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**Biostratigraphical investigation of
borehole 6704/12-GB1 from the
Gjallar Ridge on the Vøring Plateau**

Report for the Seabed Project

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ABSTRACT

Borehole 6704/12-GB1 (67°1'35.2"N, 4°57'25.6"E) is a cored geotechnical boring drilled on the Gjallar Ridge on the Vøring Plateau as a part of the Seabed Project. The seafloor is at 1351 mbms (meters below mean sea level), and the borehole is drilled down to 160.15 mbsf (meters below seafloor). In the borehole 50 cm long cores were sampled in 3.5-16 m intervals. 12 levels were investigated for planktonic and benthic foraminifera, *Bolboforma* (calcareous cysts), dinoflagellate cysts and diatoms. The interval from between 76.0 and 95.18 m is of Early Pleistocene age (1.8-0.78 Ma) and contains mainly glacial sediments probably deposited in a water depth comparable to the present.

The interval from between 111.0-160.15 m is Middle Miocene age (12.3-11.2 Ma) and contains mostly pelagic sediment. One sample (118.5-118.83 m) contains both pelagic and glacial sediments. The water depth was probably close to or somewhat deeper than the present.

The large difference in age between the sample 95.18 m and 111.0 m indicates a large hiatus in the intervening beds.

INTRODUCTION

Borehole 6704/12-GB1 (67°1'35.2"N, 4°57'25.6"E) is a cored geotechnical boring drilled on the Gjallar Ridge on the Vøring Plateau as a part of the Seabed Project which focuses on the sea bed conditions, soil conditions and shallow geology in the deep water areas on the continental slope of the Norwegian Sea continental margin. The seafloor is at 1351 mbms (meters below mean sea level), and the borehole is drilled down to 160.15 mbsf (meters below seafloor).

6704/12-GB1 is situated close to the Ocean Drilling Program Leg 104 Sites 642-644 and the Deep Sea Drilling Project Sites 339-342 (Fig. 1). Micropaleontological, palynological, lithostratigraphical, geochemical and paleomagnetic investigations of these boreholes are reported in the reports of Talwani and Udintsev et al. (1976) and Eldholm, Thiede and Taylor et al. (1987, 1989), and in several other papers and reports (Jansen and Sjøholm, 1991; Spiegler and Müller, 1992; Müller and Spiegler, 1993; Fronval and Jansen, 1996; Koç, 1996 and Koç, 1997). These investigations, together with the results from a list of other ODP/DSDP-boreholes in the North Atlantic and the Norwegian Sea, make correlation with and dating of 6704/12-GB1 uncomplicated.

The primary objective of this study is to date the sediments of the Kai Formation. A secondary objective is to interpret depositional environments based on microfaunal contents. The lower part of the Naust Formation is analysed to detect and quantify a possible hiatus between the two formations. All absolute ages are based on Berggren et al. (1995).

MATERIAL AND METHODS

In borehole 6704/12-GB1 50 cm long cores were sampled in 3.5-16 m intervals. 12 levels were investigated for planktonic and benthic foraminifera, *Bolboforma* (calcareous cysts), dinoflagellate cysts and diatoms in these cores. For analyses of foraminifera and *Bolboforma* 70-80 g material was used. The samples were disaggregated with water without dispersant. The identifications of foraminifera and *Bolboforma* were done in the 106-500 µm fraction. In some samples the fractions <63-106 µm and >500 µm were also investigated.

The palynomorphs were extracted from 15-20 g material, using conventional preparation methods involving removal of carbonates and silica by HCl and HF, respectively. The organic residues were subsequently oxidised with nitric acid to remove pyrite and some of the amorphous organic matter.

The diatoms were extracted from 1-2 g material using HCl and H₂O₂ to remove carbonates and organic matter.

Important foraminifer, *Bolboforma* and diatom taxa are shown in Plate 1-6.

PLANKTONIC FORAMINIFERAL AND *BOLBOFORMA* BIOSTRATIGRAPHY

The high-latitude planktonic foraminiferal associations are low diversity faunas composed of long-ranging species. In general, it is not possible to apply the standard zonations established for low latitudes (Blow, 1969, 1979; Bolli and Saunders, 1985), or for northern temperate regions (Berggren, 1972; Poore and Berggren, 1975; Poore, 1979; Weaver and Clement, 1986), because the index fossils used for these zonal definitions are often absent in high-latitude assemblages. Studies of Ocean Drilling Program Leg 104 Sites 642, 643, and 644 on the Vøring Plateau in the Norwegian Sea have produced a local high-latitude Neogene zonation (Spiegler and Jansen, 1989; Spiegler, 1996). Just as important for the dating of the sediments is the zonation of *Bolboforma* established through ODP/DSDP-drilling in the Norwegian Sea and the North Atlantic (Spiegler & Müller, 1992; Müller & Spiegler, 1993). Most of these zones are calibrated with nannoplankton and paleomagnetic data.

NEOGLOBOQUADRINA PACHYDERMA (SINISTRAL) ZONE

Category: Informal partial range zone

Boundary criteria: The top of the zone may extend above the uppermost investigated sample (76.0-76.2 m). The base of the zone is marked by the lowest occurrence of *N. pachyderma* (sinistral).

Depth range: 76.0-95.18 m.

Material: Three core samples.

Age: Early Pleistocene (partly based on other biostratigraphical evidence).

Lithostratigraphic unit: Naust formation.

Equivalent zones: *N. pachyderma* (sinistral) Zone of Weaver and Clement (1986), *N. pachyderma* (sinistral) Zone of Spiegler and Jansen (1989) and Subzone NSP 16b of King (1989).

In-place assemblage: In the uppermost sample *N. pachyderma* (sinistral) is common. Individuals with encrusted testes are completely dominant over individuals with unencrusted tests. A few specimens of *N. pachyderma* (dextral) are also recorded in the uppermost sample. The two lowermost samples contain only a few specimens of *N. pachyderma* (sinistral, encrusted) (Fig. 2).

Reworked assemblage: A few specimens of *Heterohelix* sp. are recorded in the uppermost sample. These have been derived from Upper Cretaceous sediments. One specimen of *Bolboforma fragori* was recorded in the 86.37-86.48 m interval. It has been reworked from Middle to Upper Miocene deposits.

Remarks: *N. pachyderma* (sinistral, encrusted) has its first frequent occurrence at 1.8 Ma in the North Atlantic and at the Vøring Plateau in the Norwegian Sea (Weaver and Clement, 1986; Spiegler and Jansen, 1989). This test morphology has a very sporadic occurrences in older sediment.

BOLBOFORMA FRAGORI – BOLBOFORMA SUBFRAGORI ZONE

Category: Informal partial range zone.

Boundary criteria: The top of the zone is taken at the highest occurrence of *B. fragori* and *B. subfragori*. The base is marked by the highest occurrence of *B. badenensis* and the highest common occurrence of *B. compressispinosa*.

Depth range: 111.0-131.05 m.

Material: Three core samples.

Age: Middle Miocene (partly based on other biostratigraphical evidence).

Lithostratigraphic unit: Kai Formation.

Equivalent zones: *B. fragori/B. subfragori* Zone of Spiegler and Müller (1992) and Müller and Spiegler (1993) and Subzone NSP 14a of King (1983).

Assemblage: This zone characterised a very productive, moderately high diversity planktonic fossil assemblage of *Bolboforma*, foraminifera, radiolaria and diatoms. *B. fragori* and *B. laevis* are the most common *Bolboforma* species. Other important species include *B. subfragori* and *B. clodiusi*. A few specimens of *B. pseudohystrix*, *B. reticulata* and *B. compressispinosa* are also recorded (Fig. 2).

Neogloboquadrina atlantica (dextral) and *Globigerina bulloides* are the most common foraminifera. Other important species include *Neogloboquadrina acostaensis*, *Turborotalita quinqueloba*, *Globigerinita glutinata*, *N. atlantica* (sinistral) and *Neogloboquadrina praehumerosa*.

Remarks: A *B. fragori/B. subfragori* Zone is described from deposits with an age of 11.7-10.3 Ma from the North Atlantic and the Vøring Plateau (Spiegler and Müller, 1992; Müller and Spiegler, 1993).

N. atlantica (dextral), *N. acostaensis* and *N. praehumerosa* are reported from deposits of Middle to Late Miocene age on the Vøring Plateau (Spiegler and Jansen, 1989; Müller and Spiegler, 1993).

BOLBOFORMA COMPRESSISPINOSA – BOLBOFORMA BADENENSIS ZONE

Category: Informal partial range zone.

Boundary criteria: The top of the zone is taken at the highest occurrence of *B. badenensis* and the highest common occurrence of *B. compressispinosa*. The base of the zone is undefined.

Depth range: 146.0-160.15 m.

Material: Five core samples.

Age: Middle Miocene.

Lithostratigraphic unit: Kai Formation.

Equivalent zones: *B. compressispinosa* Zone and *B. badenensis* Zone of Spiegler and Müller (1992) and Müller and Spiegler (1993).

Assemblage: This zone is also characterised a very productive, moderately high diversity planktonic fossil assemblage of *Bolboforma*, foraminifera, radiolaria and diatoms, except for sample 156.2-156.29 m which contains only radiolaria and diatoms. *B. badenensis* and *B. pseudohystrix* are the most common *Bolboforma* species. Other important species include *B. compressibadenensis*, *B. fragori* (upper part) and *B. laevis* (upper part). A few specimens of *B. clodiusi* and *B. subfragori* are also recorded (Fig. 2).

G. bulloides and *N. atlantica* (dextral) are the most common foraminifera. Other important species include *N. atlantica* (sin), *N. acostaensis*, *G. glutinata* and *N. praehumerosa*. A few specimens of *Globorotalia puncticulata* are also recorded at one level.

Remarks: A *B. compressispinosa* Zone and a *B. badenensis* Zone are recorded from deposits with an age of 12.3-11.7 Ma from the North Atlantic and the Vøring Plateau (Spiegler and Müller, 1992; Müller and Spiegler, 1993).

N. atlantica (dextral), *N. acostaensis* and *N. praeumerosa* are reported from deposits of Middle to Late Miocene age on the Vøring Plateau (Spiegler and Jansen, 1989; Müller and Spiegler, 1993).

