The Pleistocene to Middle Eocene stratigraphy and geological evolution of the western Barents Sea continental margin at well site 7316/5-1 (Bjørnøya West area)

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Pleistocene to Eocene stratigraphy and geological evolution of the thick Cenozoic fan deposits on the western Barents Sea continental margin SW of Bjørnøya are interpreted on the basis of seismic data and the results of biostratigraphic analysis (foraminifera, dinoflagellate cysts and radiolaria) from exploration well 7316/5-1. Strontium isotope ages are also obtained from three levels. The biostratigraphic analysis reveals seven informal zones based on foraminifera, four informal zones based on dinoflagellates, and five zones based on radiolaria fauna. Glacially derived Upper Pliocene and Pleistocene sediments rest unconformably on a Lower Oligocene to Lower Miocene section. An unconformity between the Lower Oligocene and Middle Eocene is also recorded. Prior to this investigation Oligocene sediments had not been encountered in exploration wells in the Barents Sea. The Oligocene benthonic foraminiferal fauna found in well 7316/5-1 is very similar to the fauna recorded in outcrop at Forlandsundet. Strontium-isotope correlation suggests, however, that the Oligocene section found in the Barents Sea is 5–6 m.y. older than that found at Forlandsundet.

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1. Introduction

Well 7316/5-1 is located in the southwestern part (73°31′N, 16°26′E) of the Vestbakken volcanic province (Fig. 1), and was the first well drilled to test the hydrocarbon potential of the clastic deposits in the Tertiary basins of the western Barents Shelf. The well is also the northwestern-most exploration well drilled on the Norwegian continental shelf to date. The well was drilled by Norsk Hydro a.s. on behalf of the PL 184 licence, which has now been relinquished. In order to assure that the results reported here are consistent with electric logs and other technical information concerning this well, all depths at this site are expressed as metres below the rig floor (m RKB) throughout the remainder of this paper. Therefore, 477 m must be subtracted from m RKB in order to convert these depths to metres below the sea floor. The well was drilled to a total depth of 4027 m RKB and is classified as a gas discovery after encountering a 18 m gas column in Middle Eocene sandstones at 1340 m RKB.

The Cenozoic succession of the western Barents Shelf is the result of several phases of extensive erosion and redeposition, and its stratigraphic interpretation has not been straightforward. Based on varying age determinations of the sequences, several different depositional history scenarios have been proposed for the Cenozoic basin development of this shelf margin area (Spencer et al. 1984; Nøttvedt et al. 1988; Vorren et al. 1991; Eidvin et al. 1993; Sættem et al. 1994). The objectives of the present study are to redate the upper part of well 7316/5-1 (i.e. the Pleistocene to Middle Eocene succession between 567 and 1600 m) by means of foraminifera, dinoflagellates, radiolaria and strontium-isotope analysis. We have also correlated the well stratigraphy to the seismic, and this provides the basis for a stratigraphic and regional geological model for the PL 184 licence and adjacent areas.

Previous studies of particular relevance to our work include the redating of the Palaeogene and Neogene sequences in wells 7117/9-1 and 7117/9-2 on the Senja Ridge, and of 7119/7-1 in the Tromsø Basin (Eidvin et al. 1993), together with the study of shallow cores which recovered Upper Palaeocene, Middle Eocene, Lower Miocene and Upper Pliocene–Pleistocene strata in the Bjørnøya West area (Sættem et al. 1994, Mørk & Duncan 1993) (Figs. 1, 2). Recent biostratigraphic information and paleomagnetic datings from the Ocean Drilling Program Leg 104 on the Vøring Plateau in the Norwegian Sea, provide further relevant information used to interpret and calibrate the stratigraphic data obtained from the micropalaeontology and palynology of well 7316/5-1. There are few earlier papers on Cenozoic foraminifera and dinoflagellates from the Barents Shelf area. Oligocene benthonic foraminifera have been described from Forlandsundet on Spitsbergen (Fig. 2) by Feyling-Hanssen & Ulleberg (1984), while Palaeogene dinoflagellates have been documented from Spitsbergen by Manum (1960), Head (1984, 1989) and Manum &

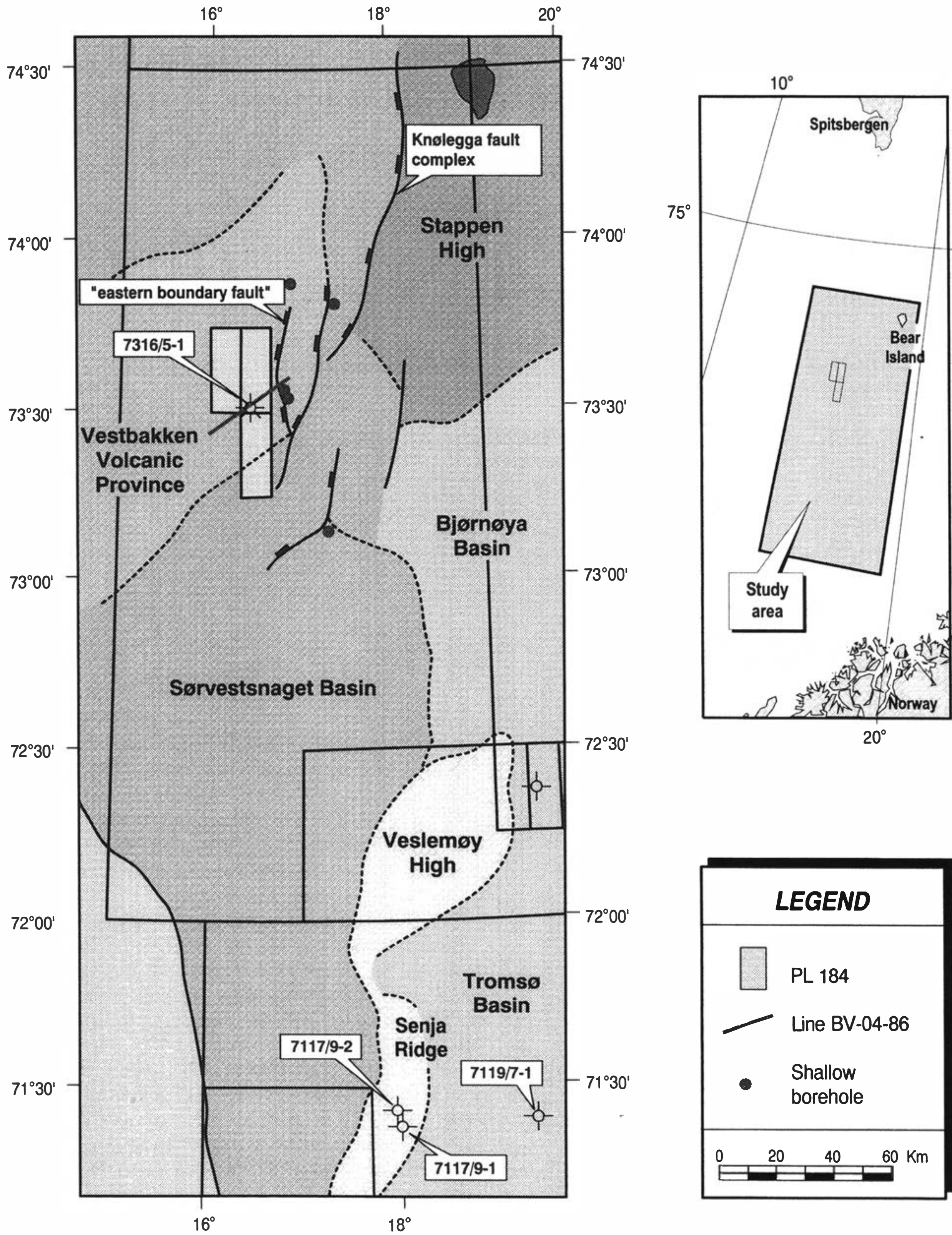


Fig. 1. Location of the regional seismic line NPD BV-04-86 and well 7316/5-1. Main structural features and location of other wells and shallow boreholes referred in the text are also shown.

Throndsen (1986). In the present study strontium-isotope analyses are carried out on tests of benthonic calcareous foraminifera from the Forlandsundet section, and some of the samples are re-examined for dinoflagellates.

This paper is an updated and revised version of the contribution by Eidvin et al. (1994). All absolute ages are based on Berggren et al. (1985) if not stated otherwise.

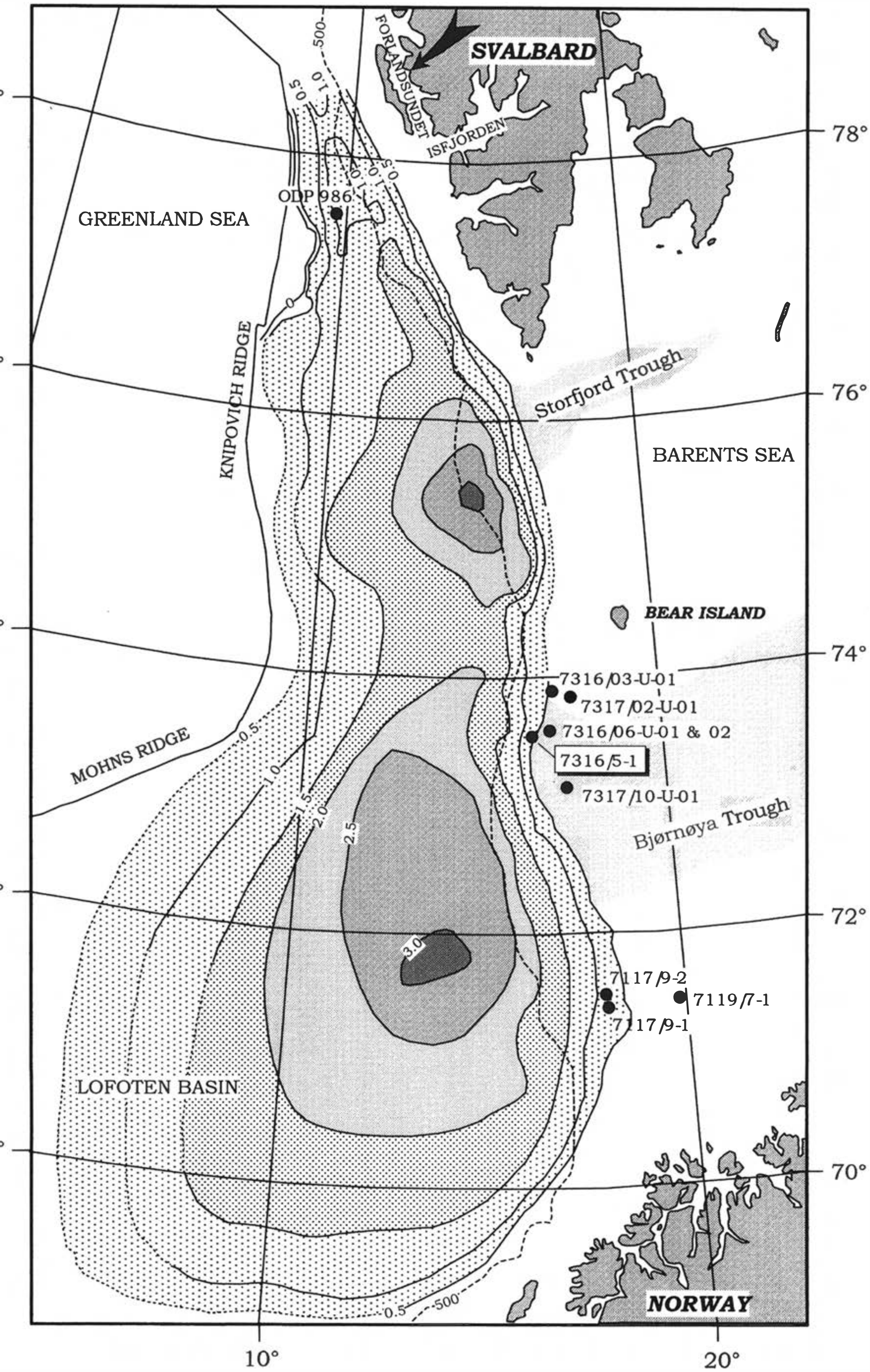


Fig. 2. Location of well 7316/5-1 and wells, shallow boreholes and ODP-borehole referred to in the text. The map is an isopach map of the glacial sediments along the western Barents Sea-Svalbard continental margin. Contour interval 0.5 s twt (modified after Faleide et al. 1996).

2. The geological setting

2.1 Seismic interpretation

Well 7316/5-1 is drilled at shotpoint 2058 on the NE-oriented seismic line NPD BV-04-86, and this line is used to illustrate the well tie (Figs. 1, 2).

The description below compares the biostratigraphically defined intervals with a regional seismic interpretation performed by the Norwegian Petroleum Directorate prior to the drilling of the well (Figs. 3, 4).

Interval 477–948 m RKB (454–925 m MSL) (Pleistocene–Upper Pliocene). – The base of this interval at 1123 ms twt can be correlated to the intra-Upper Pliocene horizon (i.e. base 'clastic wedge') (Figs. 3, 4). The event represents a marked angular discordance, both east and west of the well site. The reflection has a variable amplitude, and is very weak and difficult to interpret towards the west. The horizon has a dip of ca. 1.5° to the west.

Interval 948–960 m RKB (925–937 m MSL) (Lower Miocene). – On the seismic this 12-m-thick interval is recorded between 1123 and 1134 ms twt. The reflection at the base of the interval is continuous and exhibits strong amplitude across the licence area. The event defines a marked syncline east of the well site towards the eastern boundary fault (Fig. 3). West and south of the well site the reflection is truncated by the base Pliocene unconformity.

The reflection representing the intra-Lower Miocene horizon (Fig. 3) appears to coincide with the lower sequence boundary of a thick unit (more than 350 ms, i.e. approximately 380 m at shotpoint 1670, Fig. 3). Miocene and possible Pliocene sediments are preserved in the syncline east of the well. In the upper part of the sequence there is a marked break (truncating the wedge east of the well) possibly corresponding to the Middle–Late Miocene interval. The lower part of the sequence exhibits a parallel reflection pattern. The upper part exhibits indications of progradation from the east.

Interval 960–982 m RKB (937–959 m MSL) (Lower Miocene–Lower Oligocene). – Based on biostratigraphic evidence, only a general Early Miocene–Early Oligocene age can be inferred for this sequence. The reflection described above may represent the intra Miocene or the base Miocene, but it may also be associated with a larger hiatus. The interval 960–982 m is above the intra Oligocene reflector, recognized at about 1180 ms (1009 m RKB, 986 m MSL) in 7316/5-1.

The lower part of the shallow borehole 7316/06-U-01 (to the east of 7316/5-1, Fig. 2) is dated as Early Miocene (Sættem et al. 1994). On the seismic profile it appears that these deposits are also located below the reflector described above. It appears, however, that the sequence penetrated in 7316/06-U-01 is either condensed or truncated by a hiatus in well 7316/5-1.

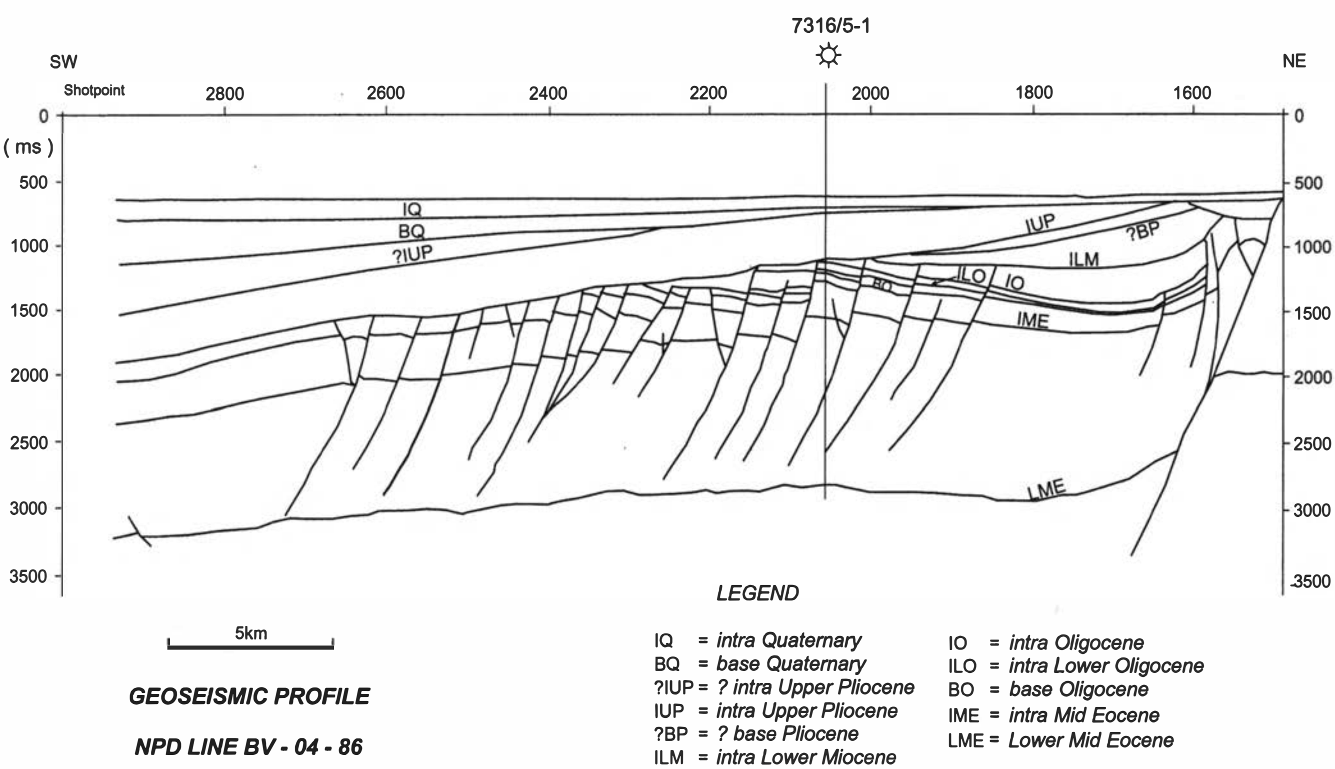


Fig. 3. Digitized seismic line NPD BV-04-86. Location in Fig. 1.

