Marine Geology, 112 (1993) 109–131
Elsevier Science Publishers B.V., Amsterdam

Chronology of Tertiary fan deposits off the western Barents Sea: Implications for the uplift and erosion history of the Barents Shelf

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(Received June 29, 1992; revision accepted January 12, 1993)

ABSTRACT

Eidvin, T., Jansen, E. and Riis, F., 1993. Chronology of Tertiary fan deposits off the western Barents Sea: Implications for the uplift and erosion history of the Barents Shelf. *Mar. Geol.*, 112: 109–131.

A combined biostratigraphic and seismic study was performed on three holes drilled in the western Barents Sea. Two holes penetrate the thick sedimentary wedge which forms a large fan located off a trough on the Barents Sea Shelf, the Bjørnøyrenna Fan. The study shows that the fan was built over a short time span in the late Pliocene–Pleistocene, mainly due to glacial erosion of the Barents Shelf region. This contrasts earlier age assignments which concluded that fan-deposition started in the Oligocene. The results have a major impact on the understanding of trough mouth fan formation and has important bearing on the history of the sedimentary basins of the Barents Shelf.

Introduction

Thick Tertiary fan deposits cover the Western Margin off the Barents Sea, and are believed to be depocenters for erosion products from Cenozoic uplift and erosion of the Barents Shelf area (Spencer et al., 1984; Nøttvedt et al., 1988; Vorren et al., 1991). The fans are easily identified as positive bathymetric features extending the continental slope westward off the western margin of the Barents Sea. Major portions of the upper sedimentary sequence on the adjoining Barents Shelf are evidently removed. Beneath the relatively thin Pleistocene cover, only sediments of Eocene age or older are observed (Sigmond, 1993). Vorren et al. (1991) and Nøttvedt et al. (1988) calculated that the volume of sediments contained in the Barents Sea margin fans corresponds to a layer of approximately 1000 m uniform thickness eroded off the adjacent drainage area. Although there are major uncertanties contained in such calculations, they provide a gross estimate pointing to the fans as being formed as a response to major erosion phases on the shelf.

While it is of general interest to date the build-up of the fans in order to better understand their formation history, we undertook the present study also due to the importance of the erosion history for understanding sedimentary basin evolution to aid petroleum prospecting in the Barents Sea. Major uncertainties were inherent in earlier datings of the fans. Different industry consultants arrived at widely different age estimates, leading to very different interpretations of the geological history of the Western Barents Margin. Unpublished consultant reports proposed an Eocene age of the lower part of the wedge. This problem also affects the published literature: Spencer et al. (1984) concluded that the base of the sedimentary wedge (Unit IIIA) is a major hiatus. Sediments above this hiatus appeared to range from Miocene to late Pliocene, which led the authors to conclude that

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the unit boundary could be intra-Oligocene partly based on the same holes as studied in this paper. Nøttvedt et al. (1988) also gave an age of mid-Oligocene for the base of the fan, but provided no new documentation for this assumption. Vorren et al. (1990) used downlap on oceanic crust and magnetic anomalies to date the bottom of the wedge and proposed a mid-Oligocene age. This was later revised by Vorren et al. (1991) who also considered the biostratigraphic evidence reported in this paper. However, Vorren et al. (1991) propose that the lower unit of the wedge is of mid- to late-Miocene age, in contrast to the younger age indicated from our studies, based on downlap on oceanic crust of Anomaly 5 age. The discrepancy with the results provided in this contribution lies in the seismic correlation and the question of whether the lower parts of the wedge are represented in the holes we have studied.

The main reason for the earlier dating discrepancies originates from the large influence of redeposited material in the fan deposits. We tried to overcome this problem by utilizing as many criteria as possible, and employing a critical attitude to material and methods, thereby developing criteria which are robust, disregarding the biostratigraphic information that arises from redeposition.

Our initial hypothesis was that the fans were young, and of Plio-Pleistocene age. This was based on gravity anomaly modelling performed by Fjeldskaar and Riis (1988), and by the similarities in seismic signature with Plio-Pleistocene deposits off middle Norway. This possibility was already pointed out by Nansen (1904), who viewed the bathymetric expression of the fans as a product of glacial erosion and deposition.