BENTHIC FORAMINIFERAL BIOSTRATIGRAPHY

Neogene benthic foraminifera are described from open ocean high-latitude areas at ODP Sites 642, 643, and 644 on the Vøring Plateau (Leg 104) (Osterman and Qvale, 1989). The benthic foraminiferal zonation also broadly follows that of King (1983 and 1989) where a micropalaeontological zonation for Cainozoic sediments of the North Sea is outlined.

ELPHIDIUM EXCAVATUM ZONE

Category: Informal partial range zone.

Boundary criteria: The top of the zone may extend above the uppermost investigated sample (76.0-76.2 m). The base of the zone is marked by the lowest occurrence of *E. excavatum*.

Depth range: 76.0-95.18 m.

Material: Three core samples.

Age: Early Pleistocene (partly based on other biostratigraphical evidence).

Lithostratigraphic unit: Naust formation.

Equivalent zones: Zone A1 of Osterman and Qvale (1989) and Zone NSB 17 of King (1983).

Assemblage: The uppermost sample (76.0-76.2 m) and the lowermost sample (95.1-95.18 m) contain relatively scarce faunas of benthic foraminifera. Calcareous forms are dominant, but agglutinated species are also recorded. The sample in the middle of the unit (86.37-86.48 m) is barren of benthic foraminifera. Characteristic species are *E. excavatum*, *Pullenia bulloides*, *Sigmoilopsis schlumbergeri* (agglutinated), *Cibicides wuellerstorfi*, *Cassidulina teretis*, *Bulimina striata*, *Nonion affine*, *Virgulina* sp. and *Epistominella* spp. (Fig. 2).

Remarks: The benthic foraminifera in this zone are characteristic Pliocene-Pleistocene taxa. Some of the species range back to the Miocene and the Oligocene.

MARTINOTTIELLA COMMUNIS – *UVIGERINA PYGMEA LANGERI* ZONE

Category: Informal partial range zone.

Boundary criteria: The top of the zone is taken at the highest occurrence of *Martinottiella communis* and *Uvigerina pygmaea langeri*. The base of the zone is undefined.

Depth range: 111.0-160.15 m.

Material: 9 core samples.

Age: Middle Miocene (partly based on other biostratigraphical evidence).

Lithostratigraphic unit: Kai Formation.

Equivalent zones: Zone B of Osterman and Qvale (1989), Zone NSB 13a and probably Zone NSA 11 and Zone NSA 12 of King (1989).

Assemblage: This zone contains a rich benthic fauna of mainly calcareous foraminifera. A few agglutinated taxa are also present. *P. bulloides*, *N. affine*, *M. communis* (agglutinated), *Cibicides dutemplei* and *Oridoralis umbonatus* are the most frequent forms. Other

characteristic taxa include *C. teretis*, *Ehrenbergina variabilis*, *Pyrgo murrhina*, *Cibicides grossus* and *Cibicides telegdi* (upper part) (Fig. 2).

Remarks: *U. pygmaea langeri* is described from Middle to Late Miocene deposits in The North Sea (King, 1989) and on the Vøring Plateau (Osterman and Qvale, 1989). *M. communis* is known from Middle to Late Miocene deposits on the Vøring Plateau (Osterman and Qvale, 1989). *E. variabilis* is described from the Upper Oligocene to the Upper Miocene on the Norwegian continental shelf (Skarbø and Verdenius, 1986) and from the Upper Miocene on the Norwegian Sea continental shelf (Stratlab, 1988; Eidvin et al., in press). *C. grossus* is known from the Upper Pliocene and the lowermost Lower Pleistocene on the Norwegian continental shelf (King, 1989; Knudsen and Asbjørndottir, 1991; Pedersen, 1995; Poole and Vorren, 1993; Stratlab, 1988, Eidvin et al., in press and Eidvin et al., 1993). *C. grossus* is, however, recorded in deposits as old as Late Miocene in the Netherlands (Doppert, 1980), but to our knowledge it has not been reported from the Middle Miocene.

DINOFLAGELLATE CYST BIOSTRATIGRAPHY

The 12 samples analysed for palynomorphs yielded relatively rich and diverse assemblages of dinoflagellate cysts. The Pleistocene samples from 76.0-95.18 m contain dominantly reworked Paleogene and Mesozoic taxa, while in situ forms are less frequent. Some of the Pleistocene events recognised in 6704/12-GB1 appear to be consistent with events reported elsewhere in the North Atlantic and the Norwegian-Greenland Sea, allowing a tentative subdivision of the Pleistocene succession into two dinoflagellate zones.

Informal dinoflagellate cyst zonation for the Cenozoic of the Norwegian Sea have been published by Manum et al. (1989) for the Eocene-Miocene, Mudie (1989) for the Late Miocene-Pleistocene and Poulsen et al. (1996) for the Oligocene-Pliocene. Most relevant for the present study are the zonations proposed by Manum et al. (1989) and by Mudie (1989) for the Vøring area. Based on recent data from ODP Leg 162 and new, revised data from Leg 104 and Leg 151, a chronostratigraphically better constrained dinoflagellate zonation for the Neogene of the Norwegian Sea is currently being developed. This zonation is based on the youngest occurrences (first downhole occurrences/last appearance datums), and is here applied to the Pleistocene of 6704/12-GB1. The Middle Miocene deposits of 6704/12-GB1 is correlated to the Middle Miocene *Cannosphaeropsis passio* Zone as defined by de Verteuil and Norris (1996) in the U.S mid Atlantic area.

MELITASPHAERIDIUM CHOANEPHORUM ZONE

Category: Concurrent range zone.

Boundary criteria: The top of the zone is defined by the highest occurrence of *M. choanephorum*, but probably extends above the uppermost investigated sample. The base of the zone is defined by the highest occurrence of *Amiculosphaera umbracula*.

Depth range: 76.0-86.48 m.

Material: One core sample.

Age: Early Pleistocene.

Lithostratigraphic unit: Naust Formation.

In-place assemblage: Characteristic species are *Achomosphaera andalousiensis*, *Brigantedinium* spp., *Melitasphaeridium choanephorum*, common *Operculodinium centrocarpum* and abundant *Spiniferites* spp. (Fig. 3).

Reworked assemblage: The zone contains abundant reworked Paleogene, Cretaceous and Jurassic dinoflagellate cysts.

Remarks: Mudie and Harland (1996) placed the last appearance datum (LAD) of *M. choanephorum* at the base of the Brunhes magnetostratigraphic chron. This corresponds to the base of the Middle Pleistocene (0.78 Ma).

AMICULOSPHAERA UMBRACULA ZONE

Category: Concurrent range zone.

Boundary criteria: The interval between the highest occurrence of *Amiculosphaera umbracula* to the highest occurrence of *Reticulatosphaera actinocoronata*.

Depth range: 86.37-95.18 m.

Material: Two core samples.

Age: Early Pleistocene.

Lithostratigraphic unit: Naust Formation.

In-place assemblage: The zone is characterised by *Amiculosphaera umbracula*, *Operculodinium israelianum*, *Nematosphaeropsis labyrinthea*, abundant *Bitectatodinium tepikiense*, common *Operculodinium centrocarpum* and abundant *Spiniferites* spp. (Fig. 3).

Reworked assemblage: The zone contains abundant reworked Paleogene, Cretaceous and Jurassic dinoflagellate cysts.

Remarks: Mudie and Harland (1996) questionably placed the LAD of *A. umbracula* at 1.6 Ma in the Early Pleistocene. This agrees with the observed LAD of this species in ODP Leg 162 Site 986 on the Svalbard margin (Smelror, in press.). However, Poulsen et al. (1996) used among others the LAD of *A. umbracula* to define the top of their Qty1 Zone. This zone was correlated to calcareous nannoplankton Zones NN18-19. In ODP Leg 162 Hole 907A the last occurrence of *A. umbracula* is noted in the Late Pliocene, and to our knowledge there are no records of its LAD in the Norwegian Sea in sediments as young as the top of NN19 (0.45 Ma).

CANNOSPHAEROPSIS PASSIO ZONE

Category: Formal taxon range zone defined by de Verteuil and Norris (1996).

Boundary criteria: The interval between the lowest and highest occurrence of *Cannosphaeropsis passio* (de Verteuil and Norris, 1996).

Depth range: 111.0-160.15 m.

Material: 9 core samples.

Age: Middle Miocene.

Lithostratigraphic unit: Kai Formation.

Assemblage: The assemblage is characterised by *Cannosphaeropsis passio*, common *Labyrinthodinium truncatum*, common to abundant forms of the *Batiacasphaera/Cerebrocysta* group of Head et al. 1989, *Barssidinium wrennii*, *Operculodinium piaseckii* and "*Headinium miocenicum*" (Fig. 3).

Remarks: *Cannosphaeropsis passio* is previously not reported from the Norwegian Sea, but forms assigned to *C. utinensis* by Manum et al. (1989) (from ODP Site 643) and Smelror (1996) (from the Kai Formation in well 6407/1-2) are most likely conspecific with *C. passio*. In the type area in the U.S. mid-Atlantic margin de Verteuil and Norris (1996) found that *C. passio* is restricted to the Late Serravalian, i.e. strata correlatable to the upper NN6 and the NN7-8 calcareous nanofossils zones.

DIATOM BIOSTRATIGRAPHY

Previous studies from ODP Legs 104 and 151 from the Vøring and Iceland Plateaus have shown that Pleistocene sediments are barren of diatoms. However, in the pre-Pleistocene the main biogenic component is diatoms, a siliceous microfossil group that enables high resolution biostratigraphy (Eldholm, Thiede and Taylor et al., 1987; Koç, 1996; Koç, 1997 and Koç and Scherer, 1996 and Scherer and Koç, 1996). All of the diatom zones, which are described in these papers and reports, are calibrated with paleomagnetic data.

BARREN INTERVAL

Depth range: 76.0-95.18 m.

Material: Three core samples.

Age: Early Pleistocene (based on other biostratigraphical evidence).

Lithostratigraphic unit: Naust Formation.

Remarks: The absence of diatoms in this unit indicates a Pleistocene age for this interval (Koç, 1996; Koç, 1997; Koç and Scherer, 1996).

SYNEDRA PULCHELLA INTERVAL

Authors: Koç and Scherer (1996).