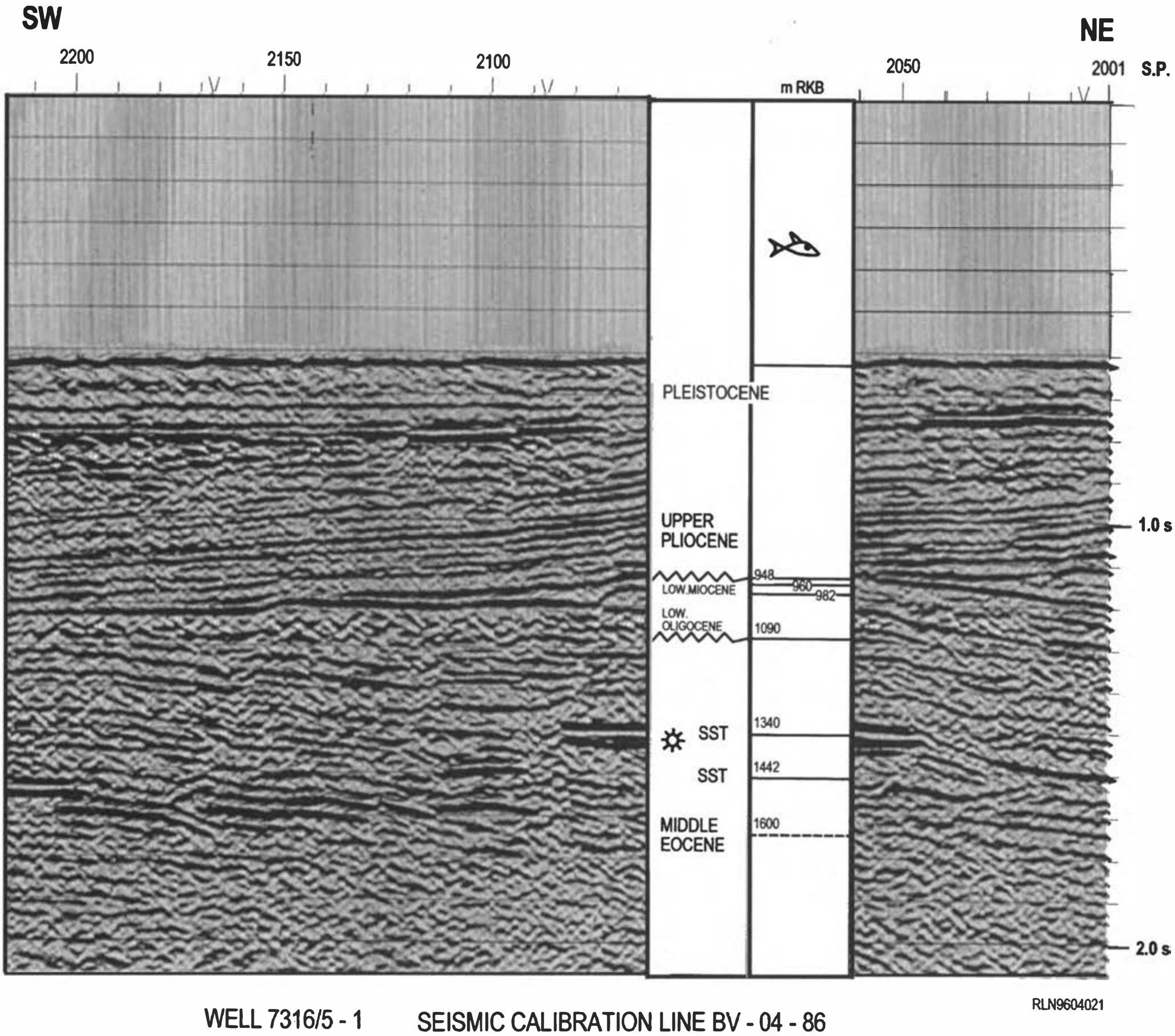


Fig. 4. Correlation between well and seismic profile.

East of 7316/5-1, the sequence thickens from about 50 ms to more than 250 ms twt (Fig. 3). The interval shows a transparent character with little indication of stratification, as might be expected for a sequence deposited in an outer shelf/slope environment (Sættem et al. 1994). The thinning of the sequence towards the well location is possibly due to condensing of the Lower Miocene–Upper Oligocene deposits.

Interval 982–1090 m RKB (959–1067 m MSL) (Lower Oligocene). – This interval occurs between 1154 and 1255 ms twt at the well site. The base of the sequence corresponds to the base Oligocene seismic marker (Fig. 3). In addition, there are two mapped seismic horizons within this interval, i.e. one weak intra Oligocene reflection picked at 1180 ms (1009 m RKB, 986 m MSL) and one strong, more continuous, intra Lower Oligocene reflector recognized at 1205 ms (1036 m RKB, 1013 m MSL).

The weak reflection picked at 1180 ms is better expressed further east and defines the base of the transparent interval described above. The stronger reflections at 1205 ms and 1255 ms which occur towards the base of the Lower Oligocene sequence appear as minor sequence boundaries, but both reflectors exhibit subtle truncation of underlying sequences. The Lower Oligocene unit appears to become thinner towards the eastern boundary fault (in contrast to the overlying sequences), but becomes gradually thicker to the west. West of the well site, parts of the Lower Oligocene unit are eroded and rest directly beneath the base Pliocene.

Interval 1090–1600 m RKB (1067–1577 m MSL) (Middle Eocene). – The interval between 1090 and 1600 m RKB (lowermost studied sample) corresponds to the seismic unit between 1255 and 1731 ms twt in the well. Upper Eocene deposits are not present in the well, and the upper boundary of this unit corresponds to a major unconformity. The reflector exhibits a marked truncation of older strata east of the well.

The Middle Eocene sequence exhibits almost parallel bedding, but with weaker amplitudes than the overlying Oligocene sequence. Towards the east the reflectivity appears somewhat stronger at some levels, but becomes very weak towards the west and also deeper than 1731 ms.

The upper sandy unit (top at 1492 ms twt) in the Middle Eocene sequence contains an 18 m gas column. This is accompanied by a marked increase in amplitude (bright spot) in the small rotated fault block penetrated by the well.

An intra-Middle Eocene horizon is recognised at 1550 ms twt (1392 m RKB, 1369 m MSL) between the two sandy units. An approximate correlation to the shallow drill site 7316/06-U-02 to the east (Sættem et al. 1994) (Fig. 2) indicates that the sediments recovered in the shallow core correlate to the sequence between 1400 and 1600 m RKB in 7316/5-1.

2.2 Lithology and lithostratigraphy of 7316/5-1

2.2.1 The Nordland Group (567–948 m RKB; 94–475 m below the sea floor)

This section has been observed in 29 sidewall cores, one conventional core (Core 1; 896-906.6 m RKB) and ditch cuttings below 887 m RKB (Figs. 5, 6). The interval consists of clay-rich diamicton interbedded with unconsolidated coarse- to medium-grained sand. The sand beds are 5–58 m thick, including a 52-m-thick unit at the base of the section. Structureless sand lacking laminations characterizes Core 1, which penetrated the upper portion of this basal unit. Subangular to angular pebbles and stones of both sedimentary and crystalline rocks occur throughout the core, both as distinct layers and dispersed intervals. The uppermost 20–25 cm of the core penetrated a large block of sedimentary rock. Crystalline pebbles interpreted as dropstones also occur in some of the sidewall cores. The clay-rich interbeds also contain significant concentrations of sand and pebbles.

The lithologies observed in this section are similar to the glaciomarine sediments of the Norwegian Sea. The sand units presumably accumulated during the sea-level lowstands associated with glacial stadia. The basal sand unit may be attributed to a glaciofluvial meltwater delta. The larger stones are interpreted as ice-rafted dropstones.

The glaciomarine sediments of the Vøring Plateau have been the subject of recent studies by Jansen (1991, 1993 and 1995) and Jansen & Sjøholm (1991), and the results of these investigations provide the best basis for inferring the age of the Nordland Group at 7316/5-1. There are traces of ice-dropped material in sediments as old as nearly 12 m.y. on the Vøring Plateau. The frequency of such ice-rafted material increases during the period of 6.5–5.5 Ma, which correlates with the Messinian Stage. The pronounced Messinian sea-level fall observed at many localities globally is attributed to an expansion of the Antarctic ice cap. The frequency of ice-dropped material remains relatively low between 5.5 Ma and 2.6 Ma, but the great increase in the supply of ice-dropped material after about 2.6 Ma reflects the marked expansion of northern European glaciers. This latter age is taken as the maximum age of the Nordland Formation at 7316/5-1.

2.2.2 The Sotbakken Group (948–1600 m RKB (lowest sample analysed); 475–1127 m below sea floor)

The upper part of this interval (i.e. 948–1090 m) comprises a bedrock sequence not previously encountered in other exploration wells in the western Barents Sea. However, in the absence of an alternative established lithostratigraphic name these sediments are assigned to the Sotbakken Group of Dalland et al. (1988).

The Sotbakken Group has been sampled by five sidewall cores (948–1022 m RKB), two conventional cores (Core 2; 1347.5-1374.4 m RKB, and Core 3; 1460.5–1472 m RKB) and ditch cuttings at 2–20 m intervals (Figs. 5, 6). The petrophysical logs support the lithological interpretation. The section consists primarily of claystone, which is slightly silty. Thin limestone beds are present throughout, especially below 1500 m RKB. Sand stringers and layers up to 4 m thick are present in the section above 1090 m RKB. The two cores penetrated sand units at 1442–1469 m RKB and 1330–1380 m RKB. Core 3 from the lower sandstone unit includes infrequent clay and silt interbeds, but the sand is generally coarse-grained and structureless. This unit is interpreted as a composite turbidite deposited on or near the basin floor. Core 2 from the upper arenaceous unit consists of fine-grained sand with frequent clay and silt laminations. Cross-bedding and planar laminations are present throughout the core, and the entire unit is interpreted to be of shallow marine origin.

3. Material and methods

The aborted pilot hole drilled down to 906 m was sampled with sidewall cores. From a depth of 567–885 m a total of 28 sidewall cores with a 10–20 m sample interval has been examined. Return of cuttings in the main hole started at 887 m. Cutting samples have been obtained with a 10 m sampling interval in most of the examined successions. In some intervals samples have been taken at 2–5 m intervals. Three conventional cores were taken at the following levels: 896–906.6 m, 1347.5–1374.4 m and 1460.5–1472 m. Among the sidewall cores from the main hole only six plugs from between 920 and 1022 m were available for this study. The biostratigraphic analyses from 887 to 1600 m are largely based on cutting samples, and consequently the biostratigraphic interpretation and correlation is based mainly on last-appearance datums (LADs) of the various taxa.

All the available sidewall cores, convential cores and cutting samples taken from 567 to 1600 m were analysed for foraminifera, dinoflagellates, radiolaria and diatoms. From some sample levels both sidewall cores and cuttings were analysed. For analyses of foraminifera in the conventional core samples and the cuttings, 50–110 g material was used. The foraminiferal identifications were done in the 0.07–0.50 mm fraction. Whenever possible, 300 individuals were counted in each analysis. In order to better identify the foraminiferal assemblages, a number of samples rich in terrigenous grains were gravity separated in heavy liquid. Less material was available from the sidewall cores (20–50 g from the pilot hole, and only 8–17 g from the main hole), and from these samples the material less than 0.1 mm was saved for palynological analyses. Palynomorphs were extracted from both cuttings and cores from 20–30 g material, using conventional preparation methods involving removal of carbonates and silica by HCl and HF, respectively. The organic residues were subsequently oxidized with nitric acid to remove pyrite and some of the amorphous organic matter.

The assemblage composition of radiolaria larger than 100 mm in diameter was recorded in the foraminifera preparations of the sidewall core material. A separate set of samples weighing approximately 20–30 g each from the cuttings and the convential cores was prepared for siliceous microfossil examination and split into the fractions <45 μ, 45–250 μ and >250 μ.

In addition to the biostratigraphic analyses, six samples from well 7316/5-1 and four samples from the Forlandsundet section were picked for strontium-isotope analysis (Table 1). The analyses were performed on the tests of *in situ* benthonic calcareous foraminifera. The tests representing the samples A_1 and A_2 in 7316/5-1 are from cutting samples from five different levels between 987 and 1015 m. Sample B is also from cuttings and represents four levels in the interval 1050–1070 m. In order to obtain sufficient material for the isotope analyses, it was necessary to combine material from different levels. Samples C_1–C_3 are all from 1472 m representing the lowermost conventional core. The samples 228M, 244M, 248M and 19M from Forlandsundet on Spitsbergen are from the section described by Feyling-Hanssen & Ulleberg (1984).

4. Biostratigraphic results

4.1 Well 7316/5-1

Foraminifera, dinoflagellates and radiolaria occur with variable abundance and diversity throughout the interval under investigation (587–1600 m). In addition to the fossil assemblages regarded as in place and representing the correct age of the sediments at the time of deposition, there are variable quantities of fossils derived from earlier depositional phases. These latter constituents are dominant in some parts of the section, which may be interpreted as lowstand fan complexes. Biostratigraphic subdivision of the Pleistocene–Upper Pliocene section is based entirely on foraminifera, as *in situ* dinoflagellates and radiolaria are very rare or absent. A total of seven informal foraminifera biozones (BB-FA to BB-FG), four informal dinoflagellate zones (BB-DA to BB-DD), and five radiolaria zones (BB-RA to BB-RE) are recognized in the Pleistocene to Middle Eocene strata of 7316/5–1. B = Barents Sea, B = Bjørnøya West (Figs. 5–7). Figures 5 and 6 contain range charts of the most important species. Eidvin et al. (1994) include range charts of all registered species, but without some modifications performed in this study.

4.1.1 Foraminifera zones

Foraminifera of variable diversity and assemblage composition occur in most of the investigated samples in the study interval (567–1600 m), but there are three intervals interpreted as being represented exclusively of redeposited older taxa, specimens redistributed as a result of drilling contamination (caved), or species with very long stratigraphic ranges. The assemblages from the bedrock section below the glaciogene overburden either have no equivalents in the Vøring scientific drillings or are more confidently correlated to sections in northern Europe. Consequently, it has been concluded that the most appropriate procedure under these circumstances is to employ a system of seven informal local zones, based primarily on the frequency of specimens regarded as *in situ*, and the ratio of calcareous and agglutinated tests.

NEOGLOBOQUADRINA PACHYDERMA (SINISTRAL) – *ELPHIDIUM EXCAVATUM* – *CASSIDULINA RENIFORME* ZONE

Category: Informal local assemblage zone.

Designation: BB-FA.

Informal local boundary criteria: The top of the zone extends above the uppermost investigated sample (567 m) and probably near the sea floor. The base of the zone is marked by the lowest common occurrence of *N. pachyderma* (sin.), *E. excavatum* and *C. reniforme*.
Depth range: 567 (uppermost investigated sample) – 670 m.

Age: Pleistocene.

Material: Nine sidewall cores.

Equivalent zones: Assemblage Zone A of Eidvin et al. (1993) described from wells 7117/9-1 and 7117/9-2 on the Senja Ridge and 7119/7-1 in the Tromsø Basin. *Neogloboquadrina pachyderma* (sin., enc.) Zone of Spiegler & Jansen (1989) and Subzone NSB 16x of King (1989).

In-place assemblage: Calcareous benthonic foraminifera are numerous and diverse in the samples above 599 m, but both diversity and abundance decline below this depth. *E. excavatum* and *C. reniforme* are the most common species. Other important species are: *Islandiella islandica*, *Bulimina marginata*, *Nonion affine*, *Angulogerina fluens*, *Islandiella norcrossi*, *Cibicides lobatulus*, *Elphidium subarticum* and *Nonion labradoricum* (Fig. 5).

Planktonic foraminifera are less frequent than calcareous benthonic taxa, but they are also common above 599 m. *N. pachyderma* (both encrusted and unencrusted varieties of the sinistrally coiled individuals) is dominant. Other important species are: *N. pachyderma* (dextral) and *Turborotalia quinqueloba*.

Reworked assemblage: *Gyroidina soldaii girardana*, *E. variabilis* and probably *P. bulloides* are reworked Miocene and Oligocene taxa. The agglutinated species: *S. spectabilis*, *Ammodiscus* sp. and *Rabdammina* sp. indicate redeposition of Palaeogene or Mesozoic sediments. The planktonic species: *Heterohelix* sp. and *Hedbergella* sp. have been derived from Upper Cretaceous sediments.