We studied holes 7117/9-1 and 7117/9-2 (Fig. 1) from the Senja Ridge, which are the only holes which penetrate the fan deposits in the Barents Sea, and compared the results with hole 7119/7-1 (Fig. 1) which is the closest hole outside of the fans. The results clearly point to the conclusion that the fan deposits are of glacial origin and were deposited in the late Pliocene and Pleistocene. These results have important bearing on the history of uplift and erosion in the Barents Sea region, with major implications for attempts to model the sedimentary basin evolution of the Barents Shelf.

Seismic interpretation

Two large fans are identified as sedimentary wedges extending westward off the western Barents Sea. They are situated off shelf troughs; one off Stordfjordrenna (Storfjordrenna Fan), and a larger fan off Bjørnøyrenna (Bjørnøyrenna Fan; Fig. 1). The margin is covered with a regional seismic grid, in parts also with detailed seismics. Only few lines extend far enough westward to cover oceanic crust. In this study we emphasize the seismic mapping of the bottom of the fans, rather than providing interpretations of internal fan sequences.

Figure 2 shows the distribution of the Bjørnøyrenna Fan depicted as the thickness of the sedimentary wedge. This is defined seismically as the thickness of sediments between the bottom of the fan and the Upper Regional Unconformity (URU). This unconformity truncates the Bjørnøyrenna Fan in its eastern part, thereby defining the eastern boundary of the fan close to Hole 7119/7-1 (Vorren et al., 1989; see also Fig. 8). The area of the two holes on the Senja Ridge is covered by a 1 × 1 km seismic grid of reasonable good quality. Figure 3 shows a seismic tie line between the holes. Based on the detailed industry seismic grid available to us, it has been straightforward to tie the local seismics to the regional seismic grid, thereby tying the reflectors from the holes to the regional reflector system and thereby to the main depocenter of the Bjørnøyrenna Fan at 72°N, north of the holes. Figures 4 and 5 illustrate the tie to the main sequences in the fan north of the holes. The fan is distinguished by the thick prograding and undeformed sediments defined by the lower unconformity (Reflector 3).

Seismic lines through the holes point to two main unconformities within the fan (Figs. 6 and 7): The upper is URU (Upper Regional Unconformity, Vorren et al., 1990), or Reflector 1, which is located at about 0.67 s, or 600 m, in both holes. Beneath this is a pronounced sequence boundary (Reflector 2 in Figs. 6 and 7) at 0.98 s in Hole 7117/9-1 and at 0.92 s in Hole 7117/9-2, corresponding to subbottom depths of 910 and 860 m, respectively. Reflector 2 is defined by its truncation of the underlying clinoforms, and it can be followed far westward before defining a paleo-