Definition of top: Highest occurrence of *S. pulchella*.

Definition of base: Highest occurrence of *Nitzschia donahuensis*.

Depth range: 111.0-119.0 m.

Material: Two core samples.

Age: Middle Miocene.

Lithostratigraphic unit: Kai Formation.

Remarks: This interval is characterised by the occurrence of *S. pulchella* and the absence of *N. donahuensis* (Fig. 4), and is described from deposits with an age of 11.7-11.0 Ma in the North Atlantic (Koç and Scherer, 1996).

NITZSCHIA DONAHUENSIS INTERVAL

Authors: Koç and Scherer (1996).

Definition of top: Highest occurrence of *N. donahuensis*.

Definition of base: Lowest occurrence of *S. pulchella*.

Depth range: 119.0-119.04 m.

Material: One core sample.

Age: Middle Miocene.

Lithostratigraphic unit: Kai Formation.

Remarks: This interval is characterised by the co-occurrence of *S. pulchella* and *N. donahuensis* (Fig. 4), and is known from deposits with an age of 12.0-11.7 Ma in the North Atlantic (Koç and Scherer, 1996).

ACTINOCYCLYS INGENS INTERVAL

Authors: Koç and Scherer (1996).

Definition of top: Lowest occurrence of *S. pulchella*.

Definition of base: Lowest occurrence of *Denticulopsis praedimorpha*.

Depth range: 119.04-160.15 m.

Material: Six core samples.

Age: Middle Miocene.

Lithostratigraphic unit: Kai Formation

Discussion and remarks: *N. donahuensis* is recorded in all but the lowermost sample in this interval (Fig. 4). This could indicate that FO of *N. donahuensis* is within this interval.

However, other biostratigraphical evidence indicate that the base of the interval, as known from the North Atlantic in deposits with an age of 12.9-12.0 Ma (Koç and Scherer, 1996), has not been reached in 6704/12-GB1.

PALEOENVIRONMENTS

Pleistocene

The uppermost investigated sample in the Pleistocene unit (76.0-76.2 m) is rich on planktonic foraminifera, indicating open marine and fairly deep-water conditions. The benthic foraminifera *C. teretis*, *N. affine*, *P. bulloides*, *C. wuellerstorfi* and *B. striata* are intermediate and deep-water forms (Mackensen et al., 1985; Barker, 1960). In recent deposits on the continental slope of the Norwegian Sea continental margin *C. teretis* is present at water depths of 200-2000 m (common at ca. 1500 m), *N. affine* is present at 200-1600 m (common at ca. 1000 m), *P. bulloides* is present at 400-1700 m (common at ca. 1200 m) and *C. wuellerstorfi* is present at 1000-4000 m (common at ca. 2000 m). The Pleistocene water depth was probably comparable to the present water depth in this area.

The content of Arctic species such as *E. excavatum* forma *clavata*, *E. subarcticum* and *C. reniforme* and the complete dominance of *N. pachyderma* (sinistral) in the planktonic fauna indicate cold water conditions (Feyling-Hanssen, 1983). Species of *Elphidium* are typically restricted to shallow water, and occur commonly in proximal glacial-marine environments (Osterman, 1984, 1996). Therefore, it is possible that the *Elphidium* specimens have been ice-rafted to these water depths.

The two lowermost samples in the Pleistocene unit (86.37-86.48m and 95.1-95.18 m) are scarce on calcareous foraminifera probably due to carbonate dissolution. Based on study of the ODP Sites 642-644 on the Vøring plateau, Jansen et al. (1989) showed that a persistent calcite dissolution period characterised most of the Matuyama Chron until about 1.1 Ma. This was probably due to the fact that reduced deep-water ventilation enriched the CO₂-content of the deep-water.

Middle Miocene

The large concentration of radiolaria, diatoms, *Bolboforma* and planktonic foraminifera recorded in this unit is generally associated with normal marine conditions with little water turbulence, indicating deposition in relatively open ocean environment. Several intermediate and deep-water benthic foraminifera are also recorded including *C. teretis*, *N. affine*, *P. bulloides*, *O. umbonatus*, *P. murrhina*, *P. subcarinata* and *M. communis* (Mackensen et al., 1985; Skarbø and Verdenius, 1986). In recent deposits *O. umbonatus* is present at water depths of 1000-4000 m (common at ca. 3000 m) and *P. murrhina* is present at 2000-4000 m (Mackensen et al., 1985; Sejrup et al., 1981), but these forms may have dwelled in a shallower water depth back in the Miocene. However, the assemblage composition indicates that the Middle Miocene water depth was close to or somewhat deeper than the present. No typical shallow-water forms were recorded indicating little transport from these water depths. No typical cold water forms were either recorded.

ICE RAFTED DETRITUS (IRD) RECORD

The samples from the Pleistocene unit contain a clay-rich diamicton with small proportions of sand, silt and pebbles. The pebbles, of mainly crystalline rocks, are interpreted as ice rafted detritus (IRD). This is in accordance with Jansen & Sjøholm (1991) who described a great increase in the supply of IRD on the Vøring Plateau after about 2.6 Ma. This marked increase of IRD reflects the Late Neogene expansion of northern European glaciers.

The Miocene unit contains mostly clay. Material $>63 \mu\text{m}$ consists mainly of microfossils and some pyrite. An exception to this is sample 118.5-118.63 m where a large number of coarse minerogenic were discovered. The fragments are mainly quartz/feldspar mineral fragments and rock fragments of crystalline rocks. The shape is subangular and fragmented, typical of grains related to glacial sediments. The size varies from $100 \mu\text{m}$ to a few mm (Fig. 5). The observation of such grains in pelagic settings clearly indicate that they have been ice rafted to the location, and the grain distribution, surface texture and shape is clearly indicative of glacial origin. The coarseness of the grains are distinctive, as previous reports of Miocene minerogenic grains believed to represent IRD in Neogene deposits from the Vøring Plateau have been in the size range $125\text{-}250 \mu\text{m}$ (Jansen and Sjøholm, 1991; Fronval and Jansen, 1996). Hence this is the most conclusive proof of the existence of glaciers large enough to calve and form ice bergs hitherto found from the Miocene on the Vøring Plateau. Both diatom biostratigraphy and *Bolboforma*/foraminifer biostratigraphy document that the age of the sample is 12.3-11.2 Ma. This fits very well with the first peaks of smaller size IRD observed in ODP Site 642 (Fronval and Jansen, 1996), and clearly strengthens the arguments that glacial inception took place at the Middle/Late Miocene boundary. The origin of the grains is not easy to identify, and we propose that they originate from icebergs having drifted across from Greenland. Miocene glaciation is identified in Greenland from a number of ODP Sites (see summary in Fronval and Jansen, 1996), while large scale glaciation is believed to start later on the eastern side of the Nordic Seas.

SUMMARY AND DISCUSSION

Pleistocene (Naust Formation)

The age of the mainly glacial sediments recovered from between 76.0 and 95.18 m is determined by foraminifera and dinoflagellates (Fig. 6). The presence of the planktonic foraminifer *N. pachyderma* (sinistral, encrusted) gives an age younger than 1.8 Ma for the whole interval (Spiegler and Jansen, 1989). The presence of the dinoflagellate *M. choanephorum* indicates an age older than 0.78 Ma for the top of the interval (Mudie and Harland, 1996). The scarce calcareous foraminifer fauna in the two lowermost samples (86.37-86.48 m and 95.1-95.18 m) indicates that this part was deposited in the period of Matuyama Chron before 1.1 Ma, characterised by persistent calcite dissolution (Jansen et al., 1989).

The lithology and the foraminifera indicate deposition in a cold water environment and a water depth comparable to the present.

Middle Miocene (Kai Formation)

The age of the mainly pelagic sediments recovered from between 111.0-160.15 m is determined by foraminifera, *Bolboforma*, diatoms and dinoflagellates (Fig. 6). The top of the interval is within the *B. fragori*/*B. subfragori* Zone of Spiegler and Müller (1992) and Müller

and Spiegler (1993) which is dated to 11.7-10.3 Ma, and within the *S. pulchella* Interval of Koç and Scherer (1996) which is dated to 11.7-11.0 Ma. An age slightly older than 11.0 Ma, close to the Middle/Upper Miocene boundary (11.2 Ma), is likely for the top of the interval. The large difference in age between the sample 95.18 m of the Naust Formation and the sample 111.0 m of the Kai Formation indicates a large hiatus in the intervening beds.

The base of the interval is within the *B. compressispinosa* – *B. badenensis* Zone of Spiegler and Müller (1992) and Müller and Spiegler (1993) (12.3-11.7 Ma), and probably within the *A. ingens* Interval of Koç and Scherer (1996) (12.9-12.0 Ma). The underlying *Bolboforma reticulate* Zone, known from deposits with an age of 14.0-12.3 Ma (Spiegler and Müller, 1992; Müller and Spiegler, 1993), is not seen. The extension of the *C. passio* Zone down to ca. 160 m provides additional evidence of a maximum age of 12.6 Ma for the oldest investigated sediments. An age slightly less than 12.3 Ma is likely for the base of the interval.

One sample (118.5-118.63 m) contains both pelagic and glaciogenic sediments. The foraminifera indicate deposition in a transitional environment and a water depth probably close to or somewhat deeper than the present.

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FIGURES AND PLATES

Fig. 1. Location of core 6704/12-GB1 and ODP/DSDP-boreholes referred to in the text.

Fig. 2. Range chart of benthic and planktonic foraminifera and *Bolboforma* in core 6704/12-GB1. Hatched part is of uncertain age, and probably includes a large hiatus.

Fig. 3. Range chart of dinoflagellates in core 6704/12-GB1. Hatched part is of uncertain age, and probably includes a large hiatus.

Fig. 4. Range chart of diatoms in core 6704/12-GB1. Hatched part is of uncertain age, and probably includes a large hiatus.

Fig. 5. Image showing typical large IRD-grain from sample 118.5-118.62 mbsf. Each tick on the scalebar on the top represents 1 mm.

Fig. 6. Age determinations, fossil zones, fossil interval and lithostratigraphic units in core 6704/12-GB1. Hatched part is of uncertain age, and probably includes a large hiatus.