Remarks: All of the benthonic calcareous foraminifera here regarded as *in situ* are extant species typically associated with Pliocene–Pleistocene deposits of the Norwegian margin. *N. pachyderma* (sinistral, encrusted) has its first frequent occurrence at 1.7 Ma (Weaver & Clement 1986; Spiegler & Jansen 1989). This test morphology has only sporadic occurrences in older sediments. *N. labradoricum* also appears to be restricted to Pleistocene deposits on the Norwegian shelf. King (1989) employs *N. labradoricum* as the nominate taxon for the Pleistocene Zone NSB 16x of the northern North Sea, and this zone has been recognized on the mid-Norwegian shelf by Eidvin & Riis (1991).

UNZONED INTERVAL f1

Depth range: 670–805 m.

Material: 13 sidewall cores.

Age: Late Pliocene–Pleistocene.

Assemblage: Foraminifera are generally rare in this interval, and 7 of the 13 samples are barren. The assemblage is of low diversity and consists exclusively of benthonic taxa. Sporadic, rare occurrences of: *Elphidium bartletti*, *Elphidium* sp., *Cibicidoides pachyderma* and *Gyroidina soldanii girardana* are the only calcareous representatives. The agglutinated tests, which are severely damaged and can only be identified to genus, include: *Ammodiscus* sp., *Bathysiphon* sp., *Glomospira* sp., *Textularia* sp., *Karreriella* sp., *Reticulophragmium* sp., *Haplophragmoides* spp. and *Reophax* sp. (Fig. 5).

The occurrence of *Gyroidina soldanii girardana* at 805 m is interpreted as the result of redeposition of Lower Oligocene–Lower Miocene sediments. The agglutinated taxa are reworked from older Cenozoic and Mesozoic deposits.

Remarks: Most of the calcareous foraminifera in this interval are characteristic of Pliocene–Pleistocene sediments, and only a general Late Pliocene to Pleistocene age can be inferred.

GLOBIGERINA BULLOIDES–CASSIDULINA TERETIS ZONE

Category: Informal local assemblage zone.

Designation: BB-FB.

Informal local boundary criteria: The top of the zone is taken at the down-hole reappearance of calcareous taxa, such as *Cassidulina teretis* and *Globigerina bulloides*. The base of the zone is marked by the lowest occurrences of *Cassidulina teretis* and *Globigerina bulloides*.

Depth range: 805–885 m.

Material: Five sidewall cores.

Age: Late Pliocene.

Equivalent zones: *Geodia* sp. – *Globigerina bulloides* Assemblage Zone (D) of Senja Ridge well 7117/9-1 (Eidvin et al. 1993). *Neogloboquadrina atlantica* (sin.) Zone of Spiegler & Jansen (1989). Questionably Subzone NSB 15a and Subzone NSP 15d of King (1989).

In-place assemblage: Although foraminifera are sparse in this interval, they are significantly more common than in the immediately overlying section. Benthonic calcareous species are rare and include: *N. affine*, *C. lobatulus*, *B. marginata*, *Cassidulina tertis*, *Haynesina orbiculare* and *Gyroidina soldanii girardana. Globigerina bulloides* and *N. pachyderma* (sin., unencrusted) are the only planktonic species. Additionally, rare specimens of the sponge, *Geodia* sp., occur in this zone (Fig. 5).

Reworked assemblage: Most of the foraminifera are agglutinated species, but few of the specimens can be identified to species level. The agglutinated species include: *Glomospira charoides*, *Bathysiphon* spp., *Ammodiscus* sp., *Reticulophragmium* sp., *Haplophragmoides* sp. and *Reophax* sp. These taxa are interpreted as having been derived from Palaeogene or Mesozoic sediments.

Remarks: The benthonic calcareous foraminifera are characteristic Pliocene–Pleistocene taxa, except for *Gyroidina soldanii girardana* (Early Oligocene–Early Miocene). *G. bulloides* is common in Upper Pliocene sediments older than 2.3 Ma on the Vøring Plateau (Spiegler & Jansen 1989).

UNZONED INTERVAL f2

Depth range: 885–949 m.

Material: Three conventional core samples taken from 897.4–905.2 m, two sidewall cores and five ditch cuttings samples at about 10 meters intervals.

Age: Late Pliocene.

Assemblage: Although the declines in the frequency and diversity at the upper boundary of this interval zone are not as severe as at the top of Unzoned Interval f1, most of the specimens in this interval are regarded as reworked. One specimen of *N. affine* and one indeterminate planktonic species are the only calcareous species.

The agglutinated fauna is poorly preserved and includes *Bathysiphon* sp. as the most common species. *G. charoides*, *R. placenta*, *Glomospira* sp., *Ammodiscus* sp. and *Haplophragmoides* sp. are also present. Most of these taxa are Mesozoic to Early Palaeogene in age. *R. placenta* has been reported from the Lower Eocene to Upper Miocene in the North Sea (King 1989).

Remarks: *N. affine* is most common in Pliocene–Pleistocene sediments, but occurs as early as the Oligocene. Unzoned Interval f2 occupies the base of what is interpreted as the glaciogene overburden, and is dated as Late Pliocene based on lithological correlation. There is a distinct lithologic break between the base of this zone and the underlying unit, which is also marked by a regional reflector.

RETICULOPHRAGMIUM PLACENTA ZONE

Category: Informal local partial range zone.

Designation: BB-FC.

Informal local boundary criteria: The top of the zone is taken at the highest consistent occurrence of *R. placenta*. The base of the zone is marked by the highest occurrences of *Turrilina alsatica* and *Angulogerina tenuistriata*.

Depth range: 948–982 m.

Material: Three sidewall cores and two ditch cutting samples.

Age: Early Oligocene–Early Miocene.

Equivalent zones: Questionably Zone NSA 10 of King (1989).

Assemblage: Only rare, agglutinated foraminifera occur in this zone. Although few in number, they are somewhat more common than in the overlying interval. *R. placenta* has a consistent but rare occurrence. Other important species are *Bathysiphon* spp., *Ammodiscus* sp., *Haplophragmoides* sp. and *Spiroplectammina* sp. (Fig. 5).

Remarks: In the North Sea *R. placenta* occurs in Lower Eocene to Middle Miocene sediments and additionally has a short occurrence in the uppermost Upper Miocene section (King 1989). The other agglutinated taxa are of Mesozoic or Palaeogene age, but some species may range as high as basal Miocene in the North Sea area (King 1989).

It is difficult to determine the precise age of this zone based on foraminifera. The sediments cannot be older than Early Oligocene, based on the age of the underlying zone. Only a general Early Miocene to Early Oligocene age can be inferred on the basis of the foraminifera. The dinoflagellate cysts distributions indicate an Early Miocene age for the sediments above 960 m, which are distinguished by a regional seismic reflector, but there are no discernible differences in the foraminifera fauna at this depth.

TURRILINA ALSATICA – ANGULOGERINA TENUISTRIATA ZONE

Category: Informal local total range zone.

Designation: BB-FD.

Informal local boundary criteria: The top of the zone is taken at the highest occurrence of *T. alsatica* and *A. tenuistriata*. The base of the zone is taken at the lowest consistent occurrence of *T. alsatica*.

Depth range: 982–1090 m.

Material: One sidewall core and 17 ditch cutting samples at 3–15 m intervals.

Age: Early Oligocene.

Equivalent zones: Questionably, Subzone NSB 7a or Subzone NSB 7b of King (1989) and Zone NSR 7A of Gradstein & Bäckström (1996).

Assemblage: Foraminifera are significantly more numerous in this interval than in the immediately overlying zone. Both calcareous benthonic and agglutinated taxa are present, but the calcareous species (mostly benthonic) are dominant. A single indeterminate planktonic foraminifera was observed at 1045 m. The two nominate species characterize the assemblages, although both species have sporadic rare occurrences in the ditch cuttings from the section below this zone. *T. alsatica* and *A. tenuistriata* are most common and occur through most of the unit. Other important species are: *Gyroidina s. girardana*, *Cibicides dutemplei*, *Eponides pygmeus*, *Stilostomella adolphina*, *Cibicides telegdi*, *Bolivina* cf. *antiqua*, *Globulina munsteri*, *Globulina inaequalis*, *Gyroidinoides* sp. 1 (Ulleberg 1974), *Cibicides aknerianus*, *Globocassidulina subglobosa* and *N. affine*. *R. placenta* and *Reticulophragmium* sp. are the dominant agglutinated taxa (Fig. 5).

Remarks: The calcareous taxa have been described previously from the Oligocene of the North Sea region, and some species also range into Lower Miocene sediments (Batjes 1958; Christensen & Ulleberg 1974, 1985; Nuglish & Spiegler 1991; Spiegler 1974; King 1989). *Bolivina* cf. *antiqua* is restricted to Upper Oligocene–lowermost Miocene sediments in the North Sea (King 1989), but this species has been recorded from Lower Oligocene deposits on the Nordland Ridge (Mid-Norway) (Eidvin et al. in press).

Strontium-isotope analyses of these tests give an age of about 35 m.y., i.e. Early Oligocene (Table 1 and Fig. 7).

A similar fauna from an outcrop at Forlandsundet, Spitsbergen was described by Feyling-Hanssen & Ulleberg (1984), who interpreted the section as transitional Early/Late Oligocene in age. King (1989) correlated the fauna from this locality with Subzones NSB 8a or NSB 7b (Early/Late Oligocene) of his North Sea zonation.

Strontium-isotope analyses of tests from the Forlandsundet section give an age of 27.5–29.5 m.y., i.e. early Late Oligocene (Table 1).

Two regional seismic reflectors have been identified within this zone (Fig. 5). The strong seismic reflector at about 1040 m coincides approximately with minor changes in the foraminiferal assemblage, but neither the fauna nor the strontium-isotope analyses indicate a major hiatus. A weak seismic reflector is noted at 1009 m, but there is no change in the foraminifera fauna across this reflector. The base of the BB-FD Zone also coincides with a regional seismic reflector.

UNZONED INTERVAL f3

Depth range: 1090–1270 m.

Material: 18 ditch cutting samples at 2–18 m intervals.

Age: Middle Eocene (based on other biostratigraphical evidence).

Assemblage: Very few foraminifera occur in this interval. Single specimens of the calcareous benthonic species: *A. tenuistriata*, *E. pygmeus*, *G. subglobosa* and *Cassidulina* sp. were recovered from the upper part of the interval. *Cibicides* spp. and *Nonionella spissa* were recovered from the lower part of the interval. Most of the calcareous specimens from the upper part of the interval are probably caved from the overlying section.

Agglutinated taxa are somewhat more numerous but generally poorly preserved. *Bathysiphon* sp. is the most common species, but *R. placenta*, *Spiroplectammina carinata*, *Glomospira* sp., *Reticulophragmium* sp., *Haplophragmoides* sp. and *Recurvoides* sp. are also present (Fig. 5).

Remarks: Many of the calcareous specimens in the lower part of the interval and most of the agglutinated forms are poorly preserved. This indicates that most of these are reworked. Most of these forams are long ranging stratigraphically. An exception to this is *N. spissa* which is known from the Middle Eocene of Belgium (Kaasschieter 1961) and *S. carinata* which is known from Lower Eocene to Lower Oligocene in the North Sea (Charnock & Jones 1990). Both of these forms are found as single specimens near the base of the interval.

CIBICIDES PROPRIUS – SPIROPLECTAMMINA NAVARROANA – PSEUDOHASTIGERINA MICRA – PSEUDOHASTIGERINA SP. ZONE

Category: Informal local partial range zone.

Designation: BB-FE.

Informal local boundary criteria: The top of the zone is taken at the highest occurrence of *S. navarroana* and *Pseudohastigerina* sp. The base of the zone is marked by the highest occurrence of *Vaginulinopsis decorata*.

Depth range: 1270–1465 m.

Material: Two conventional core samples from a depth of 1356.5–1363.6 m and 18 ditch cutting samples at 2–17 m intervals.

Age: Early Middle Eocene.

Equivalent zones: Zone NSP 7 of King (1989) and, questionably, Zone NSR 5A of Gradstein & Bäckström (1996).

Assemblage: Agglutinated foraminifera dominate the moderately rich fauna, but some calcareous taxa are also present. *R. placenta* is the most common agglutinated species, *S. navarroana*, *S. carinata*, *Bathysiphon* spp., *Reticulophragmium* spp., *Haplophragmoides* spp. and *Cribrostomoides* sp. are also present (Fig. 5).

Among the calcareous assemblages, benthonic species are most common, and *C. proprius* has the most consistent distribution. *Bulimina ovata*, *Cibicides* sp., *Pullenia* śp., *Alabamina* sp. and *Quinqueloculina impressa* have more sporadic occurrences. There are irregular occurrences of the planktonic species *Pseudohastigerina micra* and *Pseudohastigerina* sp.

Remarks: The calcareous foraminifera found in this zone are all previously described from Palaeogene deposits in western and central Europe. *C. proprius* is described from the Lower–Upper Eocene of The Netherlands (Doppert & Neele 1983) and Belgium (Kaasschieter 1961). *B. ovata* is described from the Lower Eocene of the DSDP Site 338 on the Vøring Plateau (Hulsbos et al. 1989) and from Upper Eocene deposits in Belgium (Kaasschieter 1961). *Q. impressa* is known from the Middle Eocene in The Netherlands and from Upper Eocene sediments in Belgium and England (Kaasschieter 1961).

The planktonic species *P. micra* was described from the Lower to Upper Eocene section of The Netherlands (Doppert & Neele 1983). King (1989) has described a *Pseudohastigerina* spp. (Zone NSP 7) from the lower Middle Eocene of the North Sea.

The agglutinated species *R. placenta* is described from the Lower Eocene to Upper Miocene of the North Sea (King 1989). *S. navarroana* is described from the Lower–Middle Eocene of the North Sea and Haltenbanken (Gradstein et al. 1994; Gradstein & Bäckström 1996). *S. carinata* is known from the Lower Eocene to Lower Oligocene in the North Sea (Charnock & Jones 1990). The other agglutinated taxa are characterized by long stratigraphic ranges including the Mesozoic and Palaeogene.

CIBICIDES PROPRIUS – VAGINULINOPSIS DECORATA – SPIROPLECTAMMINA NAVARROANA – PSEUDOHASTIGERINA MICRA ZONE

Category: Informal local total range zone.

Designation: BB-FF.

Informal local boundary criteria: The top and bottom of the zone are taken at the highest occurrence and lowest consistent occurrence of *V. decorata*.

Depth range: 1465–1572 m.

Material: Two conventional core samples from a depth of 1465–1472 m and 11 ditch cutting samples at approximately 10 m intervals.

Age: Early Middle Eocene.

Equivalent zones: Zone NSP 7 of King (1989) and questionably Zone NSR 5A of Gradstein & Bäckström (1996).

Assemblage: A rather rich foraminifera fauna of both calcareous and agglutinated species occur in the zone. The benthonic calcareous taxa include: *C. proprius*, *V. decorata*, *B. ovata* and *Anomalina ypresiensis* as the most common species. *Anomalina acuta*, *Alabamina midwayensis*, *Elphidium latidorsatum*, *Lenticulina cultrata*, *Planulina burlingtonensis* and *Pullenia quinqueloba* are also present (Fig. 5).

The only planktonic species, *Pseudohastigerina micra*, has a rare and sporadic distribution in Zone BB-FF.

The agglutinated fauna includes *R. placenta* and *S. navarroana*, which are the most common species and occur through the whole zone. *S. carinata*, *Bathysiphon* sp., *Reticulophragmium* sp. and *Cribrostomoides* sp. are also present.

Remarks: The previous known distribution of *C. proprius* and *B. ovata* in western and central Europe is described above under Zone BB-FE. *V. decorata* has been reported from Middle–Upper Eocene strata in The Netherlands (Doppert & Neele 1983) and Upper Eocene of Belgium (Kaasschieter 1961). *V. decorata* has a rare and sporadic distribution in Lower Eocene sediments on the Vøring Plateau (DSDP 338) (Hulsbos et al. 1989). *A. ypresiensis* and *A. acuta* are described from the Lower-Middle Eocene in Belgium (Kaasschieter 1961; Doppert & Neele 1983). *A. midwayensis* is described from the Upper Palaeocene–Lower Eocene in The Netherlands (Doppert & Neele 1983), while *E. latidorsatum* is reported from the Lower Eocene in Belgium (Kaasschieter 1961). *L. cultrata* is described from the Lower Eocene to Lower Oligocene (most common in the Middle Eocene) in The Netherlands (Doppert & Neele 1983). *P. burlingtonensis* is known from the upper Lower–Middle Eocene in The Netherlands (Doppert & Neele 1983), and from the Eocene in Belgium (Kaasschieter 1961). *P. quinqueloba* is described from Lower Eocene sediments on the Vøring Plateau (Hulsbos et al. 1989) and from the Upper Eocene in Belgium (Kaasschieter 1961).

The known stratigraphic ranges of *R. placenta*, *S. navarroana*, *S. carinata* and *P. micra* were discussed above under Zone BB-FE.

The recovered foraminifera fauna suggests an early Middle Eocene age for Zone BB-FF in 7316/5-1. A strontium-isotope analysis on the tests recovered in the core sample at 1472 m in the uppermost part of the zone give an age of 46–47 m.y., i.e. early Middle Eocene (Table 1 and Fig. 7).

SPIROPLECTAMMINA NAVARROANA – SPIROPLECTAMMINA CARINATA ZONE

Category: Informal local partial range zone.

Designation: BB-FG.