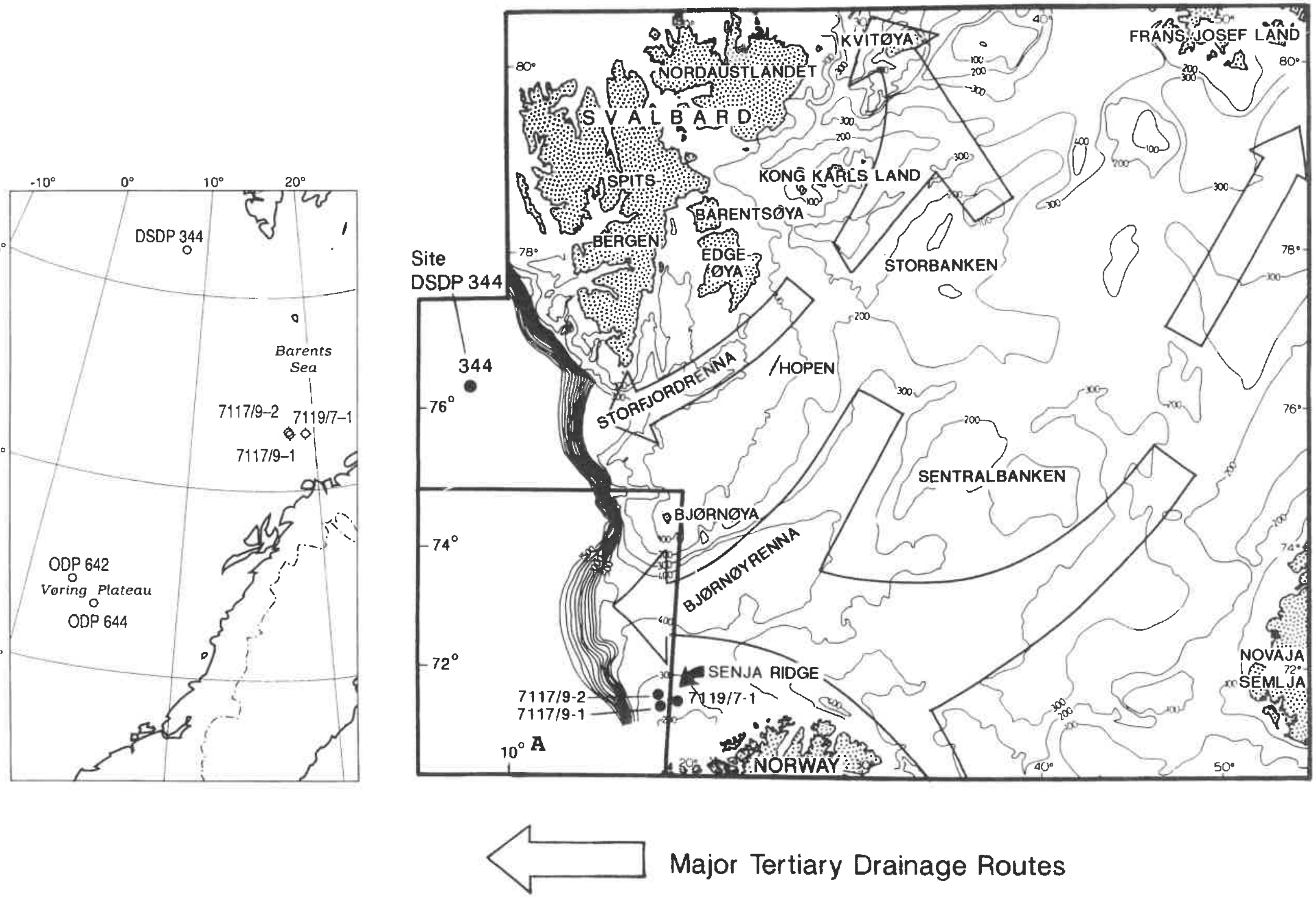

Fig. 1. Map of the Barents Sea and the Norwegian Sea with holes indicated. Also indicated are ODP/DSDP sites referred to in the text. Box *A* defines area shown in Fig. 2. Tertiary drainage routes are according to Nøttvedt et al. (1988).