Plate 1. SEM-photomicrographs of Pleistocene and Middle Miocene planktonic foraminifera. **1.** *Neogloboquadrina atlantica* (sinistral). **2.** *Neogloboquadrina atlantica* (dextral). **3.** *Neogloboquadrina pachyderma* (sinistral, encrusted). **4.** *Globigerinita glutinata*. **5.** *Globigerina bulloides*. **6.** *Neogloboquadrina acostaensis*.

Plate 2. SEM-photomicrographs of Middle Miocene *Bolboforma*. **1.** *Bolboforma subfragori*. **2.** *Bolboforma fragori*. **3.** *Bolboforma clodiusi*. **4.** *Bolboforma compressispinosa*. **5.** *Bolboforma pseudohystrix*. **6.** *Bolboforma badenensis*.

Plate 3. SEM-photomicrographs of Middle Miocene benthic foraminifera. **1.** *Oridoralis umbonatus*. **2.** *Uvigerina pygmaea langeri*. **3.** *Cibicides dutemplei*. **4.** *Cibicides grossus*. **5.** *Martinottiella communis*.

Plate 4-6. Digital images of Middle Miocene diatoms. The size vary between 5-100 μm .

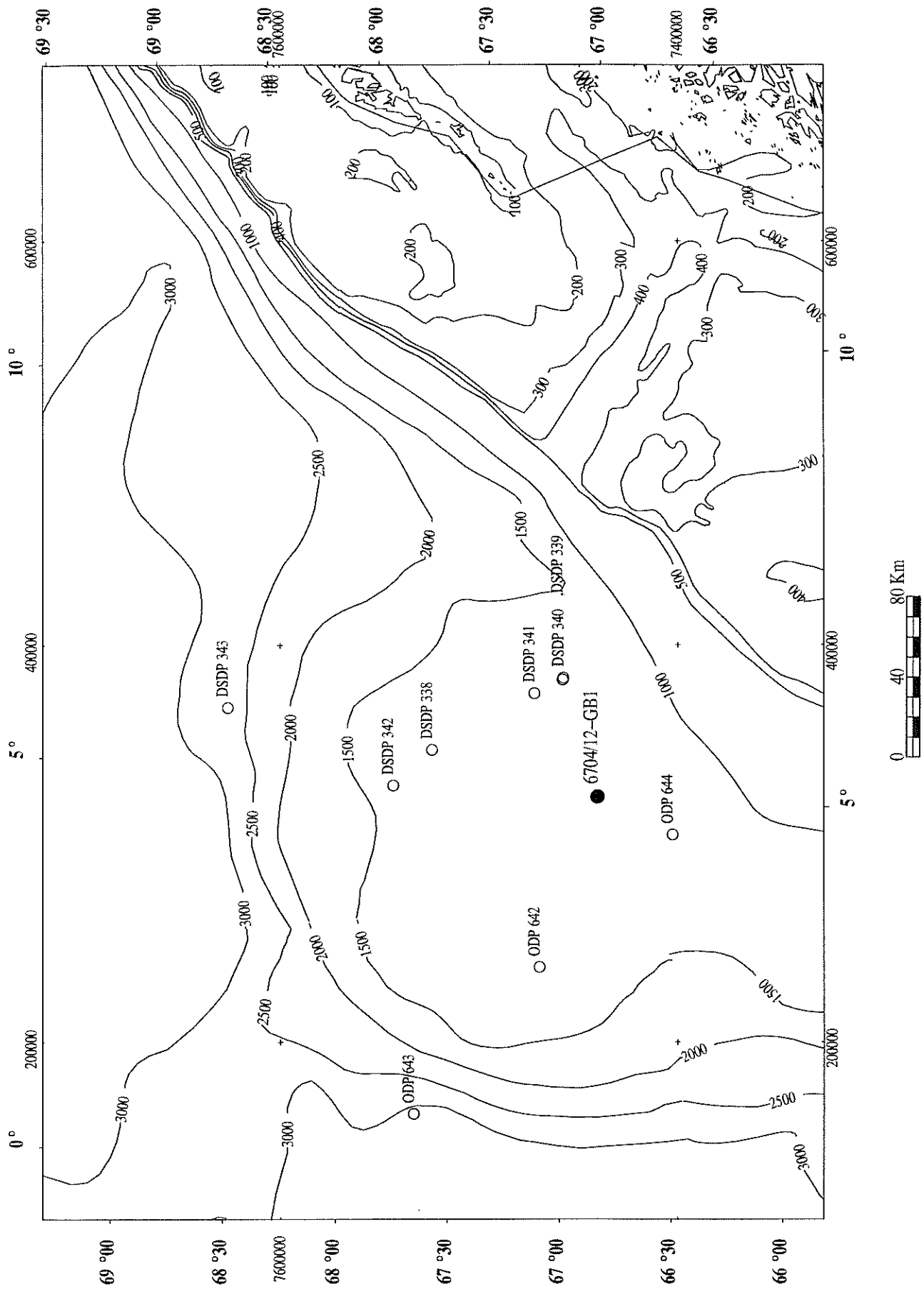
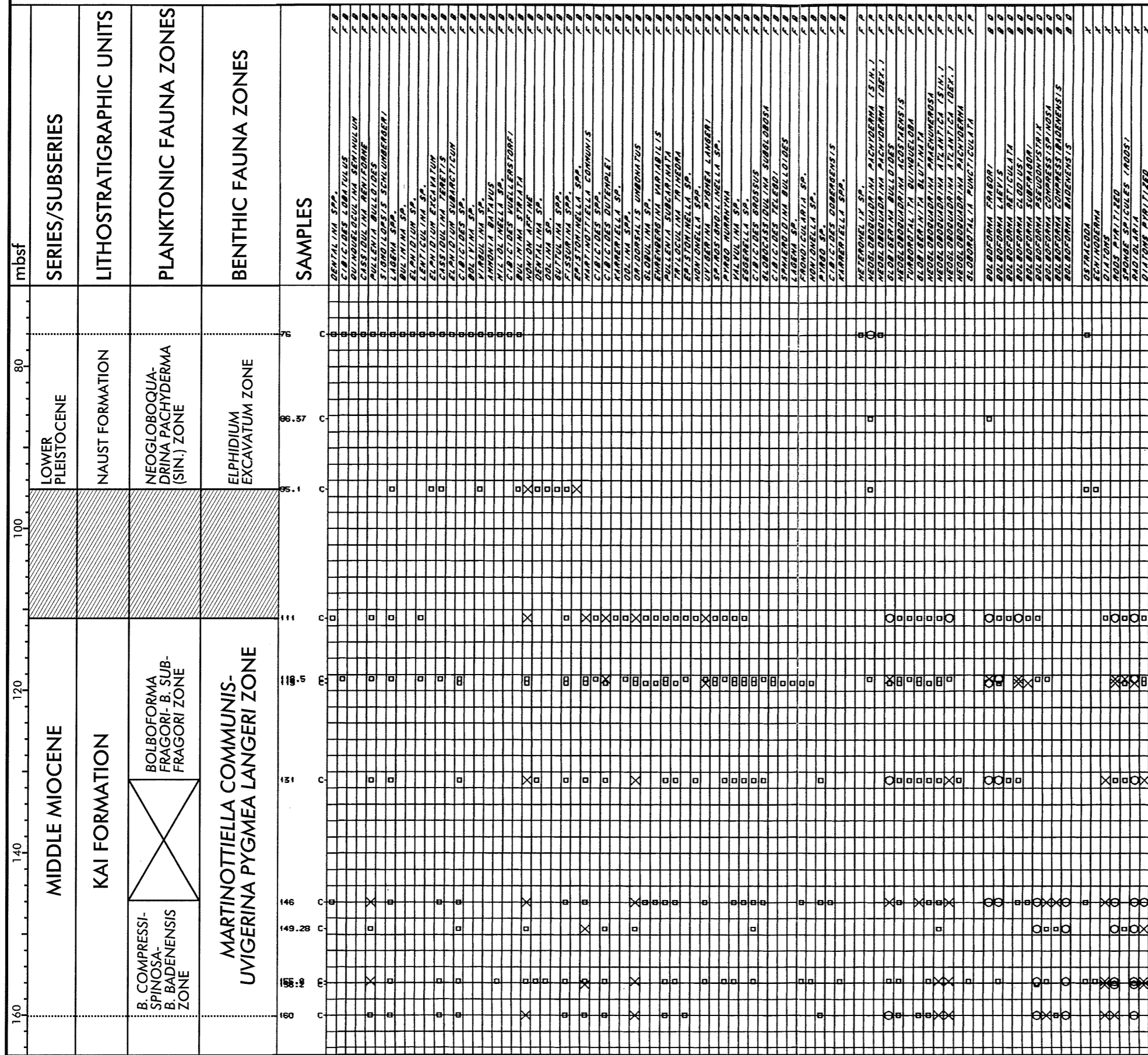


Fig. 1

FORAMINIFER AND BOLBOFORMA ZONES

(Fig. 2)

6704/12-GB1



Water depth: 1357 M (MSL)

□ Rare × Common ○ Abundant FB = Benthic Forams FP = Planktonic Forams
X = Misc. other Fossils BQ = Bolboforma C = Core