Informal local boundary criteria: The top of the zone is taken at the lowest consistent occurrence of *V. decorata*. The base of the zone is undefined.

Depth range: 1572–1600 m (lowest sample analysed).

Material: Four ditch cutting samples at 10 m intervals.

Age: Early Middle Eocene.

Equivalent zones: Questionably, Zone NSR 5A of Gradstein & Bäckström (1996).

Assemblage: The assemblage consists almost exclusively of agglutinated foraminifera. *R. placenta* dominates the fauna, but *S. carinata*, *S. navarroana*, *Bathysiphon* sp. and *Reticulophragmium* sp. are also important constituents. Only one specimen of the calcareous form *V. decorata* has been found in the uppermost sample (Fig. 5).

Remarks: The known stratigraphic ranges of *R. placenta*, *S. carinata* and *S. navarroana* were discussed above under Zone BB-FE. An early Middle Eocene age is inferred for the zone.

4.1.2 Dinoflagellate zones

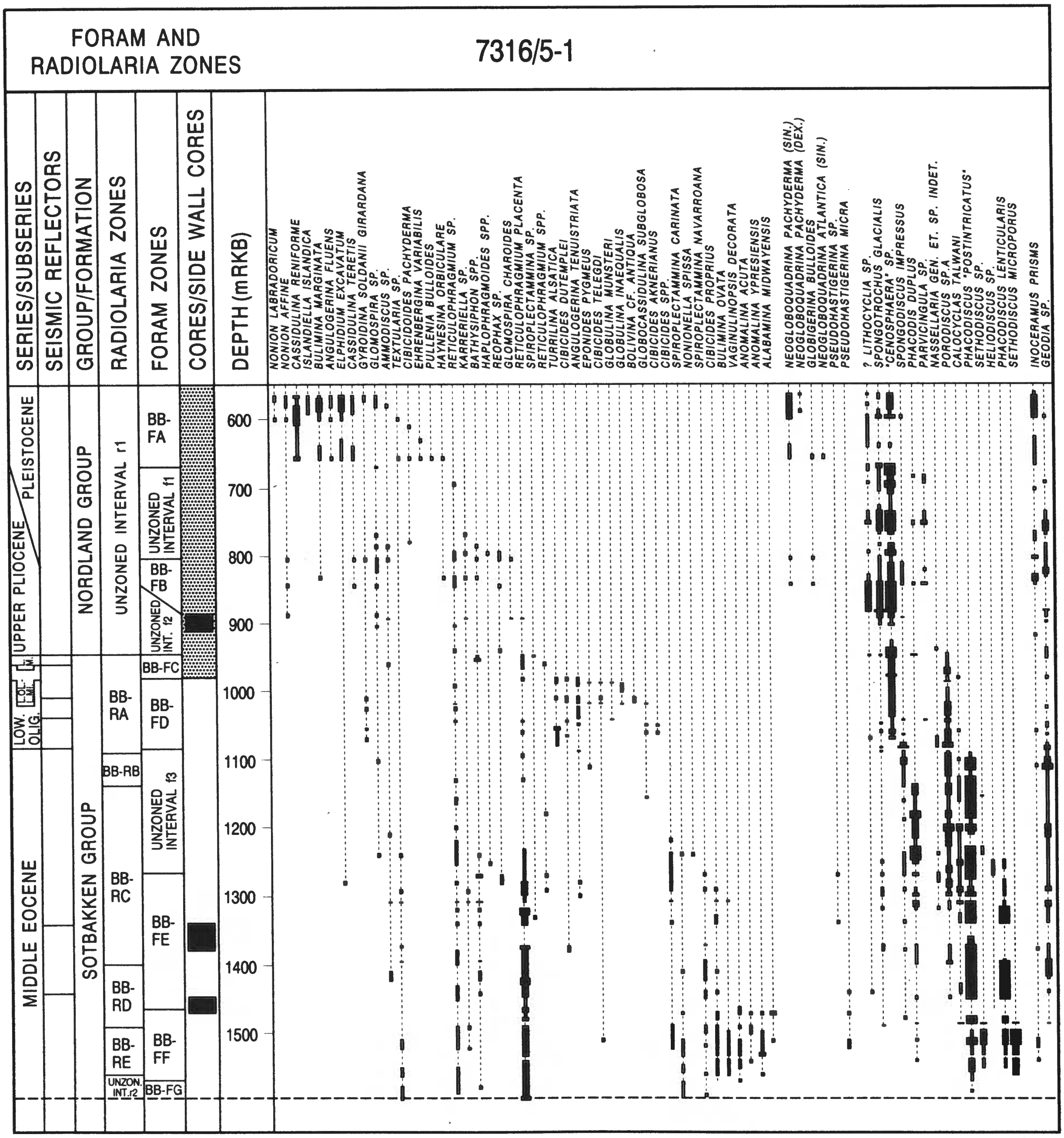
The dinoflagellate biostratigraphy as of well 7316/5-1 is partly correlated to the zonation defined in the ODP Leg 104, Site 643 on the Vøring Plateau (Manum et al. 1989; Mudie 1989). However, many of the stratigraphically important species described from ODP Leg 104, Site 643 have not been recovered in 7316/5-1, and the present correlations are thus regarded as tentative. The stratigraphic interval between 567 and 948 m contains only sporadic *in situ* dinoflagellates, and it has not been possible to make correlations to any of the Vøring Plateau dinoflagellate zones in this interval. Below 992 m four informal dinoflagellate zones are identified which are partly correlated to the zones defined by Manum et al. (1989) on the Vøring Plateau.

UNZONED INTERVAL d1

Depth range: 578–948 m.

Material: Five ditch cutting samples at 8–10 m intervals, 19 sidewall cores at 4–46 m intervals, 1 core at 905.2 m.

Assemblage: The interval between 567 and 948 m is rich in dinoflagellates (more than 140 species are identified), but only very few of these are interpreted to be *in situ*. Typical Pliocene–Pleistocene forms such as *Achomosphaera andalousiensis* (656 m) and *Bitectatodinium tepikiense* (676 m) are observed, but these species may also occur in the Miocene and Holocene. The rich and



Water depth: 454m MSL (477m RKB)

CORED INTERVAL

INTERVAL WITH SIDE WALL CORES

Fig. 5. Range chart of the most important foraminifera and radiolaria in the investigated interval of well 7316/5-1.

diversified dinoflagellate flora contains dominantly recycled Palaeogene (i.e. Upper Palaeocene–lowermost Eocene, Middle Eocene and Lower Oligocene) species, but there are also reworked Jurassic, Lower and Upper Cretaceous, and Miocene dinoflagellates in this Pleistocene–Upper Pliocene unit.

Remarks: Both *A. andalousiensis* and *B. tepikiense* are extant species (Harland 1992), and their stratigraphic ranges extend back to the Middle Miocene (mid-Serravalian Stage) and basal Miocene, respectively (Williams et al. 1993). These two very limited occurrences provide only marginal evidence of a broadly Neogene age for the upper part of the interval, which is inadequate for meaningful correlation. Therefore, the interval has not been zoned.

UNZONED INTERVAL d2

Depth range: 948–960 m.

Material: Two sidewall cores at 948 m and 955 m, one ditch cutting sample at 950 m.

Age: Early Miocene.

Assemblage: The interval contains a moderately rich and fairly diverse dinoflagellate flora, but only few of these are *in situ*. *Lejeunecysta hyalina* and *Apteodinium* sp. 1 occur in all three samples from the zone. *Pentadinium laticinctum* is found at 955 m. *Impagidinium patulum* occurs in the samples from 948 m and 950 m (Fig. 6). According to Manum et al. (1989) *I. patulum* does not occur in sediments older than Early Miocene in Leg 104, Site 643 on the Vøring Plateau. According to Powell (1992) the oldest occurrence of *I. patulum* coincides with the base of nannofossil biozone NN2. *Spiniferites pseudofurcatus* is noted in the samples from 950 m and 955 m. This species is common in the Lower Miocene, but is also found in older deposits.

Cordosphaeridium cantharellum is recorded at 948 m and 955 m. This species does not usually occur in sediments younger than Early Miocene (Powell 1992), and it does not occur above the Lower Miocene beds in Leg 104, Site 643 on the Vøring Plateau (Manum et al. 1989). The samples at 950 m and 955 m also contain *Invertocysta tabulata*. On the Vøring Plateau this species is restricted to the Lower Miocene (Manum et al. 1989). *Systematophora placacantha* has its youngest occurrence at 950 m. According to Powell (1992), this species does not usually range above the Middle Miocene. *Hystrichosphaeropsis obscura* noted at 955 m usually has a restricted occurrence in the Miocene (Powell 1992). The presence of *Problematicum* sp. IV Manum 1976 at 955 m is also noteworthy. Manum et al. (1989) found this species only in the Lower Miocene in Leg 104, Site 643 on the Vøring Plateau.

Recycled dinoflagellates in this zone include Upper Jurassic, Lower Cretaceous, Upper Cretaceous and Palaeogene taxa.

Remarks: The lowest occurrence of *I. patulum* is here found in the underlying zone due to caving. Both the upper and the lower boundary of the interval coincide with seismic reflectors. Across the upper boundary there is a marked lithological change.

UNZONED INTERVAL d3

Depth interval: 960–992 m.

Material: Four ditch cutting samples at 2–10 m intervals, one sidewall core at 970 m.

Assemblage: More than 50 species of dinoflagellates are recorded from this unit. Most of these are, however, reworked and no *in situ* forms which can be used for age determination of this interval were recorded. Species of unspecified Eocene–Early Oligocene age dominate the assemblages, but recycled Upper Palaeocene–lowermost Eocene, Upper Cretaceous and Lower Cretaceous species are also present.

Remarks: A general Early Oligocene to Early Miocene age is inferred for this zone based on its stratigraphic position in relation to the overlying Early Miocene interval and the underlying Early Oligocene BB-DA Zone.

ZONE BB-DA

Category: Informal local concurrent range zone.

Designation: BB-DA.

Informal local boundary criteria: Interval from lowest appearance of *Impagidinium* sp. 1 to the uppermost occurrence of *Chiropteridium mespilanum* at 992 m.

Depth range: 992–1010 m.

Material: Two ditch cutting samples at 992 m and 1000 m.

Age: Early Oligocene.

Equivalent zone: Partly time-equivalent to the *Impagidinium* sp. 1 Zone of Manum et al. (1989).

Assemblage: More than 30 species of dinoflagellates were recorded in this zone. Most of these are reworked from Eocene–Lower Oligocene deposits, but also recycled Cretaceous taxa have been found. *Chiropteridium mespilanum* occurs at 992 m (Fig. 6). This species is regarded as a stratigraphic marker typical for uppermost Lower Oligocene to lowermost Upper Oligocene strata (Powell 1992). In Leg 104, Site 643 on the Vøring Plateau this species is restricted to the Upper Oligocene *Systematophora* sp. 1 Zone of Manum et al. (1989). Strontium-isotope analyses from Zone BB-DA in 7316/5-1 give, however, an Early Oligocene age of ca. 35 Ma. This inconsistency may be explained by the diachronous appearance of the biostratigraphic marker fossils or that the age of the *Impagidinium* sp. 1 Zone on the Vøring Plateau is poorly constrained (in contrast to many of the other biozones in Leg 104, Site 643, there is no palaeomagnetic control on the age in this zone). It is also possible that the key fossil *Impagidinium* sp. 1 is caved at 1000 m in 7316/5-1. Since we have no firm evidence of Upper Oligocene deposits in the well, this latter explanation is not very likely.

Remarks: The lower boundary of Zone BB-DA coincides with a seismic reflector, which is rather poorly expressed at the drill site but becomes stronger towards the east.

ZONE BB-DB

Category: Informal local interval zone.

Designation: BB-DB.

Informal local boundary criteria: Interval from the lowest appearance of *Impagidinium* sp. 1 down to the appearance of *Glaphyrocysta paupercula* at 1080 m.

Depth range: 1010–1080 (1090) m.

Material: 13 ditch cutting samples at 3–15 m intervals, 1 sidewall core at 1022 m.

Age: Early Oligocene.

Equivalent zone: Partly time-equivalent to the *Areosphaeridium*? *actinocoronatum* Zone of Manum et al. (1989).

Assemblage: Zone BB-DB contains a moderately rich and fairly diverse dinoflagellate microflora. Several of the recorded species have a relatively broad stratigraphic range in the Palaeogene, and the frequency relation between *in situ* Oligocene forms and reworked Eocene specimens is difficult to determine. *Lejeunecysta hyalina* has a consistent appearance through the zone. Other common species are *Apteodinium* sp. 1, *Deflandrea phosphoritica*, *Wetzeliella articulata*, *Systematophora ancyrea*, *Cribroperidinium giuseppei*, *Phthanoperidinium amoenum*, *Spiniferites pseudofurcatus*, *Cordosphaeridium cantharellum* and *Palaeoperidinium* sp. 1 (Fig. 6). Among these *Cribroperidinium giuseppei*, *Phthanoperidinium amoenum* and *Wetzeliella articulata* are not usually found in sediments younger than Early Oligocene. The occurrence of *Deflandrea* sp. B at 1020 m could also be of some stratigraphic significance, as this species is not found above the *Areosphaeridium*? *actinocoronatum* Zone in Leg 104, Site 643 on the Vøring Plateau (Manum et al. 1989). The presence of *Glaphyrocysta paupercula* at 1080 m is indicative of an an Early Oligocene age at this level. According to Powell (1992) this species is restricted to the earliest Oligocene RPe Zone.

Reworked dinoflagellates of definite Eocene age are fairly common in the zone, and include species restricted to the Middle Eocene. In addition, typical Upper Palaeocene-lowermost Eocene, Upper Cretaceous and Lower Cretaceous species are found at several levels.

Remarks: On the Vøring Plateau the *Areosphaeridium*? *actinocoronatum* Zone of Manum et al. (1989) is interpreted to cover the upper Lower Oligocene and lower Upper Oligocene strata. In 7316/5-1 *Reticulatosphaera actionocoronata* has a single occurrence at 1080 m. An Early Oligocene age of 35 Ma for Zone BB-DB is determined from strontium-isotope analyses. The lower boundary of the Lower Oligocene sequence probably extends down to the seismic reflector at 1090 m.

ZONE BB-DC

Category: Informal local interval zone.

Designation: BB-DC.

Informal local boundary criteria: The lower boundary is recognized by the lowest appearance of *Areosphaeridium arcuatum*. The upper boundary coincides with the appearance of *G. paupercula*.

Depth range: 1080 (1090)–1240 m.

Material: 12 ditch cutting samples at 3–20 m intervals.

Age: Middle Eocene.

Equivalent zone: Partly the *Areosphaeridium arcuatum* Zone of Manum et al. 1989.

Assemblage: The zone contains a moderately rich and diverse dinoflagellate flora (more than 50 species are recorded). *Deflandrea phosphoritica*, *Lejeunecysta hyalina*, *Wetzeliella articulata*, *Phthanoperidinium amoenum*, *Apectodinium homomorphum*, *Homotryblium tenuispinosum* and *Dapsilidinium simplex* are most common. Other characteristic species are *Systematophora ancyrea*, *Hystrichosphaeridium tubiferum*, *Kisselovia clathrata*, *Nummus* sp. A, *Cerebrocysta bartonensis*, *Adnatosphaeridium vittatum*, *Spiniferites pesudofurcatus*, *Cordosphaeridium cantharellum*, *Spiniferites sp.* 2 Manum et al. 1989, *Heteraulacacysta leptalea*, *Lentinia serrata* and *Samlandia chlamydophora* (Fig. 6). The oldest occurrence of *Corrudinium incompositum* at 1120 m might be of some stratigraphic significance. This species usually has its oldest occurrence in the Middle Eocene, i.e. in sediments correlatable to nannoplankton Zone NP 16 (Powell 1992).

Remarks: As discussed for Zone BB-DB the boundary between Zones BB-BD and BB-DC probably should be placed at the seismic reflector at 1090 m. Considerably fewer reworked specimens are found in this zone compared with the younger zones above. The presence of *Apectodinium quinquelatum* is evidence that Upper Palaeocene–lowermost Eocene strata have been redeposited into this Middle Eocene sequence. As in the overlying zones, recycled Cretaceous dinoflagellates are found at several levels in Zone BB-DC.

ZONE BB-DD

Category: Informal local interval zone.

Designation: BB-DD.

Informal local boundary criteria: Interval from the lowest appearance of *Adnatosphaeridium vittatum* to the lowest appearance of *Areosphaeridium arcuatum*.

Depth range: 1240–1600 m (lowermost studied sample).

Material: 32 ditch cutting samples at 3–20 m intervals, 4 sidewall cores at 1356.5 m, 1363.6 m, 1367.5 m and 1472.1 m.

Age: Middle Eocene.

Equivalent zone: Partly the *Adnatosphaeridium vittatum* Zone of Manum et al. (1989).