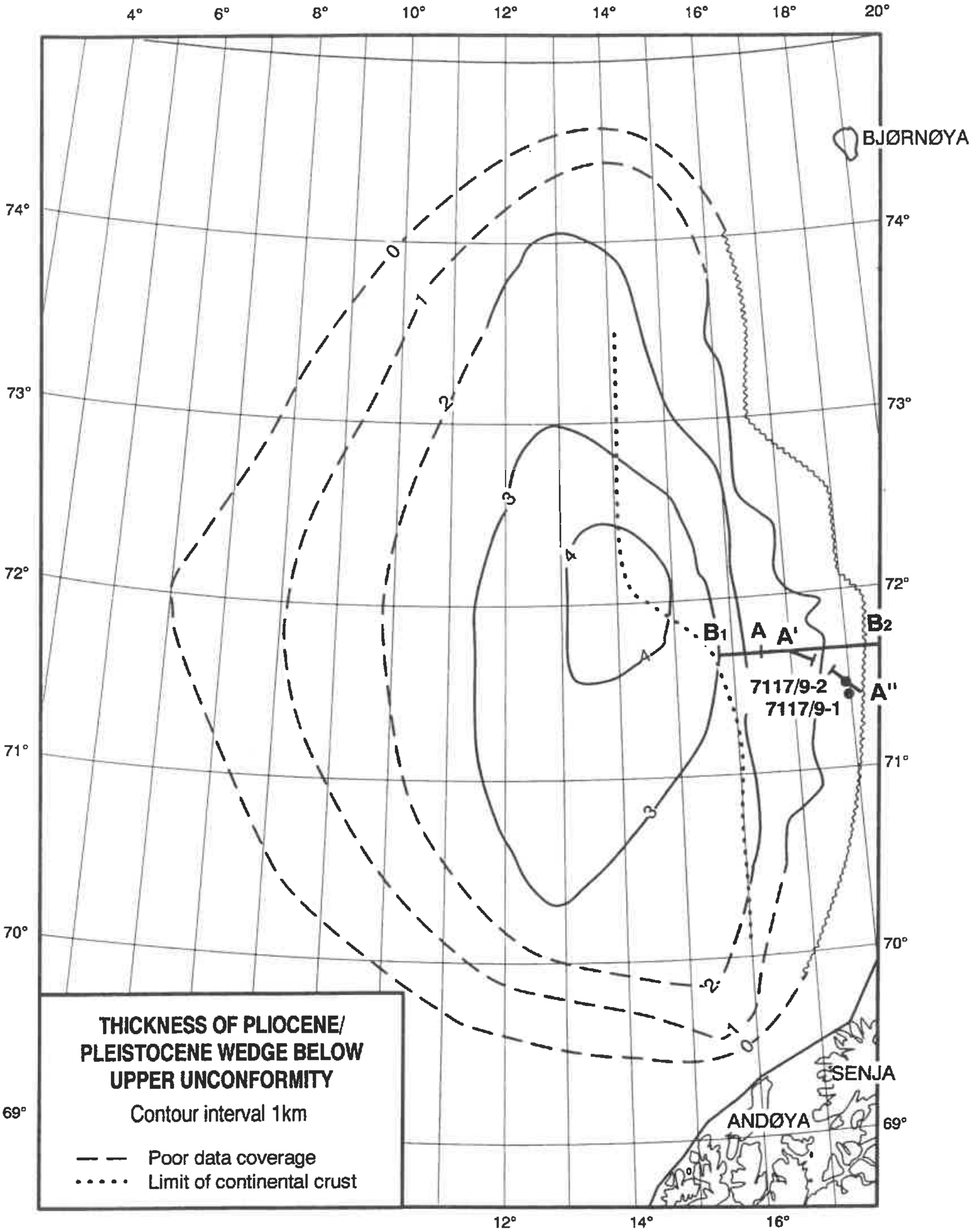

Fig. 2. Areal distribution and thickness in kilometers, of the Bjørnøyrenna Fan. Holes and the seismic lines of Figs. 4 and 5 are indicated.

"shelf-edge". To the east Reflector 2 cuts the bottom of the fan and defines the bottom of deep erosional channels in the Tromsø Basin. These erosional channels are better defined by shallow seismics, and further document the erosional character of Reflector 2. The lower boundary of the fan (Reflector 3 in Figs. 6 and 7) is also a marked sequence boundary which defines an erosional

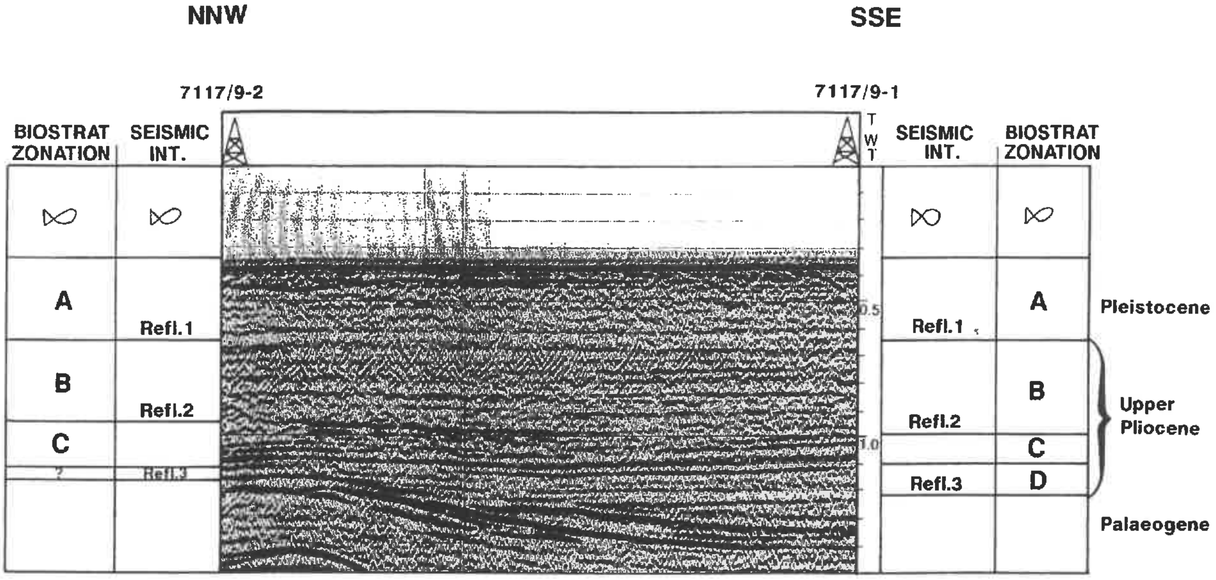

Fig. 3. Seismic tie line between holes 7117/9-1 and 7117/9-2.