RLN 9803003

Core 6704/12-GB1

Diatom stratigraphy

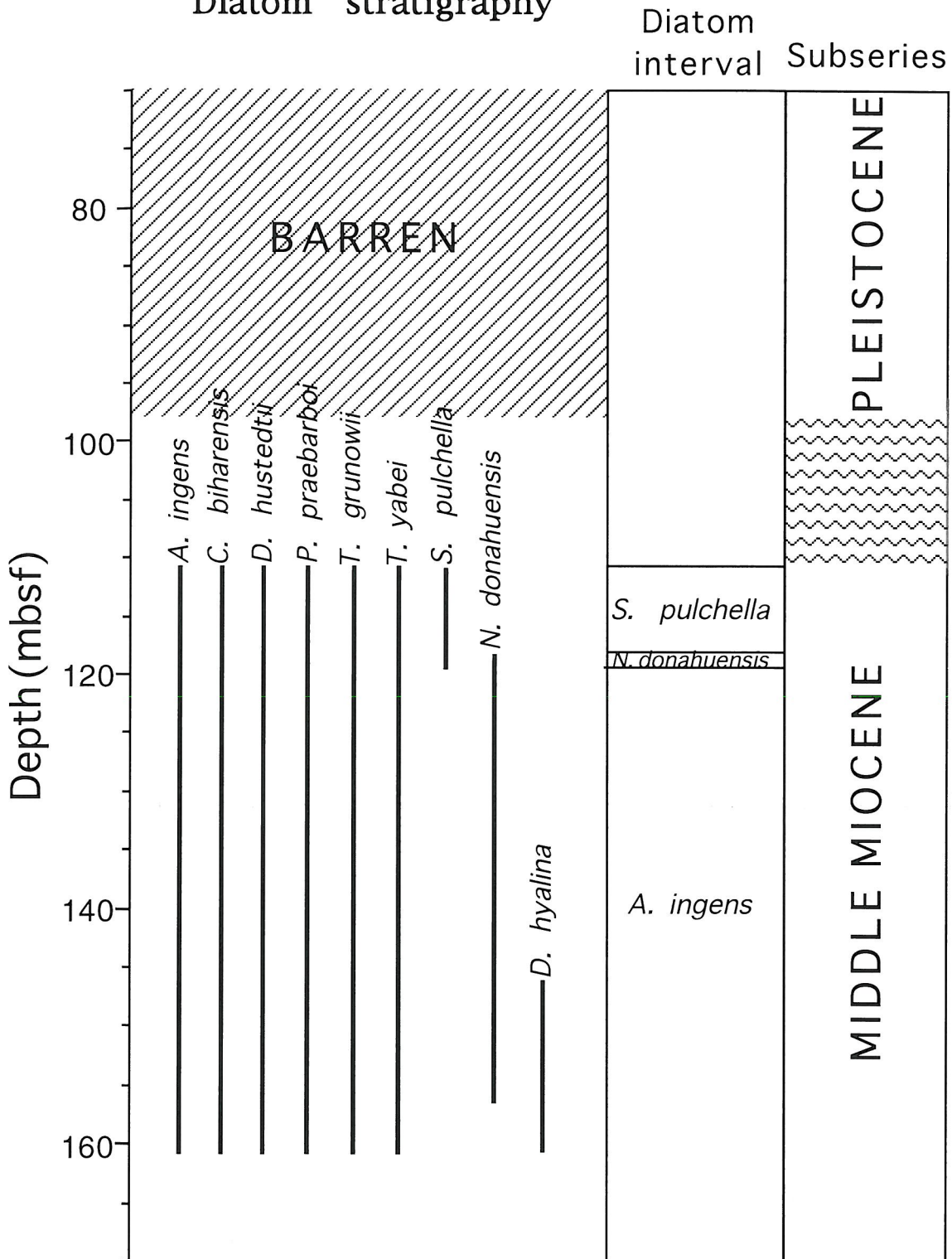


Fig. 4

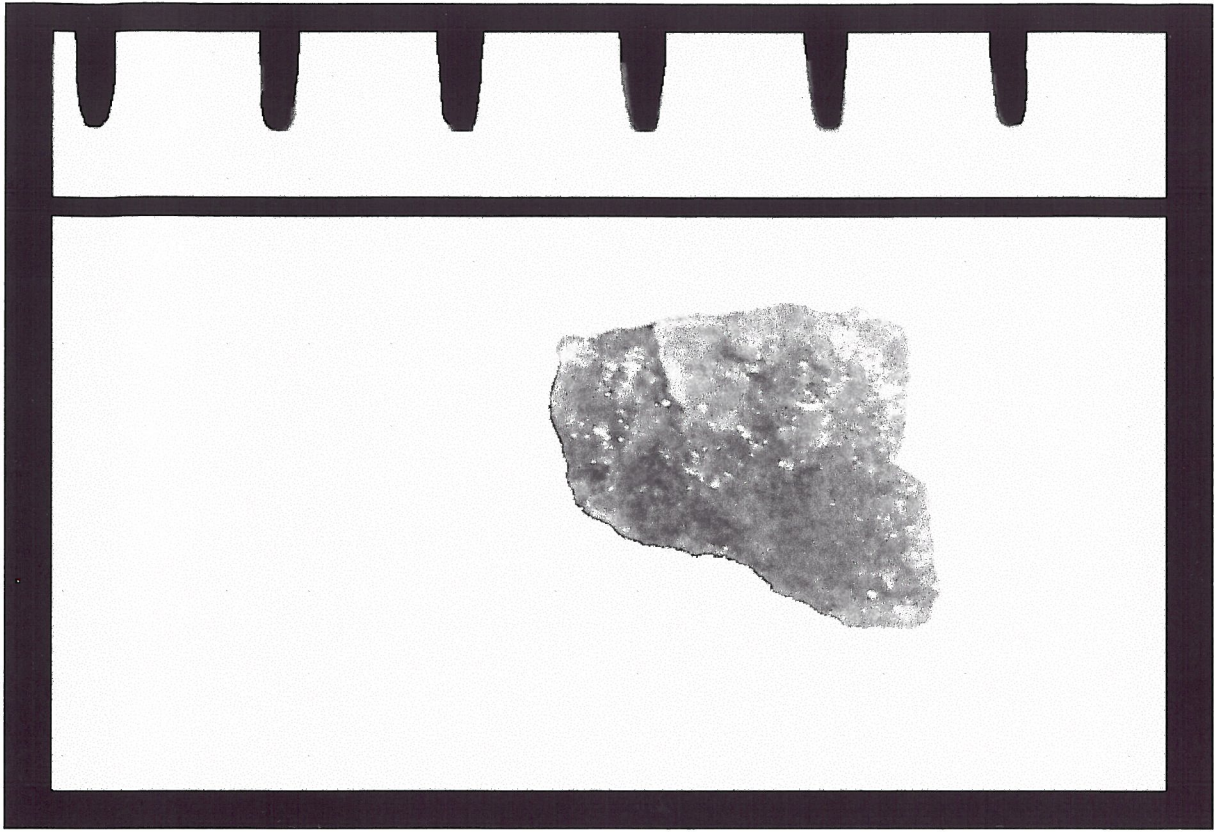
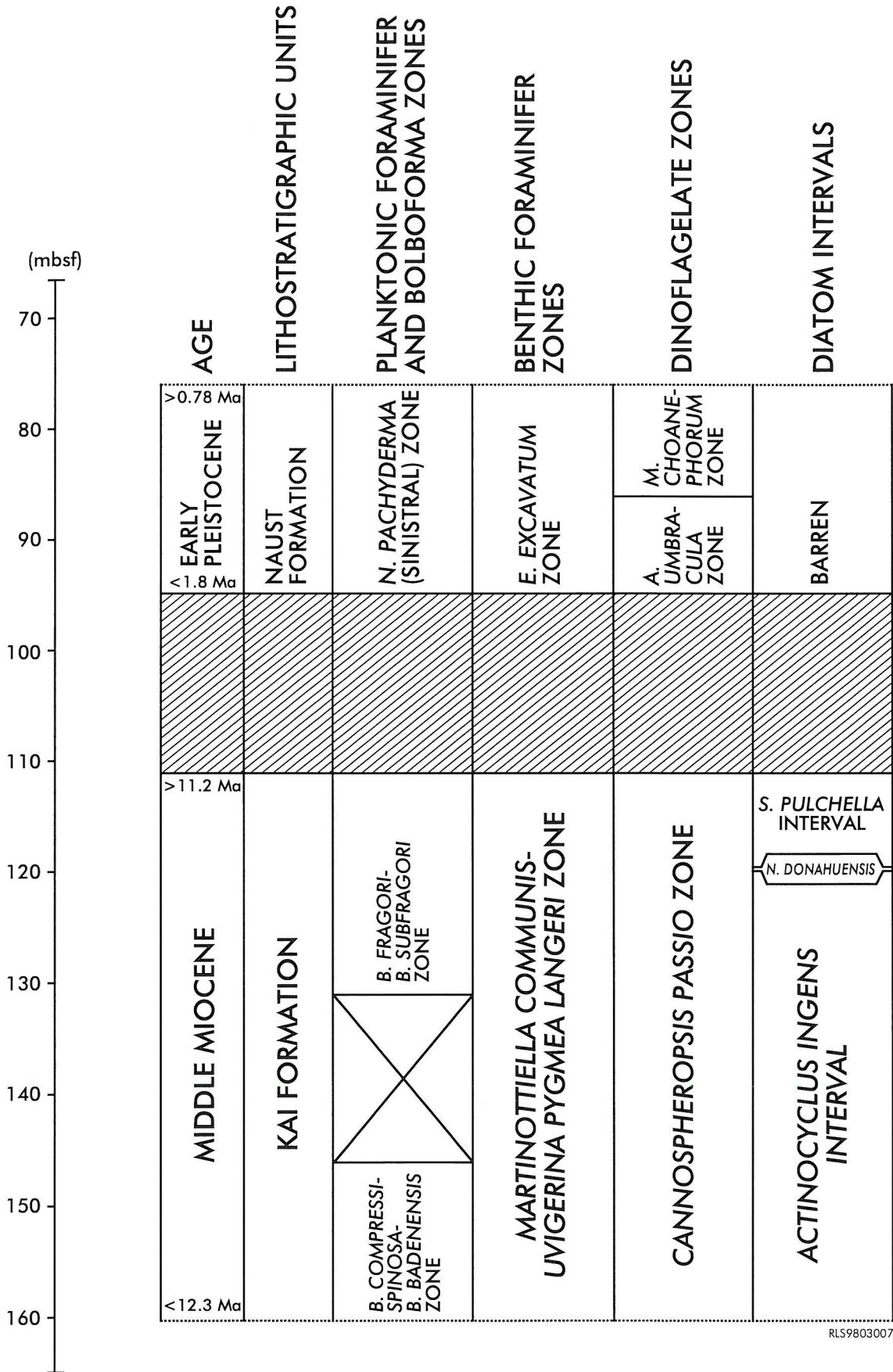