Assemblage: A rather rich and diverse (more than 70 species recorded) dinoflagellate flora has been recovered from this zone. Species which are common and have a fairly consistent appearance through the zone are: *Deflandrea phosphoritica*, *Lejeunecysta hyalina*, *Wetzeliella articulata*, *Cribroperidinium giuseppei*, *Phthanoperidinium amoenum*, *Thalassiphora delicata*, *Apectodinium homomorphum*, *Nummus* sp. A, *Adnatosphaeridium vittatum*, *Heteraulacacysta leptalea* and *Lentinia serrata*. Other characteristic species are: *Phthanoperidinium comatum*, *P. geminatum*, *P. levinumum*, *Areosphaeridium dictyoplokus*, *Deflandrea denticulata*, *Thalassiphora pelagica*, *Glaphyrocysta ordinata*, *Kisselovia clathrata*, *Dapsilidinium simplex*, *Pentadinium laticinctum*, *Lejeunecysta fallax*, *Selenopemphix nephroides*, *Spiniferites pseudofurcatus*, *S. cornutus*, *Caligodinium amiculum* and *Araneosphaera araenosa* (Fig. 6).

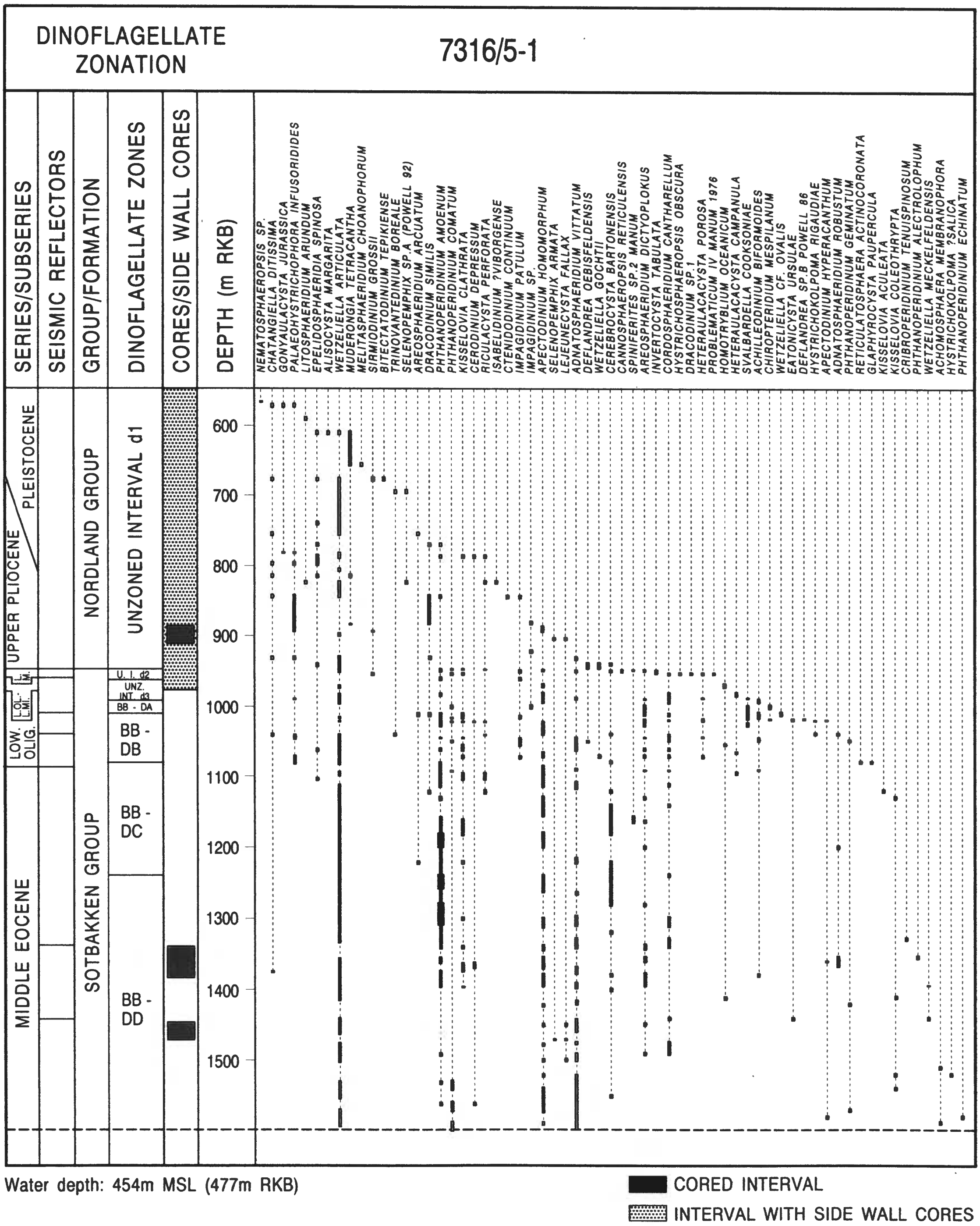


Fig. 6. Range chart of the most important dinoflagellates in the investigated interval of well 7316/5-1.

Remarks: The occurrences of *Phthanoperidinium comatum* (1600 m) and *P. geminatum* (1572) in the lowermost studied part of the zone suggest an age not older than Middle Eocene. The oldest occurrence of *Homotryblium oceanicum* at 1412 m is also evidence of an age not older than Middle Eocene at this level. Wetzeliella meckelfeldensis which is recorded at 1397 m, does not usually occur above the Middle Eocene (Powell 1992). The youngest *in situ* appearances of *Thalassiphora delicata* at 1300 m and *Eatonicysta ursulae* 1440 m also indicate an age not younger than Middle Eocene. The oldest occurrence of *Cerebrocysta bartonensis* is noted at 1400 m. Normally, this species first appears in the Middle Eocene. In Leg 104, Site 643 on the Vøring Plateau *C. bartonensis* is restricted to the *Adnatosphaeridium vittatum* Zone (Manum et al. 1989).

The proportion of reworked dinoflagellates is low in Zone BB-DD compared with in the overlying post-Eocene zones in the well. There is, however, evidence of reworking from the Upper Palaeocene–lowermost Eocene, Upper Cretaceous and Lower Cretaceous into these Middle Eocene deposits in 7316/5-1.

4.1.3 Radiolaria zones

Five new radiolaria zones are defined for the section in 7316/5-1, based on the distribution of 14 species. All of the observed specimens are in the opal-CT recrystallized phase or are pyrite replacements. Consequently, the preservation state is inadequate for detailed taxonomy, although internal structures are partially visible on some specimens. There are distinctive changes in this limited assemblage that permit biostratigraphic zonation, and it is clear that further studies will improve the chronostratigraphic resolution of these Radiolaria.

Five of the taxa in this assemblage have not been previously observed elsewhere, and their stratigraphic ranges are unknown: ?*Lithocyclia* sp., *Porodiscus* sp. A, *Nasellaria* gen. et sp. indet., *Sethmodiscus microporus* Haeckel 1887, and *Sethmodiscus* sp. Of these, *Porodiscus* sp. A and *Sethmodiscus microporus* are the nominate taxa and boundary criteria for two new zones. The remaining fauna has been observed in sediments from the Vøring Plateau or the North Sea. Seven of these taxa: ?*Lithocyclia* sp., *Spongodiscus impressus* Lipman 1952, *Phacodiscus duplus* Kozlova 1966, *Phacodiscus 'postintricatus'*, *Phacodiscus lenticularis* (Grzybowski 1896), *Sethmodiscus microporus* and *Sethmodiscus* sp. are commonly identified as ?spherical Radiolaria or *Cenosphaera* sp. by other micropalaeontologists. However, the assemblage so designated represents a taxonomically diverse collection of species, none of which met the generic definition of *Cenosphaera*. This name is totally unsuitable for these multichambered species, and a taxonomic revision is clearly necessary. The designation, '*Cenosphaera*' sp., is used here only for pyritized internal moulds lacking any indication of pore morphology, which are common to abundant in the glaciomarine sediments at this locality.

UNZONED INTERVAL r1

Depth: 567–948 m.

Assemblage: The most conspicuous member of this assemblage is '*Cenosphaera*' sp., which is abundant in 11 samples from this interval and is the dominant microfossil in the samples at 695, 739 and 754 m. ?*Lithocyclia* sp. and *Spongotrochus glacialis* have more consistent distributions in this interval than in the underlying section, where occurrences may result from caving. Specimens of both species are poorly preserved. There are six rare or common occurrences of the Cretaceous genus, *Parvicingula*, in this interval, and the pyritized specimen at 1045 m is regarded as caved.

Remarks: This interval has been dated as Late Pliocene–Pleistocene in age on the basis of foraminifera, but no indisputable Neogene Radiolaria have been observed. Opal-CT replaced Radiolaria of Cretaceous to Eocene age are variably abundant in this section and indicate extensive sediment redeposition from sources previously buried at depths exceeding 1500 m.

Spongotrochus glacialis is extant, and well-preserved specimens are common in Cenozoic siliceous sediments of the Norwegian Sea. The affinities and age of ?*Lithocyclia* sp. are unknown. Abundant occurrences of '*Cenosphaera*' sp. have been observed (RMG) in sediments of the Central Graben correlative with NSP 5 Zone of King (1989). The presence of abundant specimens of this problematical species is an indication of extensive redeposition of Lower Eocene sediments.

PORODISCUS SP. A ZONE

Category: Partial range zone.

Designation: BB-RA.

Definition: The top of the zone is taken at the highest occurrence of *Porodiscus* sp. A. The base of the zone is taken at the highest occurrence of *Phacodiscus 'postintricatus'*.

Status: new.

Depth range: 948–1095 m.

Material: Five sidewall cores from a depth of 948–1022 m and 21 ditch cutting samples at 2–10 m intervals.

Age: Early Miocene to Early Oligocene (based on other biostratigraphical evidence).

Equivalent zones: *Lithomitra* sp. A Zone of Bjørklund (1976) to *Eucyrtidium saccoi* Zone of Goll & Bjørklund (1989). Units VI to IX of Dzinoridze et al. (1978).

Assemblage: Radiolaria are consistently rare to common throughout this interval, with abundant and dominant occurrences restricted to the top and bottom of the zone. '*Cenosphaera*' sp. and *Porodiscus* sp. A are the only taxa with consistent occurrences. '*Cenosphaera*' sp. is rare to abundant in the interval 948 m (swc)–1070 m (dc). *Spongotrochus glacialis* has an irregular distribution in the interval 950 m (dc)–1092 m (dc). The top of the consistent range of *Spongodiscus impressus* occurs at 1080 m (dc) (Fig. 5).

Probable reworked occurrences include: the two single-specimen occurrences of *Calocyclas talwani* at 982 and 1060 m; the rare occurrence of *Parvicingula* sp. at 1045 m; and the rare occurrence of *Phacodiscus duplus* at 1045 m (dc). The rare occurrence ?*Lithocyclia* sp. is not regarded as *in situ*.

Remarks: Hughes (1981) reports consistent occurrences of '? spherical Radiolaria' in a borehole section from the southern North Sea (Flemish Bight) dated as Early Rupelian (his zones A–D). Although the photograph is of inadequate quality for conclusive identification, the faceted and somewhat angular shape of the '? spherical Radiolaria' (Hughes 1981, pl. 15.3, fig. 16) has similarities to *Porodiscus* sp. A and can be regarded as a weak indication of an Early Oligocene age for the *Porodiscus* sp. A Zone. However, *Porodiscus* sp. A has not been observed in the Lower Oligocene *Lithomitra* sp. A Zone of DSDP Site 337 (Bjørklund 1976; RMG, pers. obs.).

Both the top and bottom of this zone are approximately coincident with regional seismic reflectors, and both contacts are probably disconformable.

The consistent distribution of '*Cenosphaera*' sp. in frequencies ranging from rare to abundant in both ditch cutting and sidewall cores suggests that these occurrences are not the result of caving. Redeposition of significant quantities of Lower Eocene sediment must have occurred during the *Porodiscus* sp. A Chron.

PHACODISCUS 'POSTINTRICATUS' ZONE

Category: Partial range zone.

Designation: BB-RB.

Definition: The top of the zone is taken at the highest consistent occurrence of *Phacodiscus 'postintricatus'*. The base of the zone is taken at the highest occurrence of *Phacodiscus duplus*.

Status: new.

Depth range: 1095–1130 m.

Material: Five ditch cutting samples at 7–10 m intervals.

Age: Middle Eocene.

Equivalent zones: *Artostrobus quadriporus* Zone of Bjørklund (1976). Unit V of Dzinoridze et al. (1978).

Assemblage: Radiolaria are generally more numerous in this interval than in the *Porodiscus* sp. A Zone, but they are not present in the dominant frequencies that characterize some horizons in the two immediately underlying zones. The most conspicuous representatives of this zone are: *Phacodiscus 'postintricatus'*, *Spongodiscus impressus* Lipman and *Porodiscus* sp. A. Occurrences of *Calocyclas talwani* at 1103 and 1130 m are regarded as reworked (Fig. 5).

Remarks: *P. 'postintricatus'* does not occur in the *Calocyclas talwanii* and *Lophocorys norwegiensis* zones (Bjørklund 1976) of DSDP Site 338 (RMG; pers. obs.). Zone BB-RB is interpreted as stratigraphically younger than the *L. norwegiensis* Chron and is probably correlative with Zone NP 17 of Martini (1971). The *P. 'postintricatus'* Zone assemblage has not be observed in a continuously cored interval and consequently is poorly understood.

Phacodiscus 'postintricatus' differs from '*Cenosphaera*' sp. in its larger size, more discoidal shape and the surface preservation of pore morphology, which has been described as 'reticulate' by some authors.

PHACODISCUS DUPLUS ZONE

Category: Total consistent range zone.

Designation: BB-RC.

Definition: The top and base of the zone are defined at the highest consistent occurrence and lowest consistent occurrences of *Phacodiscus duplus*.

Status: new.

Depth range: 1130–1400 m.

Material: Two samples from core 2 at 1356.5 and 1363.6 m and 22 ditch cutting samples at 2–18 m intervals.

Age: Middle Eocene.

Equivalent zones: No clear equivalents on the Vøring Plateau.

Assemblage: Radiolaria are more numerous in this interval than in the two overlying zones, as a result of abundant occurrences of *Phacodiscus duplus*, *Phacodiscus 'postintricatus'* and *Porodiscus* sp. A. Radiolaria diversity is highest in this zone (9 species), which is partly the result of very extensive caving artefacts. All of the rare-to-abundant occurrences of *P. 'postintricatus'* and *Porodiscus* sp. A are interpreted as the result of caving. Additionally, the sporadic occurrences of *Spongodiscus impressus*, indeterminate Nassellaria, and very poorly preserved *Spongotrochus glacialis* may also be caved. *P. duplus* is absent at 1260 and 1280 m. *Calocyclas talwani* is rare to common and relatively consistent in its occurrence, particularly below 1200 m (dc). The rare occurrences of *Heliodiscus* sp. in the ditch cuttings at 1252, 1260, and 1270 m may be *in situ*. *Phacodiscus lenticularis* persists in reduced frequencies in the lower part of zone up to 1232 m (Fig. 5).

Remarks: The application of a stratigraphic first occurrence as a zonal boundary criterion is risky in a section controlled largely by ditch cutting samples, particularly in sections characterized by extensive caving artefacts. The distribution of *P. duplus* is disrupted by the sand unit at 1340–1365 m, where *in situ* radiolaria are very rare and *P. duplus* is absent. Otherwise, *P. duplus* has an essentially consistent occurrence in this section, and its base is clearly defined.

The occurrence of *P. duplus* at DSDP Site 338 is restricted to the base of the *Calocyclas talwani* Zone (Core 29, core catcher; RMG, pers. obs.), which coincides with a hiatus of long duration. A reliable age for the base of the *C. talwani* Zone cannot be determined on the basis of DSDP and ODP recovery. Goll (1989) placed the base of the *C. talwani* Zone at mid-Zone NP16 (of Martini 1971), and we conclude that the *P. duplus* Zone is correlative with the interval from upper Zone NP15 to lower Zone NP16. *P. duplus* has also been observed in Nordland Ridge well 6610/7-1 (RMG, pers. obs.).

Phacodiscus duplus differs from *P. 'postintricatus'* in its larger size and smooth-walled cortical lattice shell which is densely perforated by small, regularly spaced pores. Specimens of *P. duplus* in 7316/5-1 are invariably recrystallized, and the internal skeletal morphology cannot be determined. However, well-preserved specimens in the opal-A phase have been observed from the Vøring Plateau.

PHACODISCUS LENTICULARIS ZONE

Category: Interval zone.

Designation: BB-RD.

Definition: The top of the zone is taken at the lowest consistent occurrence of *Phacodiscus duplus*. The base of the zone is taken at the highest occurrence of *Sethodiscus microporus*.

Status: new.

Depth range: 1400–1490 m.

Material: Two samples from core 3 at 1465 and 1472 m, and 9 ditch cutting samples at 3–10 m intervals.

Age: Middle Eocene.

Equivalent zones: No clear equivalents on the Vøring Plateau.

Assemblage: *Phacodiscus lenticularis* has rare to abundant occurrences in this zone, but this species was not observed in the conventional core samples, which are essentially barren of radiolaria. Additionally, the species was not observed at 1375 m (dc) and 1380 m (dc). The rare occurrences of *Calocyclas talwanii* at 1432 m (dc) and 1442 m (dc) may be *in situ*, as the correct advent level of this species is unknown. The same is true of *Spongodiscus impressus*, which has four rare occurrences in the interval 1340 m (dc)–1480 m (dc). All other occurrences are regarded as displaced. These include five irregular rare occurrences of *Parvicingula* sp. in the interval 1320–1380 m and the rare occurrence of ?*Lithocyclia* sp. at 1432 m (dc), all of which are interpreted as being reworked. Caving artefacts include: common to abundant occurrences of *Phacodiscus 'postintricatus'* throughout the zone; five rare–common occurrences of *Porodiscus* sp. A in the interval 1375 m (dc)–1450 m (dc); and three rare occurrences of ?*Spongotrochus glacialis* in the interval 1320 m (dc)–1380 m (dc) (Fig. 5).