relief on the Senja Ridge. This reflector is tied into the regional seismics (Figs. 4 and 5) and documents that most of the fan is contained in the two holes we studied. The base of the wedge is not easy to define with certainty seismically where it overlies oceanic crust. Existance of slightly older sequences than the ones defined in our study thus cannot be ruled out. The reflectors correspond to biostratigraphic zonal boundaries discussed below (Fig. 3). Sættem et al. (1992) studied the northern part of the Bjørnøya wedge west of Bjørnøya and reported deep erosional channels at the base of their Unit A, which corresponds to Reflector 3 in this work. Thus the formation of deep erosional channels apparently happened earlier in the Bjørnøya area than further south in the Tromsø Basin.

Hole 7117/9-2 is located at a higher structural position in the Senja Ridge than Hole 7117/9-1 and the reflectors at the bottom of the Fan onlap towards this high. On Fig. 3 which is the seismic tie line between the holes, this is documented by the lower 50–60 ms of Hole 7117/9-1 being absent from Hole 7117/9-2. Further west there is no clear erosional boundary of the Fan, and it is thus less easy to define the lower boundary based on seismics. The error range for the determination of the bottom of the fan here is about 0–50 ms.

Figure 4 documents the seismic correlation of the units from the holes to the main depocenter of the wedge. Figure 5 shows an interpreted line extending from the shelf break, and documents the main units of the wedge. The interpretation along the part between seismic sections GBW 88-T4 and GBW 88-T3 (Fig. 4), which we do not show in detail in this figure, is regarded as relatively straightforward. Note the truncation of Paleocene–Eocene strata at the Senja Ridge, close to Hole 7117/9-2 and the downlap of the wedge further to the northwest onto supposedly Oligocene–Miocene strata.

Hole 7119/7-1 lies east of the other holes and does not contain fan sequences (Fig. 8).

Biostratigraphy

Material and methods

For biostratigraphic studies we only had cuttings at our disposal. This is far from the ideal material to work with and limits the biostratigraphic precision, both due to problems of identifying the exact sub-bottom depth to which a certain assemblage belongs and because of potential downhole contamination by sidewall fragments falling in