Fig. 5

CORE 6704/12-GB1



RLS9803007

Fig. 6

Plate 1

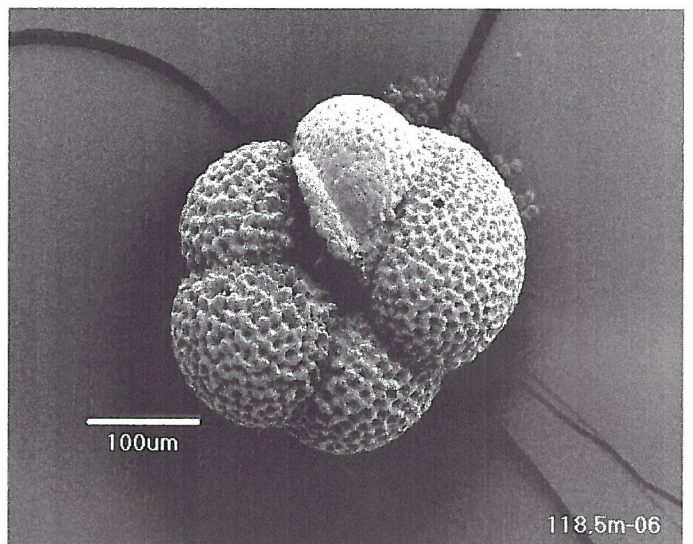
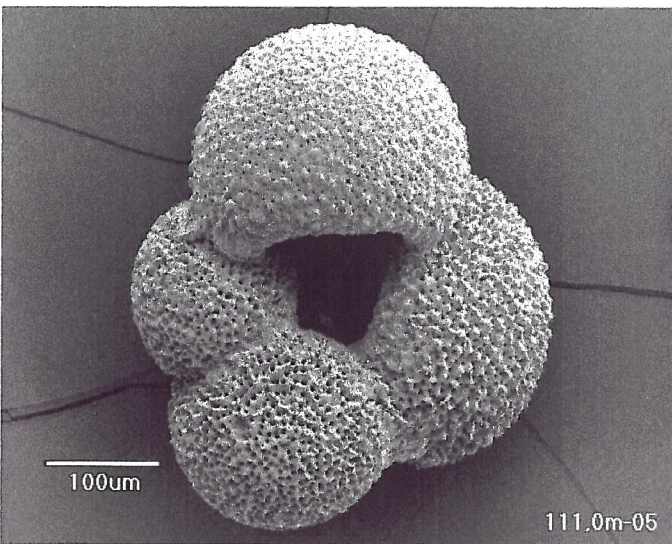
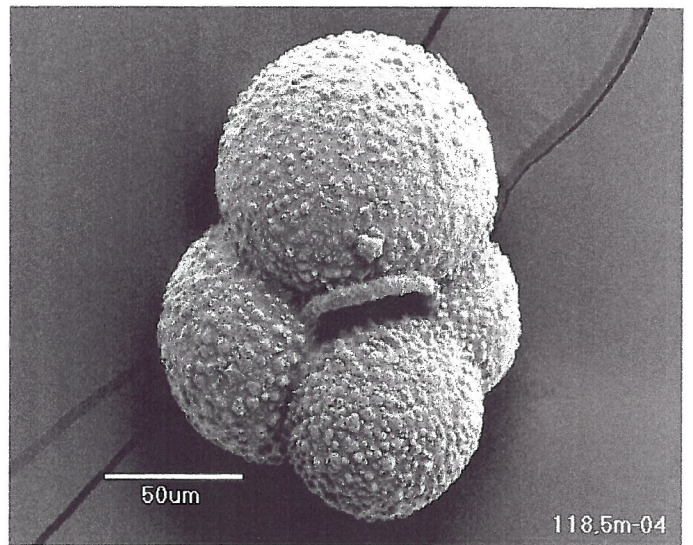
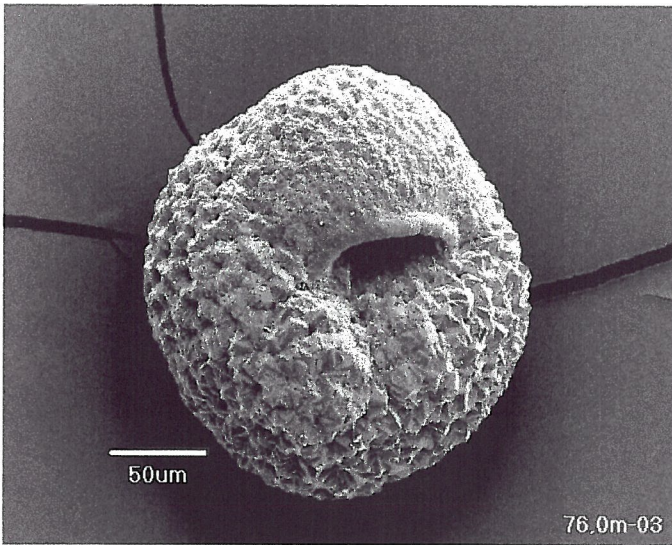
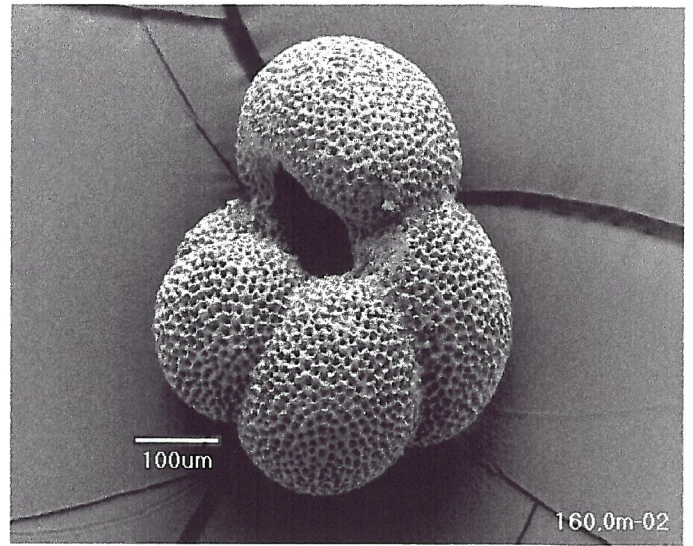
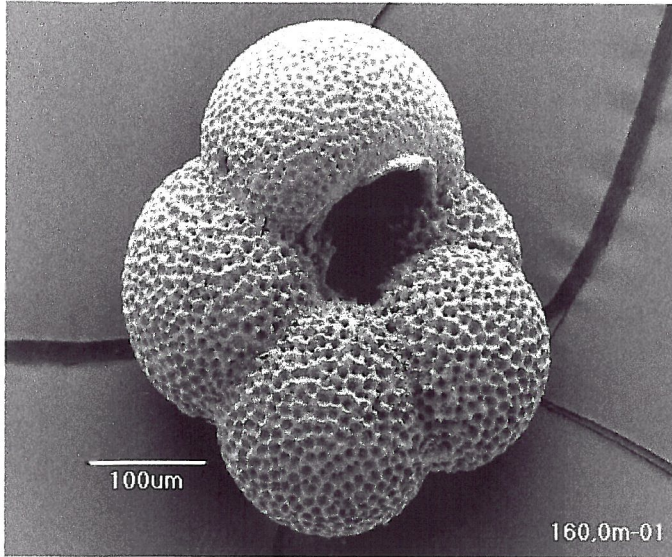


