.5–0.6 m (corrected ages based on an apparent age of 405 ± 40 years for seawater; Harkness, 1983). Zones 5 and 6 represent the Younger Dryas, between a core depth of 0.7–1.9 m, with a corrected AMS ¹⁴C age of 10,635 ± 120 BP from *Nuculoma belloti* at 0.7–0.75 m. A corrected AMS ¹⁴C age of 11,035 ± 130 BP at 1.94–2.0 m defines the upper part of zone 4, which extends downcore from 1.9 m and represents the latter part of the Lateglacial (Windermere) Interstadial.

The problem with this core, particularly before the AMS ¹⁴C chronology was available, was in deciding where to place the Lateglacial–Holocene transition and in what manner to characterize it. For example, does

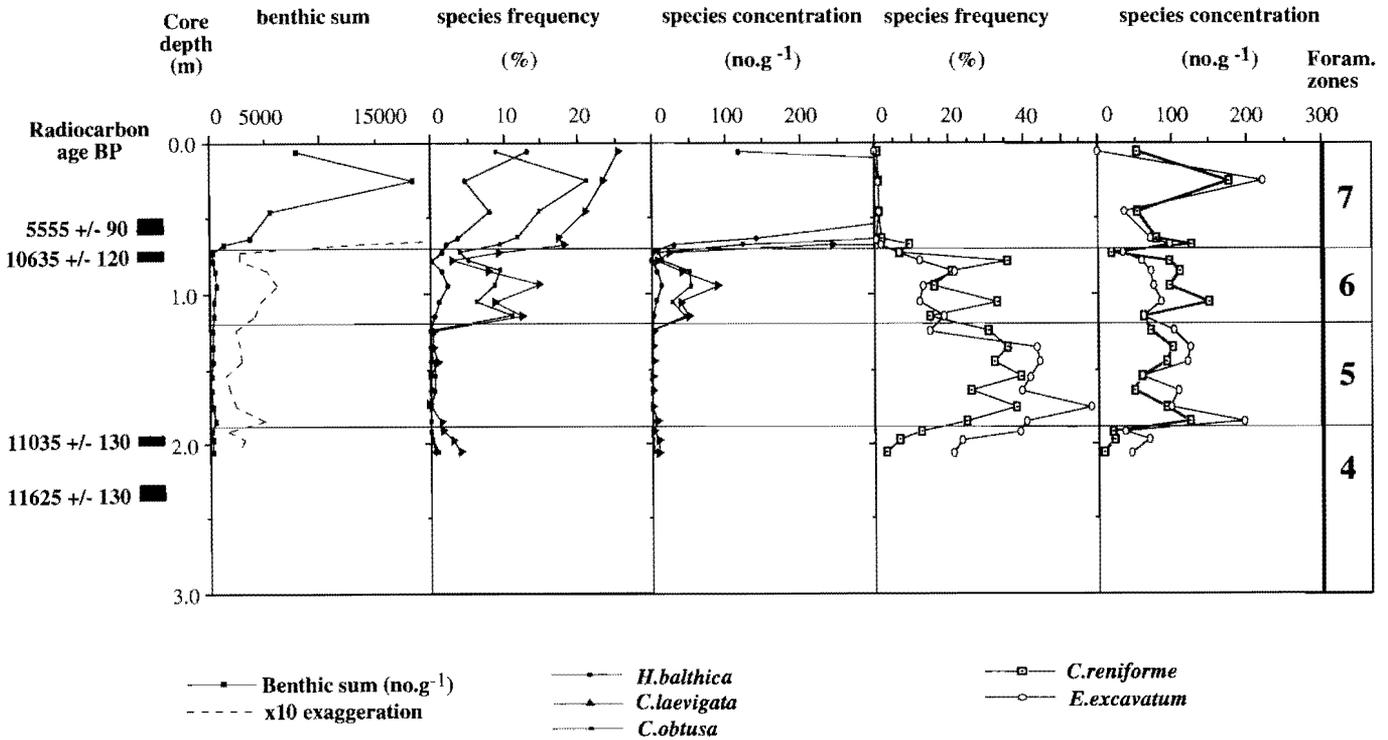


FIGURE 4. Percent frequency and concentration data for selected species from vibrocore 57/-09/89 (data from Austin, 1991).