Remarks: *Phacodiscus lenticularis* is the species referred to as *Cenosphaera* sp. by King (1989), and abundant occurrences of this taxa characterize the upper portion of Zone NSP 6. In the Barents Sea region, *P. lenticularis* clearly ranges in variable frequencies well above the top of Zone NSP 6, and abundant occurrences of this species in 7316/5-1 must represent a second younger acme, probably in Zone NSP 7. *P. lenticularis* has also been observed (RMG) in the lower Middle Eocene section of 7316/6-U-2.

The sponge *Geodia* has its lowest consistent occurrence (1442 m) in the *P. lenticularis* Zone. Specimens occurring in this zone, in the *Phacodiscus duplus* Kozlova 1966 Zone and the *Phacodiscus 'postintricatus'* Zone are small with hollow centres, and are observable only under transmitted light.

SETHODISCUS MICROPORUS ZONE

Category: Total range zone.

Designation: BB-RE.

Definition: The top and base of the zone are taken at the highest and lowest occurrence of *Sethodiscus microporus*.

Status: new.

Depth range: 1490–1562 m.

Material: Eight ditch cutting samples at 10 m intervals.

Age: Middle Eocene (based on other biostratigraphical evidence).

Equivalent zones: No clear equivalents on the Vøring Plateau.

Assemblage: *Sethodiscus microporus* is common to abundant in all eight samples from this zone. Other specimens recorded as *Sethodiscus* sp. are poorly preserved, but may also belong to this species. Consequently, the *in situ* assemblage is regarded as monospecific. All other occurrences are interpreted as caving artefacts. These latter occurrences include: rare to common *Phacodiscus lenticularis* in the interval 1490–1552 m; rare to abundant *Phacodiscus 'postintricatus'* in the interval 1490–1590 m; rare *Calocyclas talwani* and *Spongotrochus glacialis* sp. at 1490 m; and rare *Phacodiscus duplus* at 1490, 1512, and 1542 m (Fig. 5). Radiolaria are progressively more poorly preserved and less frequent with increasing depth.

UNZONED INTERVAL r2

Depth: 1562–1600 m.

Material: Five ditch cutting samples at 10 m interval.

Age: Middle Eocene (based on other biostratigraphical evidence).

Assemblage: Radiolaria are absent from this interval, with the exception of rare specimens of *Phacodiscus 'postintricatus'* at 1572 and 1590 m, which are regarded as caved.

4.2 The outcrop at Balanusviken, Sarsbukta, western Spitsbergen

Feyling-Hanssen & Ulleberg (1984) described an 8-m-thick section of Oligocene micaceous claystone cropping out under glaciomarine overburden in a coastal cliff at Balanusviken, Sarsbukta, on the east side of Forlandsundet (Fig. 2). On the basis of the foraminiferal assemblages in seven samples, these authors divided the section into two zones: the overlying *Asterigerina gurichi* Zone (TB) and the underlying *Bolivina* cf. *antiqua* Zone (TA). Among a composite assemblage of 22 taxa for the entire section, Zone TA is distinguished by occurrences of the nominate species as well as *Gyroidina s. mamillata* and *Rotaliatina bulimoides*. Zone TB is distinguished by occurrences of the nominate species as well as *Angulogerina* *gracilis*, *A. tenuistriata*, *Pullenia quinqueloba*, *Alabamina tangentialis* and *Epistominella oveyi*. Feyling-Hanssen & Ulleberg (1984) assigned a transitional Middle to Late Oligocene age to this entire section, and indicate an age equivalent to Subzones NSB 7a-NSB 8a according to King (1989).

Although the foraminiferal assemblage in Zone BB-FD of 7316/5-1 differs from that of the Balanusviken section in its generally lower diversity and poorer preservation, occurrences of *Turrilina alsatica*, *Angulogerina tenuistriata*, *E. pygmeus* and *Bolivina* cf. *antiqua* indicate a strong correlation.

New dinoflagellate cyst analyses are presented here for splits of two samples provided by Feyling-Hanssen & Ulleberg (sample 228 from Zone TB and sample 248 from Zone TA). The taxa identified in each sample are:

Sample 228: *Cribroperidinium giuseppei*, *Cordosphaeridium cantharellum*, *Deflandrea heterophlycta*, *Distatodinium paradoxum*, *Lentinia wetzelii*, *Palaeocystodinium* spp., *Phthanoperidinium comatum*, *Spiniferites ramosus*, *Spiniferites* sp. 2 (Manum et al. 1989), *Systematophora ancyrea* and *Systematophora placacantha*.

Sample 248: *Apteodinium* sp. 1, *Areosphaeridium arcuatum*, *Cometodinium* sp. 1, *Cribroperidinium giuseppei*, *Cordosphaeridium cantharellum*, *Cleistosphaeridium*? *insolitum*, *Deflandrea phosphoritica*, *Lejeunecysta hyalina*, *Spiniferites ramosus*, *Spiniferites pseudofurcatus*, *Systematophora ancyrea* and *Wetzeliella articulata*.

With the exceptions of *D. heterophlycta*, *Apteodinium* sp. 1, and *Cometodinium* sp. 1, all of the above taxa occur in the section at 7316/5-1. Extensive reworking of older Palaeogene taxa into Oligocene sediments is indicated at both localities.

The species, *C. giuseppei* and *W. articulata*, in sample 248 are normally indicative of an age not younger than the earliest Oligocene. Co-occurrences of *A. arcuatum* and *P. comatum* limit the assemblage to the range Middle Eocene to Lower Oligocene according to Manum et al. (1989) and Powell (1992). Although the stratigraphic ranges of *Systematophora placacantha*, *Cordosphaeridium cantharellum*, *Deflandrea phosphoritica* and *Spiniferites pseudofurcatus* extend above the Lower Oligocene, no dinoflagellates have been observed in the two samples from the Balanusviken section that provide conclusive

Table 1. Strontium isotope results from well 7316/5-1 and from Balanusviken at Forlandsundet on Spitsbergen. The $^{87}Sr/^{86}Sr$ ratio of the NBS 987 standard was 0.710240 ± 0.000011 during the sample analyses. Ages based on the time scales of both Berggren et al. (1985) and Cande & Kent (1995) are presented.

Sample ID	Well level	$^{87}Sr/^{86}Sr + 2$ sigma	Age (m.y.) (Berggren et al. 1985)	Age (m.y.) (Cande & Kent 1995)
7316/5-1				
A_1	987–1015 m	0.707791 ± 0.000011	ca. 35	32.8
A_2	987–1015 m	0.707795 ± 0.000008	ca. 35	32.8
B	1050–1070 m	0.707803 ± 0.000038	ca. 35	32.8
C_1	1472 m	0.707752 ± 0.000009	ca. 46–47	43.7–44.6
C_1	1472 m	0.707740 ± 0.000010	ca. 46–47	43.7–44.8
C_1	1472 m	0.707720 ± 0.000012	ca. 46–47	43.7–44.8
Fordlandsundet				
228M		0.708025 ± 0.000013	ca. 27.5	26.4
244M		0.707946 ± 0.000012	ca. 29.5	28.2
248M		0.707936 ± 0.000011	ca. 29.5	28.2
19M		0.707952 ± 0.000010	ca. 29.5	28.2

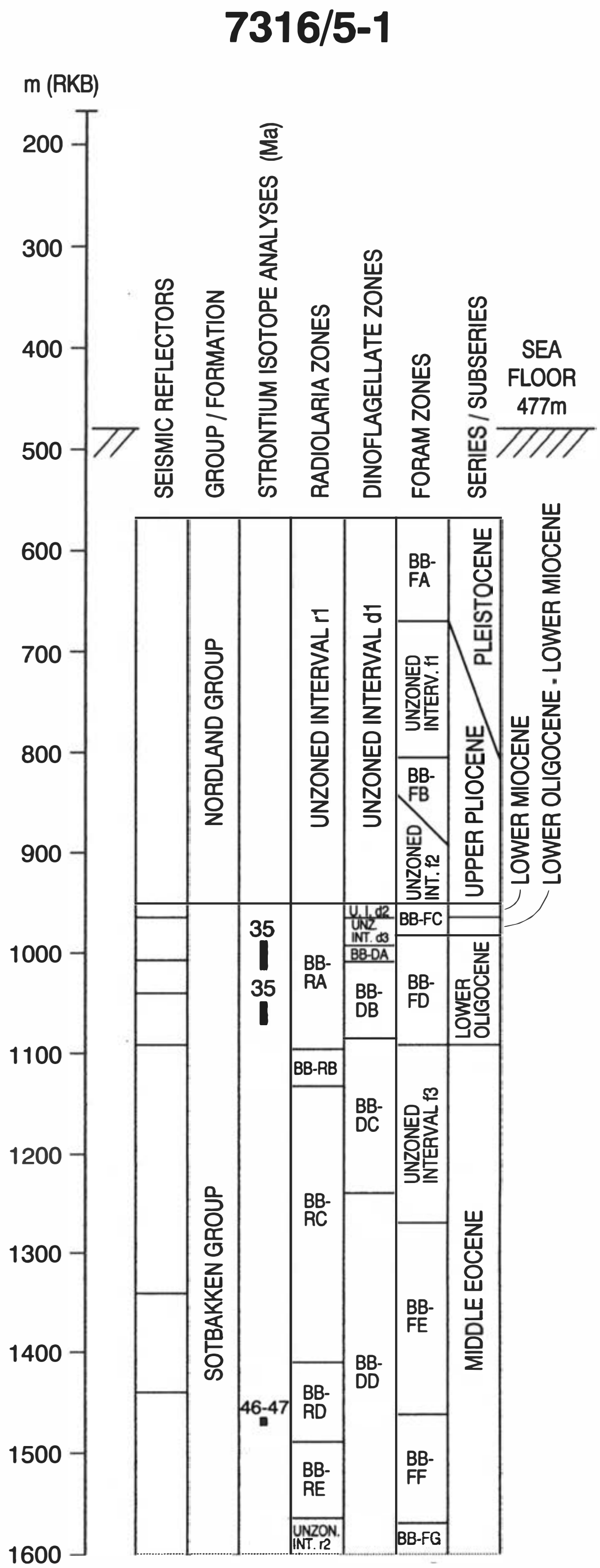


Fig. 7. Fossil zones, seismic reflectors, litostratigraphical groups, and levels investigated with strontium isotope analyses in well 7316/5-1.

evidence of a Late Oligocene or younger age. Based on the results of the strontium-isotope analyses described below, we conclude that most of the recovered specimens are reworked from Eocene and/or lowermost Oligocene deposits into the lowermost Upper Oligocene at this locality.

Manum & Throndsen (1986) proposed an age not younger than Late Eocene for the Balanusviken section based on the co-occurrence of *Cribroperidinium giuseppei*, *Kisselovia crassiramosa* and *Svalbardella cooksoniae*. Both *C. giuseppei* and *S. cooksoniae* occur in the Sotbakken Fm. of 7316/5-1 and are reported to range into the Lower Oligocene (Powell 1992). However, *K. crassiramosa* has a very restricted range in the Lower Eocene *Wetzeliella meckelfeldensis* Zone (Wme), according to Powell (1992), and the species has not been observed in the section at 7316/5-1. This apparently aberrant occurrence at the Balanusviken locality is here interpreted as the result of the extensive older Palaeogene reworking that is so evident at both localities.

5. Strontium-isotope results

Strontium-isotope analyses were conducted by the Institute for Energy Technology, Kjeller, Norway, on calcareous material (i.e. tests of calcareous benthonic foraminifera) from five samples representing three different stratigraphic levels in 7316/5-1 and four samples from the Forlandsundet section on Spitsbergen described by Feyling-Hanssen & Ulleberg (1984) (Table 1). In order to avoid problems with cavings and reworking, we analysed only stratigraphically diagnostic fossils. Ages for these samples were obtained by comparing the $^{87}Sr/^{86}Sr$-ratio to a global strontium-isotope curve. The curve compiled by the Institute for Energy Technology, is based on data from DePaolo (1986), Depaolo & Ingram (1985), Hess et al. (1986), Hodell et al. (1989, 1990, 1991), Koepnick et al. (1985) and Palmer & Elderfield (1985). A curve for the Palaeogene based on data from well-dated strata in Denmark (Y. Rundberg, pers. comm. 1996) is also used.

Samples A_1 and A_2 were taken from the interval 987–1015 m. The closely similar Sr-ratios suggest the absence of contaminated or recycled material. The Sr isotope ratio of sample B is almost identical to those of samples A_1 and A_2 (Table 1), although sample B is from a stratigraphically lower horizon (foraminifera Zone BB-FD; 1050–1070 m). The strontium ratios of both these samples convert to an age of 35 Ma (i.e. Early Oligocene) on the basis of both the curve compiled by the Institute for Energy Technology and Y. Rundberg (pers. comm. 1996).

The similarity in the Sr-constitution between samples A_1-A_2 and B suggests that the relatively strong seismic reflector at 1040 m between these sample levels does not represent a hiatus of significant duration (Fig. 7).

Samples C_1-C_3 are from conventional core 3 at 1472 m. The very similar Sr-ratios correspond to an early Middle Eocene age of 46–47 Ma (Y. Rundberg, pers. comm. 1996).

All four samples analysed from the Balanusviken section on Spitsbergen indicate a Late Oligocene age. Samples 228 and 244 are from the TB Zone and samples 248 and 19 are from the TA Zone of Feyling-Hanssen & Ulleberg (1984) (Table 1). The $^{87}Sr/^{86}Sr$ ratios for samples 244, 248 and 19 are very similar and correspond to an age of 29.5 Ma. Sample 228 is from the top of the exposure, and its strontium ratio is equivalent to an age of 27.5 Ma.

6. Conclusions

6.1 Biostratigraphy and chronology

Pleistocene–Upper Pliocene (477–948 m). – The age of the clastic wedge of mainly glacigenic sediments recovered from between 477 and 948 m is basically determined by foraminifera. Foraminifera Zone BB-FA in 7316/5-1 corresponds to faunazone A in the wells 7117/9-1 and 7117/9-2 on the Senja Ridge, and 7119/7-1 in the Tromsø Basin (Eidvin et al. 1993), and is younger than 1.7 Ma. Foraminifera Zone BB-FB corresponds to faunazone D in 7117/9-1, and is of Late Pliocene age, but older than 2.3 Ma. Based on the high content of glacigenic material down to 948 m and correlation to the Vøring Plateau (Jansen & Sjøholm 1991; Jansen 1995), a maximum age of 2.6 Ma is assigned to the oldest Pliocene deposits in 7316/5-1.

Lower Miocene (948–960 m). – Sediments of Early Miocene age are sampled only at 950 m and 960 m. The foraminifera indicate only a general Early Miocene to Oligocene age for this interval, but the recovered dinoflagellates restrict these sediments to the Lower Miocene. There is a marked lithological and seismic boundary between this and the overlying unit. Lower Miocene sediments have previously not been reported from any exploration well on the western Barents shelf, but sediments of this age were recovered in the shallow borehole 7316/06-U-01 just east of well 7316/5-1 (Sættem et al. 1994).

Lower Miocene–Lower Oligocene (960–982 m). – The recovered *in situ* foraminifera and dinoflagellates indicate only a general Early Miocene to Oligocene age for this interval, and there is only a weak indication that some of the radiolaria are of Early Oligocene age.

Lower Oligocene (982–1090 m). – Foraminifera attributed to the *Turrilina alsatica-Angulogerina tenuistriata* Zone (BB-FD) and dinoflagellates attributed to Zones BB-DA and BB-DB, together with strontium-isotope ages obtained from 987–1015 m and 1050–1070 m, date this interval to the Early Oligocene.

It is possible that the uppermost part of this section and the overlying section are a condensed (Upper) Oligocene sequence; an interpretation that is supported by the seismic profile. However, this interpretation is not evident from the biostratigraphic data.

The base of this unit coincides with a strong seismic reflection, representing a major regional sequence boundary.

Middle Eocene (1090–1600 m, lowest studied sample level). – With the exception of the foraminifera in the Unzoned Interval f3, all the fossil groups obtained from this unit suggest a Middle Eocene age. Strontium isotope ages obtained at 1472 m give an age of 46–47 Ma, supporting the age determinations based on the microfossils and palynomorphs.

6.2 Palaeoenvironments

Pleistocene–Upper Pliocene. – Almost all samples from the Pleistocene–Upper Pliocene sequence in 7316/5-1 contain glacigenic material. The recovered microfossil and palynomorph assemblages consist dominantly (foraminifera) or almost exclusively (dinoflagellates) of recycled specimens, and the radiolaria fauna in this sequence contains only reworked forms. *In situ* foraminifera have been found in faunasones BB-FA and BB-FB, but between these zones and below faunazone BB-FB there are indeterminant intervals of almost exclusively redeposited forms.

Foraminifera Zone BB-FA is fairly rich in calcareous forms, amongst which the planktonic comprise a significant part. A large proportion of planktonic foraminifera in coastal areas indicate open marine and fairly deep water conditions. The significant concentration of *B. marginata* and common occurrence of *N. affine* also indicate fairly large water depths (Qvale & van Weering 1985; Mackensen et al. 1985). The unit comprising Zone BB-FA was probably deposited in an outer shelf environment. The content of polar species such as *E. excavatum* forma *clavata*, *C. reniforme*, *I. islandica*, *I. norcrossi*, *N. labradoricum*, and the complete dominance of *N. pachyderma* (sinistral) in the planktonic fauna indicate cold water conditions (Feyling-Hanssen 1983).