Plate 2

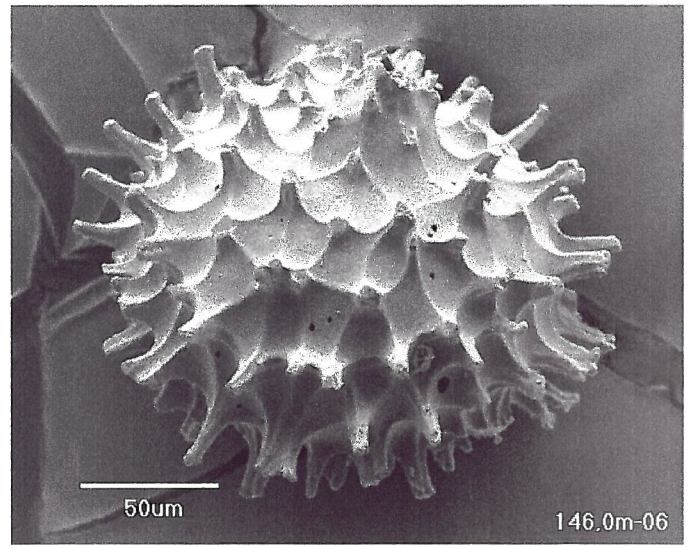
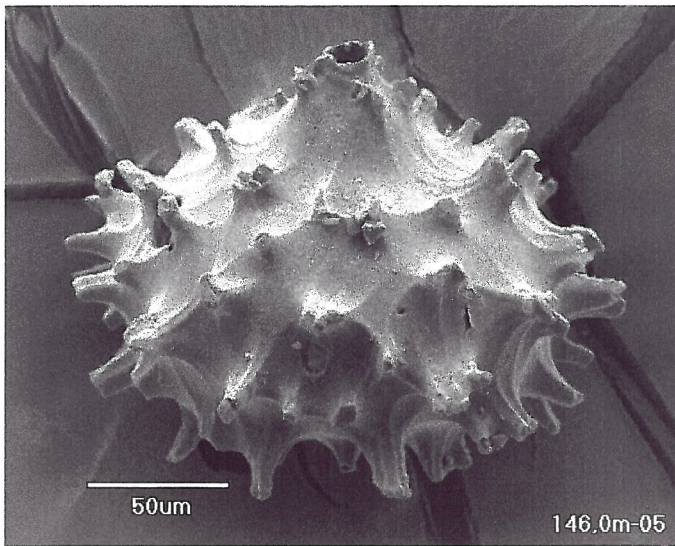
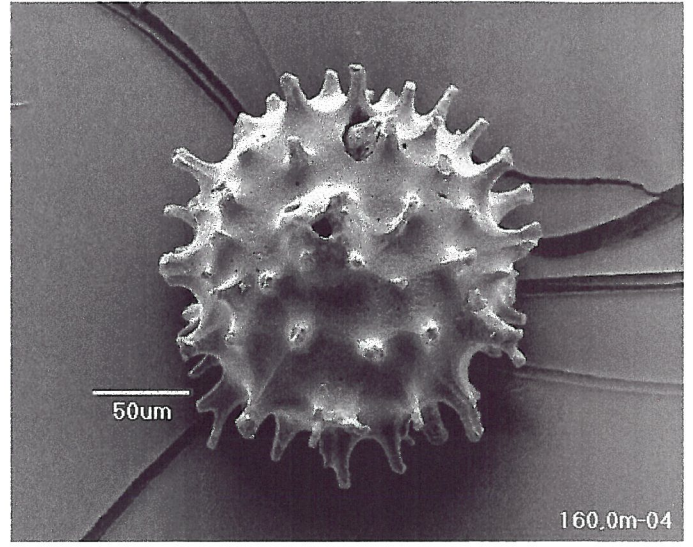
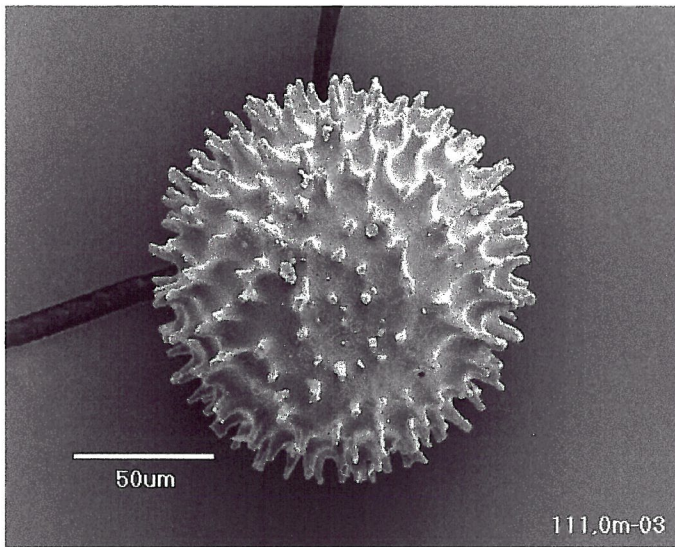
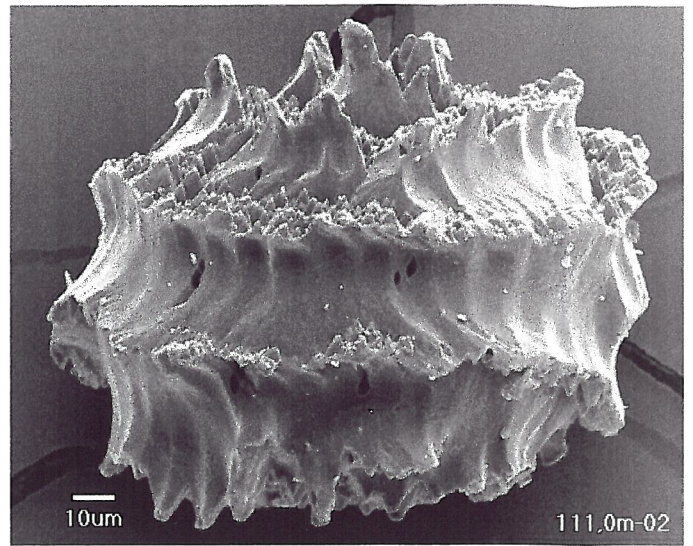
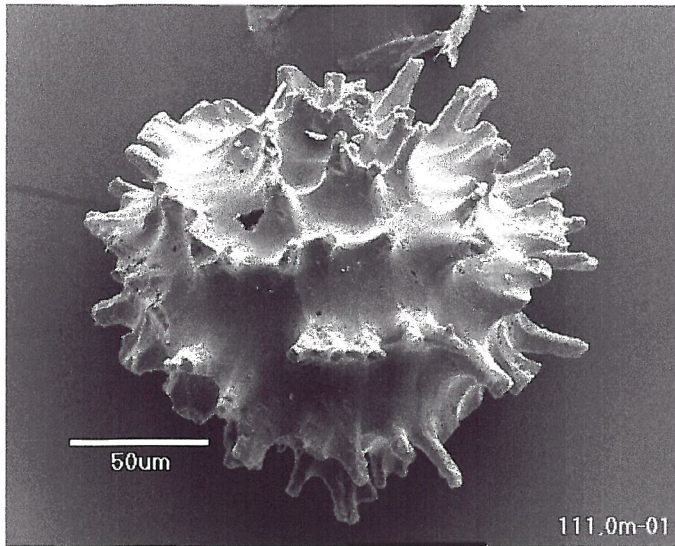
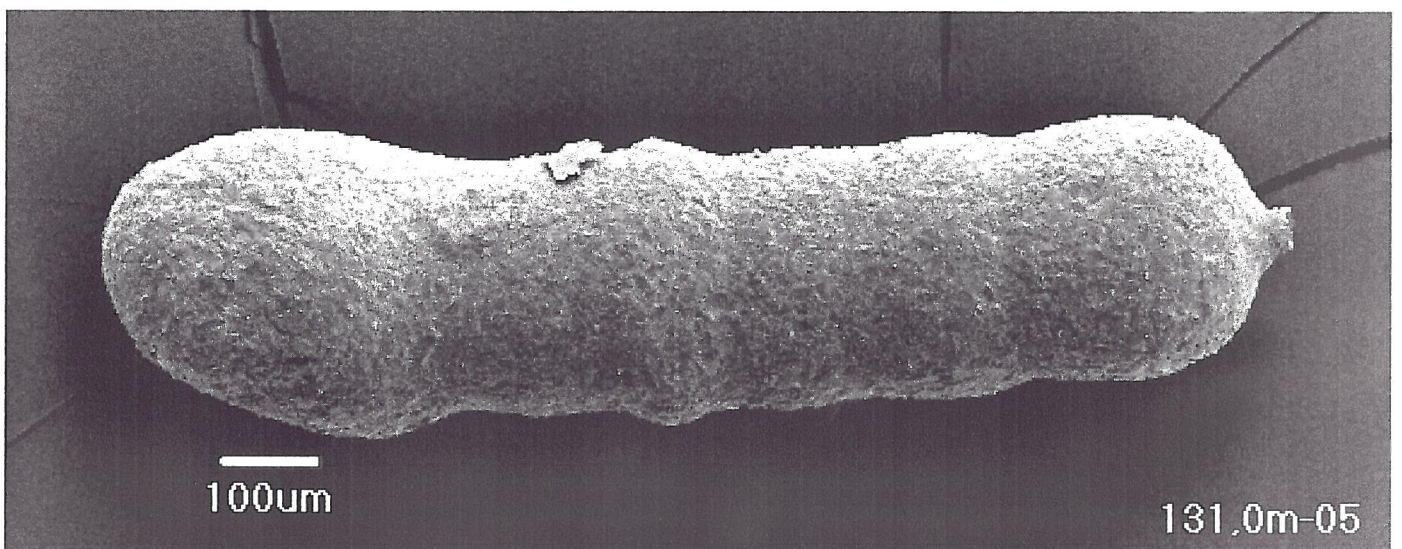
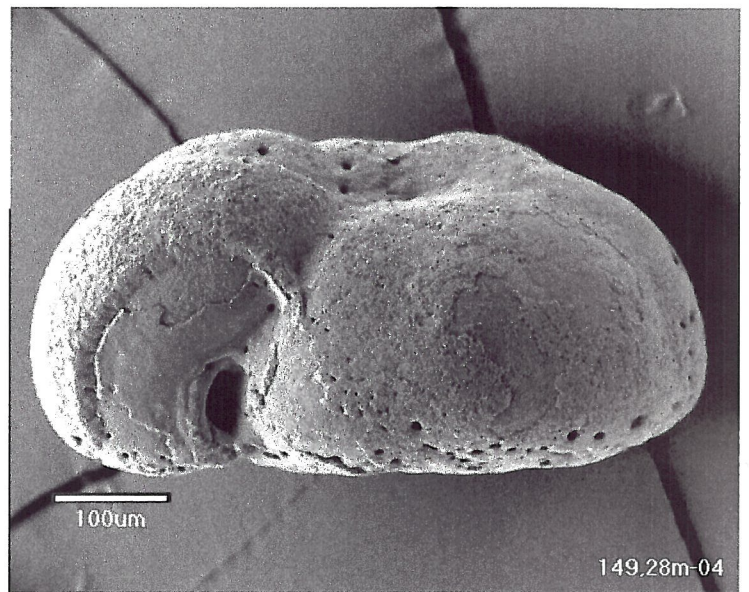
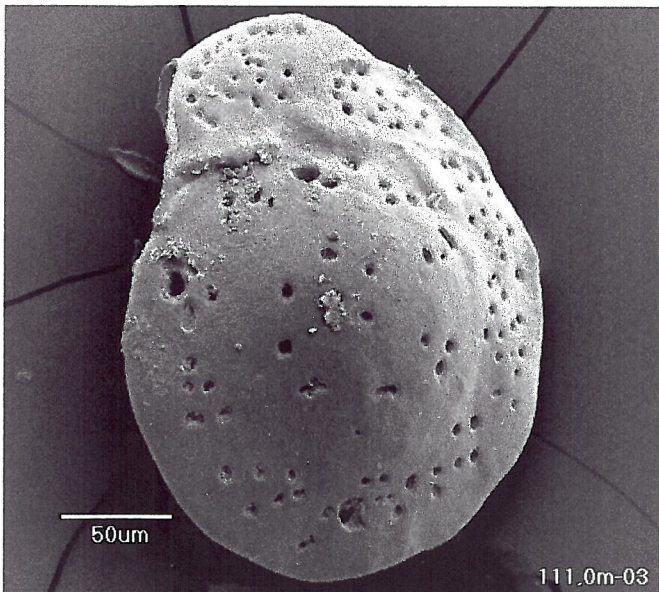
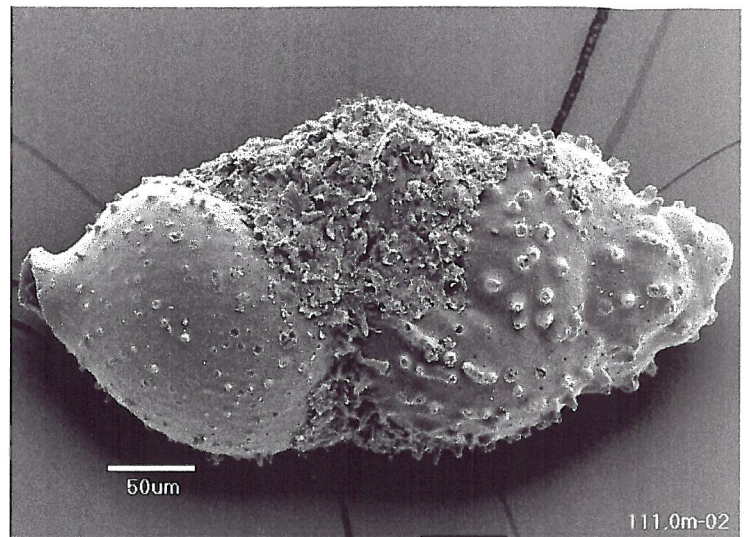
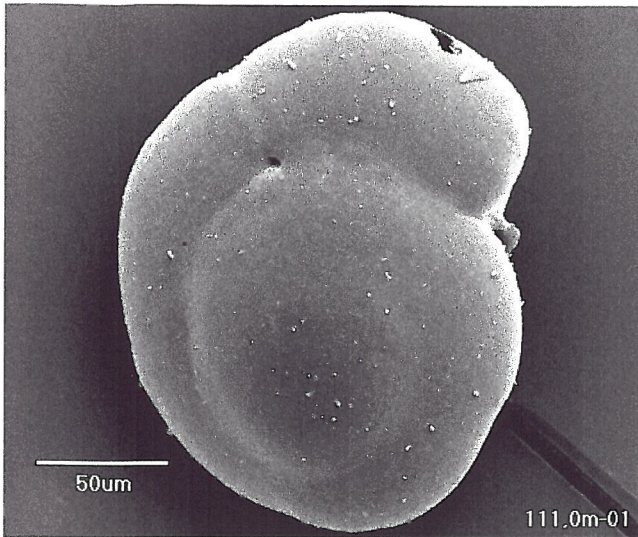
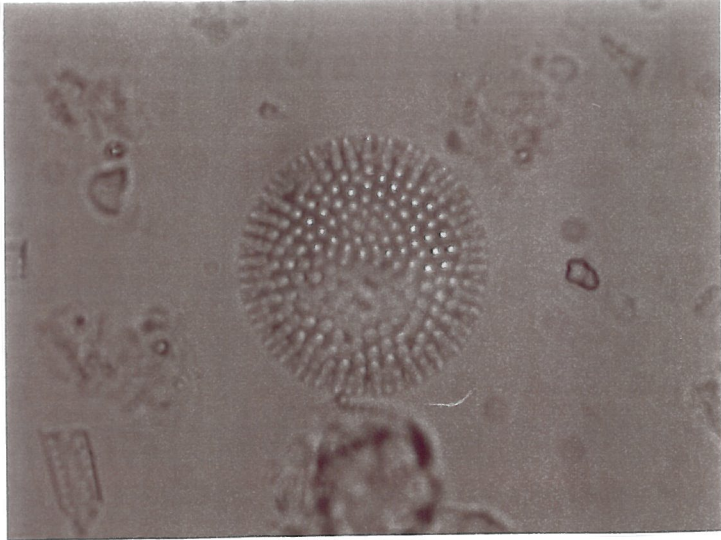