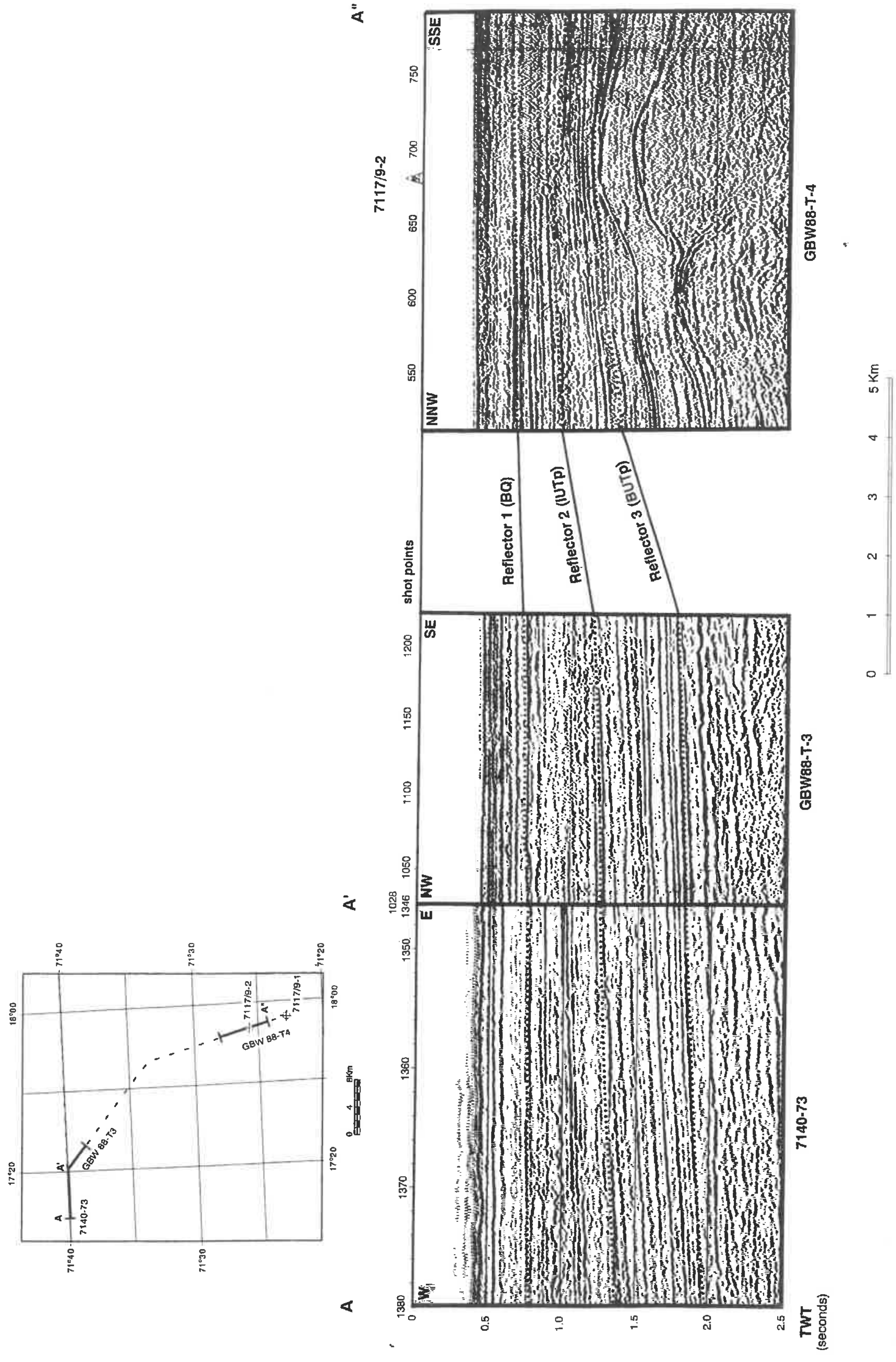

Fig. 4. Seismic line ties between Hole 7117/9-2 and the main depocenter for the Bjørnøyrenna Fan. *BQ* = base Quaternary, *IUTp* = Intra upper Pliocene, *BUTp* = base of upper Pliocene.