The Unzoned Interval f1 contains only sporadic calcareous foraminifera. The Pleistocene–Upper Pliocene sediments further to the south on the Norwegian shelf are, however, rich in calcareous forms. The absence of calcareous forms in this interval is probably due to carbonate dissolution. According to Hald et al. (1989) and Steinsund et al. (1991) dissolution of calcareous foraminifera follows the pattern of formation of heavy bottom water, created by the combination of sea ice and the influx of Atlantic water masses. The water becomes corrosive to $CaCO_3$ due to excess CO_2 from decomposition of organic matter on the shelf. The combination of low temperature and high salinity may explain this phenomenon in Recent and Upper Pleistocene deposits (Hald et al. 1989). This is probably also the case for the older Pleistocene and the Upper Pliocene sediments.

Foraminifera Zone BB-FB also contains some calcareous foraminifera, although fewer than in Zone BB-FA. This relatively low ratio of calcareous tests may also be attributed to carbonate dissolution. This possible selective dissolution of some tests impedes environmental interpretation due to the limited number of specimens. There are apparently fewer arctic forms compared to boreal species in Zone BB-FB. The content of planktonic foraminifera, and the presence of the benthonic species *N. affine*, *C. teretis* and *B. margarita* indicate open marine conditions and deposition at a water depth corresponding to the middle shelf or deeper.

The lower part of the Pleistocene–Upper Pliocene sequence (i.e. Unzoned Interval f2) is almost barren of calcareous for aminifera. As in the overlying Pleistocene–Upper Pliocene units most of the samples from this zone comprise a diamicton probably of mainly glaciomarine origin. In the middle part of this unit a cored sand unit is interpreted as a glaciofluvial meltwater delta. This indicates a fairly shallow environment for these sediments in the middle part of the unit.

Lower Miocene–Lower Oligocene. – Recycled microfossils and palynomorphs are common to dominant in the Miocene and Oligocene sequences of 7316/5-1.

In the Lower Miocene sequence the *in situ* occurrence of the dinoflagellate genera *Spiniferites*, *Systematophora*, *Invertocysta*, *Hystrichosphaeropsis*, together with *Impagidinium*, indicates an open marine environment and possible deposition on the middle to outer shelf. The occurrence of *Impagidinium*, *Systematophora* and *Spiniferites* in the Early Oligocene Zone BB-DA, and the occurrence of *Areosphaeridium*, *Spiniferites* and *Systematophora* in the Early Oligocene dinoflagellate Zone BB-DB, indicate similar depositional environments for these units.

The presence of only agglutinated foraminifera in Fauna Zone BB-FC indicates low oxic to dysoxic bottom conditions and the dissolution of any calcareous forms. According to Skarbø & Verdenius (1986), the presence of *R. placenta* indicates fairly deep water. The lack of planktonic foraminifera in the Early Oligocene Zone BB-FD suggests a restricted connection with the open ocean during the deposition of this unit. The benthonic fauna, however, contain forms associated with fairly deep water (i.e. *Bolivina* cf. *antiqua* and *Gyroidina s. girardana*), and also species linked to fairly shallow water depths (*T. alsatica* and *C. aknerianus*) (Skarbø & Verdenius 1986). Christensen & Ulleberg (1974) and Ulleberg (1985) described typical shelf faunas of benthonic calcareous foraminifera from Oligocene deposits in Denmark, with many of the species also recorded here. The previously mentioned Oligocene fauna from Forlandsundet (Spitsbergen) is also characterized as a typical shelf fauna. In conclusion, the foraminifera indicate deposition on the middle to outer shelf for the sediments comprising Zone BB-FC, and the middle part of the continental shelf for Zone BB-FD in 7316/5-1.

Middle Eocene. – The dinoflagellate floras are rich and fairly diverse in the Middle Eocene sequence. With the exception of the cored sand intervals between 1347.5–1374.4 m and 1460.5–1472 m, and in Zone BB-RE, radiolaria are also common in this unit. There is also a fairly rich foraminifera fauna, except in the Unzoned Interval f3 in the upper part of the Middle Eocene sequence. In Zone BB-FE agglutinated forms dominate, but a minor proportion of planktonic and benthonic calcareous forms also occur. In Zone BB-FF there is a fairly rich fauna of both agglutinated, calcareous benthonic and planktonic species, although the calcareous benthonic taxa are most common. Only agglutinated forms are recovered from Zone BB-FG.

The large concentration of radiolaria, which is generally associated with normal marine conditions with little water turbulence, indicates that much of the Middle Eocene sequence was deposited in relatively deep open marine environment. This interpretation is supported by the planktonic foraminifera in Zones BB-FE and BB-FF. Exceptions are the sand intervals mentioned above and the beds comprising radiolaria Zone BB-RE. The upper sand interval is interpreted as a shallow water deposit, while the lower is interpreted to represent turbidites. The sand layers contain few or no microfossils. Possible microfossils were probably winnowed from these high-energy deposits. However, within the turbiditic sand unit there are thin fine-grained layers which contain common microfossils. The benthonic foraminiferal taxa found throughout much of the Middle Eocene sequence are also indicative of fairly deep water conditions (Skarbø & Verdenius 1986).

The wide diversity of dinoflagellates, including the occurrence of *Areosphaeridium*, *Spiniferites*, *Systematophora* and *Hystrichokolpoma* (Zone BB-DD), indicates an open marine depositional environment. The fairly common occurrence of *Glaphyrocysta* and *Nummus* in the middle Zone BB-DD may indicate a somewhat more marginal marine setting for these sediments.

An outer to middle shelf environment is suggested for the Middle Eocene sequence; however, the upper sandy unit is thought to have been deposited in a significantly shallower marine environment. Low oxygen content may explain the paucity or absence of calcareous foraminifera in certain sections of the sequence.

6.3 *Tectonic history and geological evolution*

The Vestbakken volcanic province (Gabrielsen et al. 1990) is identified by a complex of acoustically opaque and high amplitude reflectors interpreted to originate from volcanic sequences. Prior to drilling of the well, the Early Eocene age for these rocks was correctly predicted by Eldholm et al. (1987), and interpreted as lava swarms and intrusives formed during the early stages of opening of the Norwegian–Greenland Sea. They interpreted the basin as lying above a thinned continental crust developed as part of a transtensional ('leaky transform') component of the regional early Tertiary dextral shear system which formed part of the progressive northward opening of the ocean basin (Faleide et al. 1988; 1996). The 'leaky transform' formed as the relative plate motion acted at an oblique angle to the curved incipient plate boundary as defined by older lineaments along which the opening was initiated (i.e. the Knølegga Fault and its associated subparallel feature, the 'eastern boundary fault') (Fig. 1).

Based on datings in well 7316/5-1 and the observed seismic correlation (this paper), the local geological evolution of the area may be summarized in seven stages as follows:

Stage 1 (Early–Middle Eocene)

After cessation of the volcanic and intrusive activity in the Early to Middle Eocene, the basin west of the 'eastern boundary fault' subsided rapidly, probably receiving predominantly fine-grained sediments from easterly provenance areas. It is possible that sediments at the well location represent the relatively distal facies of prograding wedges built out from the Knølegga and eastern boundary fault escarpments. There is some evidence of synsedimentary faulting possibly resulting from tectonically induced dewatering within this sequence. Two sandstone units (one interpreted to be of shallow marine origin; the other a slumped turbidite) are recorded in the upper part of the penetrated Middle Eocene sequence, perhaps reflecting increasing proximity to the sediment source area and/or greater activity along the fault systems.

The rapid thermal subsidence of local subbasins during the Middle Eocene is consistent with the interpreted stepwise northeasterly progradation of the spreading rift axis from Anomaly 24 time (ca. 55 Ma), and appears to have continued into the Oligocene (until Anomaly 13 time, 37–36 Ma). It is during this period that the 'leaky transform' model is most applicable.

Stage 2 (Late Middle Eocene–earliest Oligocene)

Upper Middle and Upper Eocene sediments, together with those of earliest Oligocene age, are absent in the well. East of the well location the hiatus is expressed as a subtle angular unconformity truncating older Middle Eocene sequences. It is not anticipated that this represents a period of major regional tectonism, rather that transpressive movements developed along the eastern boundary fault causing uplift and inversion of the downthrown flank. However, movements of this age are observed in the Vøring Basin, (H. Brekke, pers. comm. 1995), suggesting that there may also be a regional component. The sediments were consequently raised above the wave base, resulting in a period of mild erosion and non-deposition. This appears to have occurred in the period between 45 and 34 Ma, to some extent pre-dating, but also overlapping, the supposed initiation of the northwesterly direction of relative plate motion in the Norwegian–Greenland Sea (Anomaly 13 time, 37–36 Ma).

Stage 3 (Early Oligocene)
The Early Oligocene appears locally to have been a period of gentle subsidence accompanied by westerly tilting of the subbasin. East of the well location, intra-Oligocene reflectors appear to onlap the basal Oligocene unconformity from the west, and there is little or no evidence on seismic of significant sediment transport from the east.

Stage 4 (Late Oligocene–Early Miocene)
Upper Oligocene sediments are not proved in the well. There is no distinct hiatus or unconformity recorded locally on seismic at this level, and it is suggested that the sequence is severely condensed. This appears to have resulted from concurrent initial updoming and extensional faulting of the present PL 184-antiform, and subsidence along the downthrown flank of the 'eastern boundary fault'. It is, therefore, likely that an expanded sequence of Oligocene and Lower Miocene sediments was deposited and is now preserved in the eastern depression.

Gentle subsidence in the Early Oligocene (?34–30 Ma) was followed by a combination of reactivation of the Knølegga and its associated fault systems, and local differential subsidence during the Late Oligocene and Early Miocene (30–?20 Ma). At this time sea-floor spreading activity would have been well established to the west of the PL 184 area, promoting sedimentation in locally developed open marine basins formed between highs generated by the continuing structural readjustments to the new tectonic regime. A global eustatic lowering of sea level resulting from the initiation of the Antarctic glaciations (Vågnes et al. 1992) may also have exerted an influence in condensing Oligocene sequences, although it is not possible to quantify the relative magnitude of these events.

Stage 5 (Middle–Late Miocene)
The presence of a major intra-Lower Miocene sequence boundary in the well may be an indication of transgression across the high at this time. An interpretation of further Miocene sedimentation across the study area must remain speculative, although it is clear that stable deposition continued in the eastern depression and that regional depositional patterns appear to have involved an eastward migration of the shelf edge (as indicated by the shallow well 7316/6-U-1, Sættem et al. 1994). Two interpretations may be considered; either the PL 184 structure continued to form during the Middle to Late Miocene, resulting in a condensed sequence now removed from the high. The observed reactivation of some Oligocene faults may be cited as evidence of this, although the faulting may have occurred as late as Middle to Late Pliocene. In addition, doming due to transpression along older faults in Middle to Late Miocene times is also observed in the Vøring Basin (H. Brekke, pers. comm. 1995). Alternatively, subsidence and deposition may have developed regionally across the entire subbasin depositing approximately 500 m or more of sediments, also now removed by erosion.

Stage 6 (Miocene to Pliocene)
At some stage during the Middle to Late Miocene or Early to Middle Pliocene there was a net regional uplift of the Vestbakken province (presumably together with much of the present western Barents Sea area), accompanied by limited local reactivation of some of the Oligocene faults on the PL 184 structure. Easterly tilting was facilitated by subsidence of the hanging wall along the 'eastern boundary fault'. The precise regional background for this tectonic event (or events) is unclear, although thermal uplift associated with accelerated sea-floor spreading, together with glacio-isostatic tectonic cycles, may have been driving mechanisms. Evidence for local volcanic activity of Pliocene age (2–3 Ma) is recorded in shallow well 7316/3-U-1 (Mørk & Duncan 1993), and may lend support to the argument for a thermal component.

Stage 7 (Late Pliocene–Pleistocene)
Upper Pliocene glacial sediments rest unconformably on eroded Lower Miocene sediments at the well location. On seismic the unconformity dips at ca. 1.5° towards the west across the licence area. In the east this surface divides a younger from an older wedge of similar seismic character, the latter also resting unconformably on supposed Miocene sediments. The older wedge is not observed at the well location. Towards the west the younger unconformity erodes as deep as the equivalent of the Lower Oligocene sequence recorded in the well. That the present unconformity truncates progressively older sediments towards the west would suggest that the Stage 6 uplift involved an easterly tilt component, aided by reactivated movement along the hanging wall of the 'eastern boundary fault', assuming that the surface was originally flat.

Since the initiation of cyclic progradation of the Plio-Pleistocene wedges on the unconformity surface, westerly tilting has progressively reverted the PL 184 structure to its present position. Evidence for this is seen in the configuration of younger sequence boundaries within the main wedge, which itself has been eroded by at least two recent and distinct Quaternary erosional cycles seen as unconformities on seismic. This has been in part controlled by relative subsidence of the newly formed oceanic crust, enhanced by recent isostatic rebound of previously glaciated sediment source areas to the east. Earlier generations of similar wedges have undoubtedly been successively reworked by more intense cycles of glacially related sediment transport and deposition.

7. Discussion

The ages of the thick Cenozoic fan deposits on the western margin of the Barents Shelf have been difficult to assign, and major uncertainties were inherent in the earlier dating of the fans. Unpublished consultant reports proposed an Eocene age for the lower part of the wedge, leading Spencer et al. (1984) to conclude that the base of the sedimentary wedge (i.e. their Unit III A) is a major hiatus. Ages of the deposits above this hiatus ranged from Miocene to Late Pliocene in age, which led some authors to propose an intra-Oligocene age for the boundary (i.e. Nøttvedt et al. 1988; Vorren et al. 1990). Vorren et al. (1991) proposed that the lower unit of the wedge is of Middle to Late Miocene age, based on downlap on oceanic crust and magnetic anomalies. A similar age interpretation was used by Richardsen et al. (1993) and Knutsen et al. (1993) in their seismic stratigraphic studies of the wedge. The redating of wells on the Senja Ridge (Eidvin & Riis 1989; Eidvin et al. 1993) has provided evidence that the thick sedimentary wedge was built over a relatively short time period in the Late Pliocene–Pleistocene, mainly as a result of glacial erosion of the Barents Shelf region. Based on studies of shallow cores in the Bjørnøya West area, Sættem et al. (1992, 1994) and Mørk & Duncan (1993) also concluded that the base of the wedge is of Late Pliocene age.

The sediments directly overlying the seismic reflector at the base of unit B, as defined by Sættem et al. (1992), is younger than 0.73 Ma, according to palaeomagnetic studies of borehole 7317/10-U-01 (Fig. 2). Two $^{40}Ar/^{39}Ar$ isotopic ages of 2.34 and 2.20 ± 0.12 Ma respectively have been obtained from volcanic ash in borehole 7316/03-U-01 (Fig. 2). This delineates the base of the fan (base of unit A_0 of Sættem (1992)), (Mørk & Duncan 1993; Sættem et al. 1994). Based on lithologic correlations with ODP holes in the Norwegian Sea that have been investigated by Jansen & Sjøholm (1991) and Jansen (1995), the base of the fan in both the Senja Ridge wells (Eidvin et al. 1993) and well 7316/5-1 are believed to be no older than 2.6 Ma. However, a minimum age of 2.3 Ma for the sediments at the base of the fan (Assemblage Zone D of Eidvin et al. (1993), and Assemblage Zone BB-FB of 7316/5-1) is inferred on the basis of biostratigraphic correlations with the same ODP holes. These considerations suggest that the oldest $^{40}Ar/^{39}Ar$ age within the maximum margin of error is probably most correct. ODP Hole 986 is situated on the continental slope west of Spitsbergen and penetrated the entire fan section (Fig. 2). Palaeomagnetic and biostratigraphic studies of this hole presently undertaken will provide a much more accurate chronology of fan development in the late Pliocene.

Ages based on the strontium-isotope compositions of foraminiferal tests from the Oligocene sequences in borehole 7316/5-1 and the outcrop at Forlandsundet, Svalbard indicate that the relatively similar faunas have an age difference of 5–6 m.y. Chronologic correlations supported by strontium-isotopic ratios are significantly more accurate than traditional biostratigraphic methods for such sequences. Sea-water strontium ages of 27.5–29.5 Ma support the interpretation of Feyling-Hanssen & Ulleberg (1984) that the sequences are early Late Oligocene in age. A Late Eocene age for the outcrop at Forlandsundet based on dinoflagellate correlations (Manum & Throndsen 1986) was based on redeposited specimens, as is evident from the dinoflagellate investigation of samples from this sequence in the present study.

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References

Batjes, D. A. J. 1958: Foraminifera of the Oligocene of Belgium. *Institut Royal des sciences naturelles de Belgique, Mémoires 143*, 1–188.

Berggren, W. A., Kent, D. A. & van Couvering, J. A. 1985: Neogene geochronology and chronostratigraphy. *In* Snelling, N. J. (ed.): *The Chronology of the Geological Record. Geological Society of London Memoir 10*, 211–260.