Plate 3



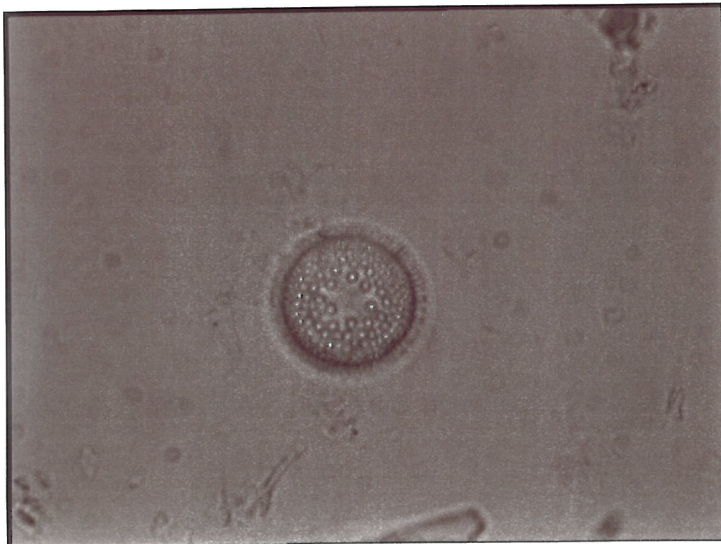
Sample 6704/12 GB1 9A, 111-111,1 m



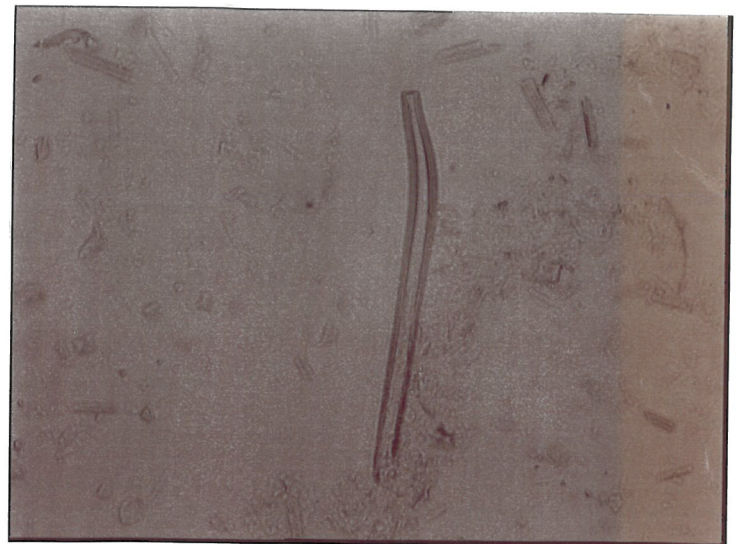
Thalassiosira yabei



Denticulopsis hustedtii

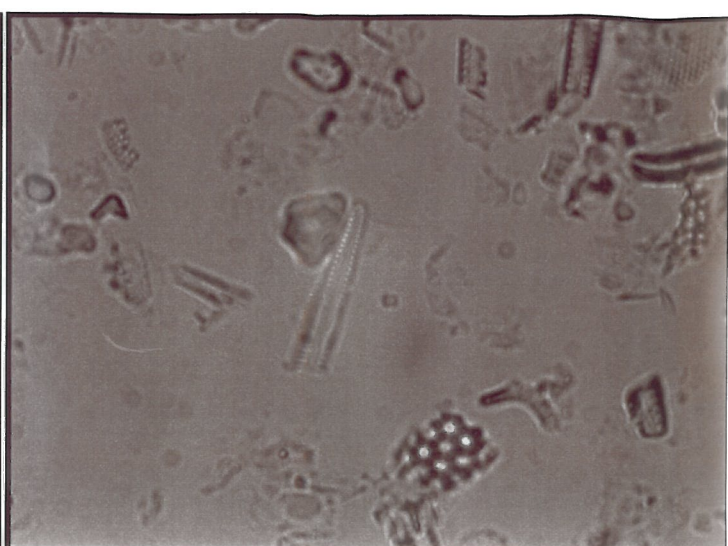


Actinocyclus ingens

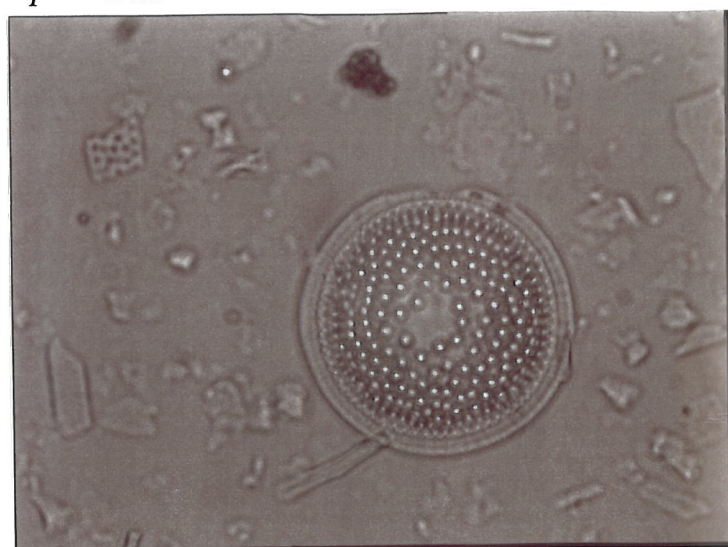


Proboscia praebarboi

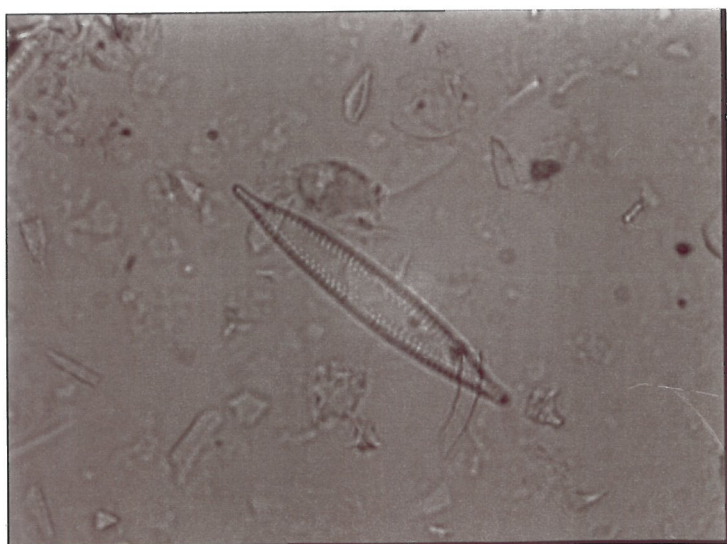
Sample 6704/12 GB1 12A, 119-119,4 m



Synedra pulchella



Actinocyclus ingens



Cymatosira biharensis



Nitzschia donahuensis

Sample 6704/12 GB1 16A, 146-146,4 m



Nitzschia donahuensis

Sample 6704/12 GB1 20, 160-160,15 m



Denticulopsis hustedtii



Thalassiosira yabei & *Cymatosira biharensis*