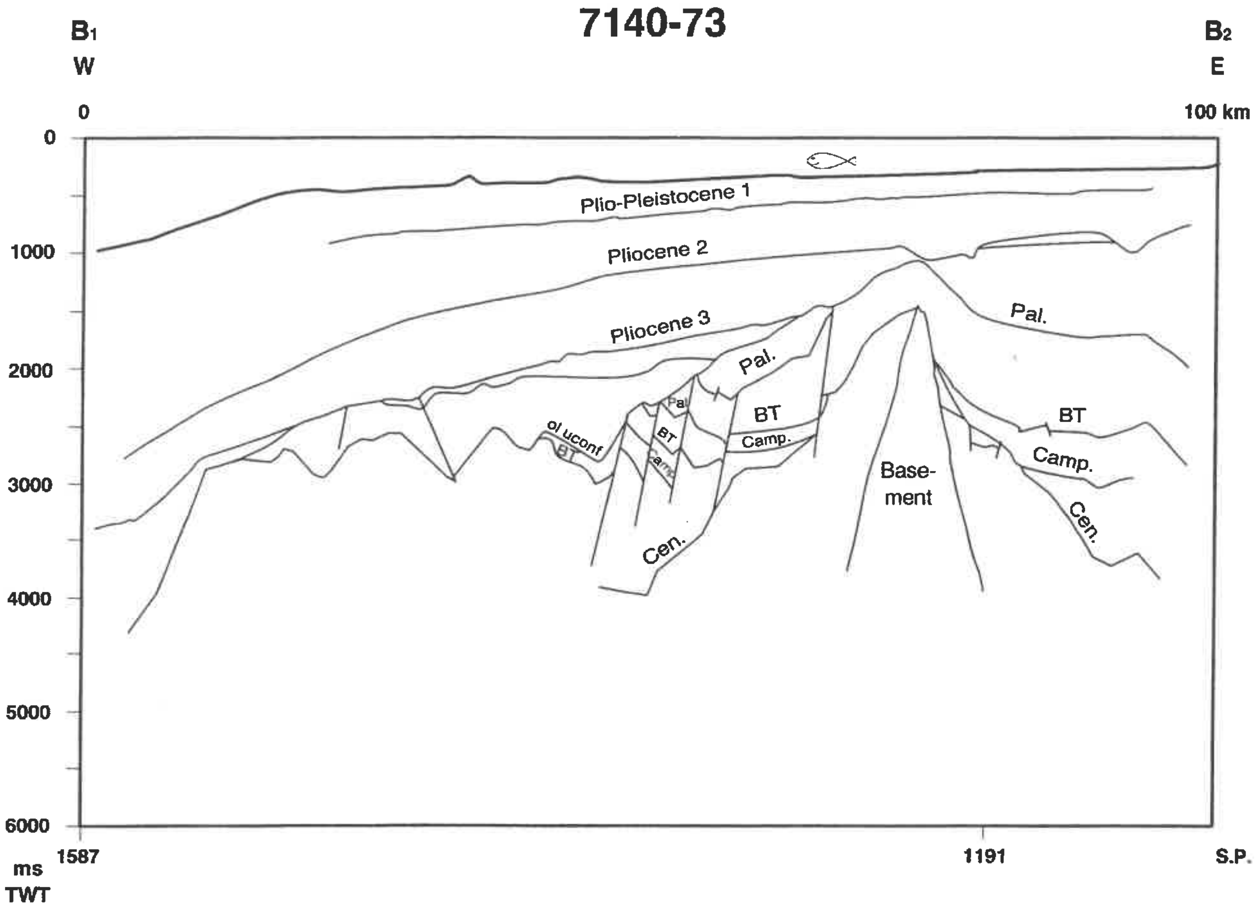

Fig. 5. Geoseismic section from the shelf edge into the wedge. The location of the line is shown on Fig. 2.

from uncased sidewalls. Because of this constraint, our interpretation is limited to markers and assemblages which are clearly defined in both holes and mark major biostratigraphic boundaries.

For the analyses 50–100 g material was used. Unconsolidated material was soaked in water and wet sieved. Consolidated material was dissolved in diluted hydrogen peroxide solution. Microfossil identifications were done in the 0.1–0.5 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.

In Hole 7117/9-1 one sample every 10 m was analyzed in general. In the two other holes we analyzed most samples at 20 m interval. In important sequences, denser sample spacing was employed.

Results

Biostratigraphic results are reported in the range charts of Figs. 9–11. Further documentation can be found in Eidvin and Riis (1989).

Based on these charts the assemblages were grouped into assemblage zones based on characteristic/frequent species. Most emphasis is placed on planktonic and benthic foraminifers.

Holes 7117/9-1 and 7117/9-2

The upper approximately 100 m of sediment were not sampled during drilling. The biostratigraphy of the upper 600–700 m in these holes is rather straightforward and unproblematic. The foraminiferal assemblages are dominated by Pliocene and Pleistocene forms with minor contribution from microfossils of late Cretaceous and early Paleogene age.