Bjørklund, K. R. 1976: Radiolaria from the Norwegian Sea, Leg 38 of the Deep Sea Drilling Project. *In* Talwani, M., Udintsev, G. et al. (eds.): *Initial Reports of the Deep Sea Drilling Project, v. 38*, 1101–1168.

Cande, S. C. & Kent, D. V. 1995: Revised calibration of geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research. Vol. 100, No. B4*, 6093–6095.

Charnock, M. A. & Jones, R. M. 1990: Agglutinated foraminifera from the Palaeogene of the North Sea. *In* Hemleben, C. et al. (eds.): *Proceedings of the 3rd International Workshop on Agglutinated Foraminifera, Tubingen 1989*, 139–244, Kluwer Academic Publisher.

Christensen, L. & Ulleberg, K. 1974: Sediments and foraminifers of the Middle Oligocene Viborg Formation, Denmark. *Bulletin of the Geological Society of Denmark 23*, 109–305.

Dalland, A., Worsley, D. & Ofstad, K. 1988: A lithostratigraphic scheme for the Mesozoic and Cenozoic succession offshore mid- and northern Norway. *NPD Bulletin No. 4*, 65 pp.

DePaolo, D. J. 1986: Detailed record of the Neogene Sr-isotopic evolution of seawater from DSDP Site 590 B. *Geology 14*, 103–106.

DePaolo, D. J. & Ingram, B. L. 1985: High-resolution stratigraphy with strontium isotopes. *Science 227*, 938–941.

Doppert, J. W. C. & Neele, N. G. 1983: Biostratigraphy of marine Palaeogene deposits in the Netherlands and adjacent areas. *Mededelingen Rijks Geologiche Dienst 37*, 3–79.

Dzinoridze, R. N., Jousé, A. P., Koroleva-Golikova, G. S., Kozova, G. E., Nagaeva, G. S., Petrushevskaya, M. G., & Strelnikova, N. I. 1978: Diatom and Radiolarian Cenozoic stratigraphy, Norwegian Basin, DSDP Leg 38., *In* Talwani, M., Udintsev, G., et al. (eds.): *Initial Reports of the Deep Sea Drilling Project v. 38* (supplement vol.), 289–427.

Eidvin, T., Brekke, H., Riis, F. & Renshaw, D. K. in press: Cenozoic Stratigraphy of the Norwegian Sea continental shelf 64°–68°N. *Norsk Geologisk Tidsskrift* (this issue, pp. 125–151).

Eidvin, T., Goll, R. M., Grogan, P., Smelror, M. & Ulleberg, K. 1994: En stratigrafisk undersøkelse av øvre del av brønn 7316/5-1 (Bjørnøya Vest). *NPD-Contribution 38*, 81 pp.

Eidvin, T., Jansen, E. & Riis, F. 1993: Chronology of Tertiary fan deposits of the western Barents Sea: implications for the uplift and erosion history of the Barents Shelf. *Marine Geology 112*, 109–131.

Eidvin, T. & Riis, F. 1989: Nye dateringer av de tre vestligte borehullene i Barentshavet. Resultater og konsekvenser for den Tertiære hevingen. *NPD-Contribution No. 27*, 44 pp.

Eidvin, T. & Riis, F. 1991: En biostratigrafisk analyse av tertiære sedimenter på kontinentalmarginen av Midt-Norge, med hovedvekt på øvre pliocene vifteavsetninger. *NPD-Contribution No. 29*, 44 pp.

Eldholm, O., Faleide, J. I. & Myre, A. M. 1987: Continental-ocean transition at the western Barents Sea/Svalbard continental margin. *Geology 15*, 1118–1122.

Ellerman, C. 1963: Beitrag zur Gliederung und Verbreitung des Tertiärs im West-Emsland. *Neues Jahrbuch fur Geologie und Palaontologie Abhandlungen 117*, 111–130.

Faleide, J. I., Myhre, A. M. & Eldholm, O. 1988: Early Tertiary volcanism at the western Barents Sea Margin. *In* Morton, A. C. & Parson, L. M. (eds.): *Early Tertiary Volcanism and the Opening of the NE Atlantic. Geological Society of London Special Publication 39*, 135–146.

Faleide, J. I., Solheim, A., Fiedler, A., Hjelstuen, B. O., Andersen, E. S. & Vanneste, K. 1996: Late Cenozoic evolution of the western Barents Sea-Svalbard continental margin. *In* Solheim, A. et al. (eds.): Impact of glaciations on basin evolution: data and models from the Norwegian margin and adjacent areas. *Global and Planetary Change 12*, 53–74.

Feyling-Hanssen, R. W. 1983: Quantitative methods in micropalaeontology. *In* Costa, L. I. (ed.): Palynology-micropalaeontology: Laboratories, equipment and methods. *NPD Bulletin 2*, 109–151.

Feyling-Hanssen, R. W. & Ulleberg, K. 1984: A Tertiary–Quaternary section at Sarsbukta, Spitsbergen, Svalbard, and its foraminifera. *Polar Research. (n. s.) 2*, 77–106.

Gabrielsen, R. H., Færseth, R. B., Jensen, L. N., Kalheim, J. E. & Riis, F. 1990: Structural elements of the Norwegian continental shelf. Part I: The Barents Sea Region. *NPD Bulletin No. 6*, 33 pp.

Goll, R. M. 1989: A synthesis of Norwegian Sea biostratigraphies: ODP Leg 104 on the Vøring Plateau. *In* Eldholm, O., Thiede, J., Taylor, E. et al. (eds.): *Proceedings of the Ocean Drilling Program, Scientific Results, v. 104*, 777–826.

Goll, R. M. & Bjørklund, K. R. 1989: A new radiolarian biostratigraphy for the Neogene of the Norwegian Sea: ODP Leg 104. *In* Eldholm, O., Thiede, J., Taylor, E., et al. (eds.): *Proceedings of the Ocean Drilling Program, Scientific Results, v. 104*, 687–737.

Goll, R. M., Smelror, M. & Verdenius, J. G. (in prep.): The Tertiary biostratigraphy of five drilled cores from the western Barents Sea.

Gradstein, F. & Bäckström, S. 1996: Cainozoic Biostratigraphy and Paleobathymetry, northern North Sea and Haltenbanken. *Norsk Geologisk Tidsskrift, Vol. 76*, 3–32.

Gradstein, F. M., Kaminski, M. A., Berggren, W. A., Kristiansen, I. L. & D'ioro, M. A. 1994: *Cainozoic Biostratigraphy of the North Sea and Labrador Shelf. Micropalaeontology, Vol. 40 Supplement 1994*, 152 pp.

Haq, B., Hardenbol, J. & Vail, P. R. 1987: Chronology of fluctuating sea level since the Triassic. *Science 235*, 1156–1167.

Hald, M., Danielsen, T. K. & Lorentzen, S. 1989: Late Pleistocene and Holocene benthonic foraminiferal distribution in the south-western Barents Sea: paleoenvironmental implications. *Boreas 18*, 367–388.

Harland, R. 1992: Dinoflagellate cysts of the Quaternary System. *In* Powell, A. J. (ed.): *A Stratigraphic Index of Dinoflagellate Cysts. British Micropalaeontological Society Publication Series*, 253–273, Chapman & Hall, London.

Head, M. J. 1984: A palynological investigation of Tertiary strata at Renarodden, West Spitsbergen. 6th International Palynological Conference, Abstract, p. 61.

Head, M. J. 1989: Palynostratigraphy of the Central Basin (Paleocene–Lower Eocene?), Spitsbergen, Abstract. *Palynology 13*, 283.

Hess, J., Bender, M. L. & Scilling, J. G. 1986: Evolution of the ratio of strontium-87 to strontium-86 in seawater from Cretaceous to present. *Science 231*, 979–984.

Hodell, D. A., Mead, G. A. & Mueller, P. A. 1990: Variation in the strontium isotopic composition of seawater (8 Ma to present): Implication for chemical weathering rates and dissolved fluxes to the ocean. *Chemical Geology (Isotope Geoscience Section) 80*, 291–307.

Hodell, D. A., Mueller, P. A. & Garrido, J. R. 1991: Variations in the strontium isotopic composition of seawater during the Neogene. *Geology 19*, 24–27.

Hodell, D. A., Mueller, P. A., McKenzie, J. A. & Mead, G. A. 1989: Strontium isotope stratigraphy and geochemistry of the late Neogene ocean. *Earth and Planetary Science Letter 92*, 165–178.

Hughes, M. J. 1981: Contribution on the Oligocene and Eocene microfaunas of the southern North Sea. *In* Neal, J. W. & Brasier, M. D. (eds.): *Microfossils from Recent and Fossil Shelf Seas*, 186–195. Ellis Horwood Ltd., Chichester.

Hulsbos, R. E., Kroon, D., Jansen, H. S. M. & van Hinte, J. E. 1989: Lower Eocene benthonic foraminifera and paleoenviornment of the outer Vøring Plateau, Norwegian Sea (DSDP Site 338). *Micropalaeontology 35*, 256–273.

Jansen, E. 1991: Miocen and Pliocen Sedimentasjon og Paleomiljø på Vøringplatået, del 1. Unpublished report for NPD. University of Bergen, 18 pp.

Jansen, E. 1993: Miocen and Pliocen Sedimentasjon og Paleomiljø på Vøringplatået, del 2. Unpublished report to NPD. University of Bergen, 28 pp.

Jansen, E. 1995: Neogen utvikling av kontinentalmarginen utenfor midt-Norge og Svalbard: erosjons-og avsetningsdynamikk, del 2. Unpublished report to NPD. University of Bergen, 20 pp.

Jansen, E. & Sjøholm, J. 1991: Reconstruction of glaciation over the past 8 m.y. from iceborne deposits in the Norwegian Sea. *Nature 349*, 600–603.

Kaasschieter, J. P. H. 1961: Foraminifera of the Eocene of Belgium. *Institut Royal des sciences naturelles de Belgique, Mémoires 147*, 1–271.

King, C. 1989: Cenozoic of the North Sea. *In* Jenkins, D. & Murray, J. W. (eds.): *Stratigraphical Atlas of Fossil Foraminifera*, 418–489. Ellis Horwood Ltd., Chichester.

Knutsen, S.-M., Richardsen, G. & Vorren T. O. 1993: Late Miocene–Pleistocene sequence stratigraphy and mass-movements on the western Barents Sea margin. *In* Vorren, T. et al. (eds.): *Arctic Geology and Petroleum Potential. Norwegian Petroleum Society Special Publication 2*, 569–602. Elsevier, Amsterdam.

Koepnick, R. B., Burke, W. H., Dension, R. E., Hetherington, E. A., Nelson, H. F., Otto, J. B. & Waite, L. E. 1985: Construction of seawater $^{87}Sr/^{86}Sr$ curve for the Cenozoic and Cretaceous: Supporting data. *Chemical Geology 58*, 55–81.

Mackensen, A., Sejrup, H. P. & Jansen, E. 1985: The distribution of living benthonic foraminifera on the continental slope and rise of southwest Norway. *Marine Micropalaeontology 9*, 275–306.

Manum, S. B. 1960: Some dinoflagellates and hystrichosphaerids from the Lower Tertiary of Spitsbergen. *Norsk Polarinstitutt Meddelelser 85*, 17–25.

Manum, S. B., Boulter, M. C., Gunnarsdottir, H., Rangnes, K. & Scholze, A. 1989: Eocene to Miocene palynology of the Norwegian Sea (ODP LEG 104). *In* Eldholm, O., Thiede, J., Tayler, R. et al. (eds.): *Proceedings of the Ocean Drilling Program, Scientific Results, v. 104*, 611–662.

Manum, S. B. & Throndsen, T. 1986: Age of Tertiary formations on Spitsbergen. *Polar Research (n. s.) 4*, 103–131.

Martini, E. 1971: Standard Tertiary and Quaternary calcareous nannoplankton zonation. *In* Farinacci, A. (ed.): *Proceedings of the Second Planktonic Conference, Roma, 1970*, Roma, Tecnoscienza, 739–785.

Mudie, P. J. 1989: Palynology and dinocyst biostratigraphy of the Late Miocene to Pleistocene, Norwegian Sea: ODP Leg 104, Sites 642 to 644. *In* Eldholm, O., Thiede, J., Tayler, R. et al. (eds.): *Proceedings of the Ocean Drilling Program, Scientific Results 104*, 587–610.

Mørk, M. B. E. & Duncan, R. A. 1993: Late Pliocene volcanism on the Western Barents Shelf Margin – Implications from petrology and ^{40}Ar–^{39}Ar dating of volcaniclastic debris from a shallow drill-core. *Norsk Geolgisk Tidsskrift 73*, 209–225.

Nuglish, K. & Spiegler, D. 1991: Die Foraminiferen der Typ-Lokalität Latdorf (Nord-Deutschland, Unter-Oligozän). *Geologisches Jahrbuch, Reihe A 128*, 179–229.

Nøttvedt, A., Berglund, L. T., Rasmussen, E. & Steel, R. J. 1988: Some aspects of Tertiary tectonics and sedimentation along the western Barents Shelf. *In* Morton, A. C. & Parson, L. M. (eds.): *Early Tertiary Volcanism and Opening of the NE Atlantic. Geological Society of London Special Publication 39*, 421–425.

Palmer, M. R. & Elderfield, H. 1985: Sr-isotope composition of sea water over the past 75 Myr. *Nature 314*, 611–641.

Powell, A. J. 1992: Dinoflagellate cysts of the Tertiary System. *In* Powell, A. J. (ed.): *A Stratigraphic Index of Dinoflagellate Cysts*, 156–251. Chapman & Hall, London.

Qvale, G. & van Weering, T. C. E. 1985: Relationship of surface sediments and benthonic foraminiferal distribution patterns in the Norwegian Channel (northern North Sea). *Marine Micropalaeontology 9*, 469–488.

Richardsen, G., Knutsen, S.-M., Vail, P. R. & Vorren, T. O. 1993: Mid-Late Miocene sedimentation on the southwestern Barents Shelf Margin. *In* Vorren, T. et al. (eds.): *Arctic Geology and Petroleum Potential. Norwegian Petroleum Society Special Publication 2*, 539–571. Elsevier, Amsterdam.

Skarbø, O. & Verdenius, J. G. 1986: Catalogue of Microfossils. Quaternary–Tertiary. *IKU Publication 113*, 19 pp.

Spencer, A. M., Home, P. C. & Berglund, L. T. 1984: Tertiary structural development of the western Barents Shelf: Troms to Svalbard. *In* Spencer, A. M. et al. (eds.): *Petroleum Geology of the North European Margin*, 109–135. Graham & Trotman, London.

Spiegler, D. 1974: Biostratigraphie des Tertiärs zwischen Elbe und Weser/Aller (Benthische Foraminiferen, Oligo-Miozän). *Geologisches Jahrbuch, Reihe A*, 27–69.

Spiegler, D. & Jansen, E. 1989: Planktonic Foraminifer Biostratigraphy of Norwegian Sea Sediments: ODP Leg 104. *In* Eldholm, O., Thiede, J., Tayler, E. et al. (eds.): *Proceedings of the Ocean Drilling Program, Scientific Results, v. 104*, 681–696.

Steinsund, P. I., Hald, M. & Pool, D. A. R. 1991: Modern benthonic foraminiferal distribution in the southwestern Barents Sea: paleooceanographic applications. *Norsk Geologisk Tidsskrift 71*, 169–171.

Sættem, J., Bugge, T., Fanavoll, S., Goll, R. M., Mørk, A., Mørk, M. B. E., Smelror, M. & Verdenius, J. G. 1994: Cenozoic margin development and erosion of the Barents Sea: Core evidence from southwest of Bjørnøya. *Marine Geology 118*, 257–281.

Sættem, J., Poole, D. A. R., Ellingsen, K. L. & Sejrup, H. P. 1992: Glacial geology of outer Bjørnøyrenna, southwestern Barents Sea. *Marine Geology 103*, 15–51.

Ulleberg, K. 1974: Foraminifera and stratigraphy of the Viborg Formation in Sofienlund, Denmark. *Bulletin of the Geological Society of Denmark 23*, 269–292.

Ulleberg, K. 1975: Foraminiferal zonation of the Danish Oligocene sediments. *Bulletin of the Geological Society of Denmark 36*, 191–202.

Vorren, T. O., Richardsen, G., Knutsen, S. M. & Henriksen, E. 1990: The western Barents Sea during the Cenozoic. *In* Bleil, U. & Thiede, J. (eds.): *Geological History of the Polar Oceans: Arctic Versus Antarctic. Nato ASI Series C, Mathematical and Physical Sciences 308*, 95–118. Kluwer, Dordrecht.

Vorren, T. O., Richardsen, G., Knutsen, S. M. & Henriksen, E. 1991: Cenozoic erosion and sedimentation in the western Barents Sea. *Marine Petroleum Geology 8*, 317–340.

Vågnes, E., Faleide, J. I. & Gudlaugsson, S. T. 1992: Glacial erosion and tectonic uplift in the Barents Sea. *Norsk Geologisk Tidsskrift 72*, 251–254.

Weaver, P. P. E. & Clement, B. M. 1986: Synchroneity of Pliocene planktonic foraminiferid datums in the North Atlantic. *Marine Micropalaeontology 10*, 295–307.

Williams, G. L., Stover, L. E. & Kidson, E. J. 1993: Morphology and stratigraphic ranges of selected Mesozoic–Cenozoic dinoflagellate taxa in the Northern Hemisphere. *Geological Survey of Canada, Paper 92–10*, 1–137.