the transition occur at the zone 5–6 or 6–7 boundary? Percentage frequency diagrams reveal that zone 6 contains both “warm-water” taxa, typical of zone 7, and “cold-water” taxa, typical of zone 5. The question which must be addressed here is whether or not such mixed assemblages are autochthonous, representing a true cold to warm transition, or whether one of the components is allochthonous. Austin and McCarroll (1992) discuss some of the problems associated with recognizing such mixed assemblages; zone 6 is not considered to represent coherent, *in situ* assemblages. Careful sub-sampling of the core, in view of the discussion above, can preclude down-wall smearing effects. Thus, the assemblages of zone 6 could have arisen from the erosion and redeposition of zone 5 type sediments or by the bioturbation downwards of zone 7 sediments. Considered alone, the percentage frequency data (Fig. 4) make the interpretation of the mixed assemblages difficult.

However, if we also consider concentration (abundance) data (Fig. 4), then it is observed that the “warm” taxa of zone 7 exhibit a major transition at the zone 6–7 boundary, with a second, less pronounced transition at the zone 5–6 boundary. Concentrations of the “cold” taxa show no significant change across the zone 5–6 or 6–7 boundaries. Clearly then, the changes in concentration data do not correspond to the changes

in percent frequency data. If this were a case of an “upwards tail” of “cold” taxa, then one might reasonably expect to see a decline in the concentration of these taxa upwards from the zone 5–6 boundary. This does not occur. Neither does the associated increase in the concentration of “warm” taxa upwards through zone 6. Instead, the concentration data are consistent with the presence of observed burrowing structures infilled by coarse sandy sediments down to a depth of 1.2 m. It is suggested that the assemblages of zone 6 are largely the product of bioturbated sediment, brought downwards by as much as 0.5 m from zone 7 and mixed with assemblages typical of zone 5. The very high foraminiferal concentrations of zone 7 are sufficient to alter the percentage frequencies, but do not alter the concentration of zone 5 taxa by very much. This interpretation supports the radiocarbon chronology, indicating that zones 5 and 6 represent accumulation during the Younger Dryas and that there is, in fact, a major unconformity at the base Holocene.

This does not mean that percent frequency data are unreliable. For example, if we consider the “cold” taxa present in zone 7 we recognize an “upwards tail” in the percent frequency diagram which is typical of many Holocene shelf sequences. However, since foraminiferal concentrations are much higher in zone 7, then

the actual concentration of these "cold" taxa may increase when compared to the values of zones 5 and 6; this implies greatly reduced terrigenous sediment input during the Holocene.

CONCLUSIONS

The basis for the recognition of disturbed foraminiferal stratigraphies lies in identifying mixed assemblages and differentiating between autochthonous and allochthonous faunal elements. It has been possible to develop quantitative models for the effects of bioturbation in the deep sea, mostly following the models of Berger and Heath (1968), only by making certain "steady-state" assumptions. These include constant sedimentation rates, a constant mixed layer, complete homogenization in the mixed layer, and no downwards penetration by burrowers beneath the mixed layer. Such assumptions, while applicable to certain deep sea settings, are not valid in the shallower marine environments of the shelf and slope. In the above examples the task of recognizing disturbed biostratigraphies has been made easier by the well constrained radiocarbon chronology and the nature of the lithological and faunal transitions under examination. Stratigraphic breaks which are associated with major faunal reorganizations, such as at the Lateglacial-Holocene boundary, serve as a reminder of the care which must be applied to biostratigraphic data. However, with careful sampling and selection of taxa the problems associated with disturbed foraminiferal stratigraphies can be minimized.

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