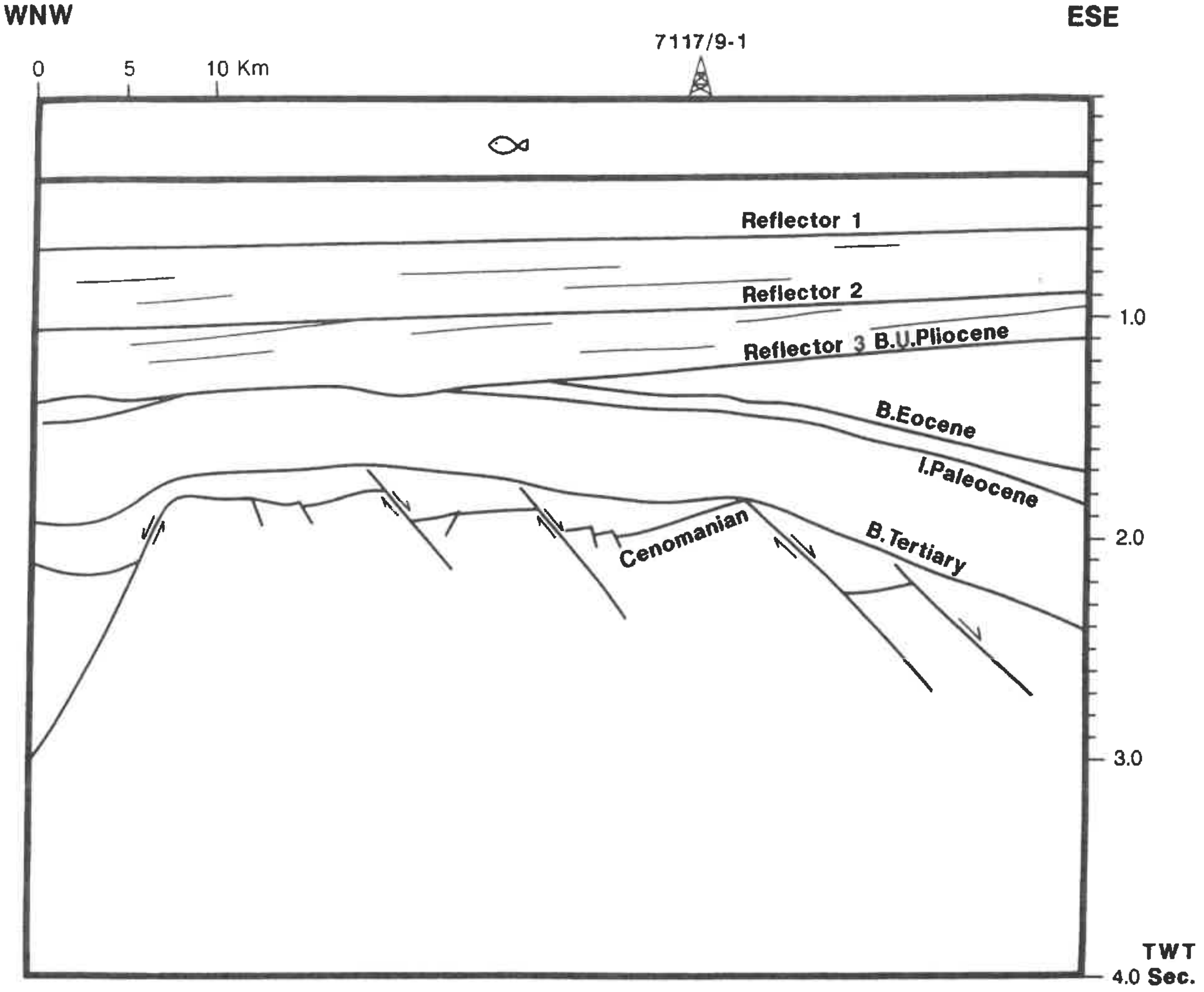

Fig. 6. Geoseismic section through Hole 7119/9-1.

Below this level and down to 1180 m in Hole 7117/9-1 and 1120 m in Hole 7117/9-2, the situation is more complicated. Eocene microfossils dominate in most levels. This was the background for the earlier unpublished industry reports assigning an Eocene age to the onset of fan build-up. There is, however, a strong influence of Plio–Pleistocene forms, somewhat less abundant fossils from the late Cretaceous, and also a mixture of fossils ranging in age from late Jurassic to Miocene. If we exclude all other fossils from consideration except the Plio-Pleistocene forms, we note that these comprise a depth zonation which is clearly identifiable in both holes at almost equal sub-bottom depths. It is possible to distinguish four different zones defined by benthic and planktonic foraminifers and one species of sponge spicules. In Hole 7117/9-1 all four zones are present, in Hole 7117/9-2 only the upper three are found. The upper limits of the zones occur at equal sediment depths in both holes. This indicates that the zonation is primary. It is unlikely to have such a zonation at equal depths in two separate holes if the Plio-Pleistocene fossils were introduced by downhole contamination. Furthermore: the zonal boundaries correspond with the main internal reflectors in the sequence and thus appear to reflect the main depositional sequences (Fig. 3), within the uncertainty imposed by the conversion of seismics to meters below sea floor. It is also

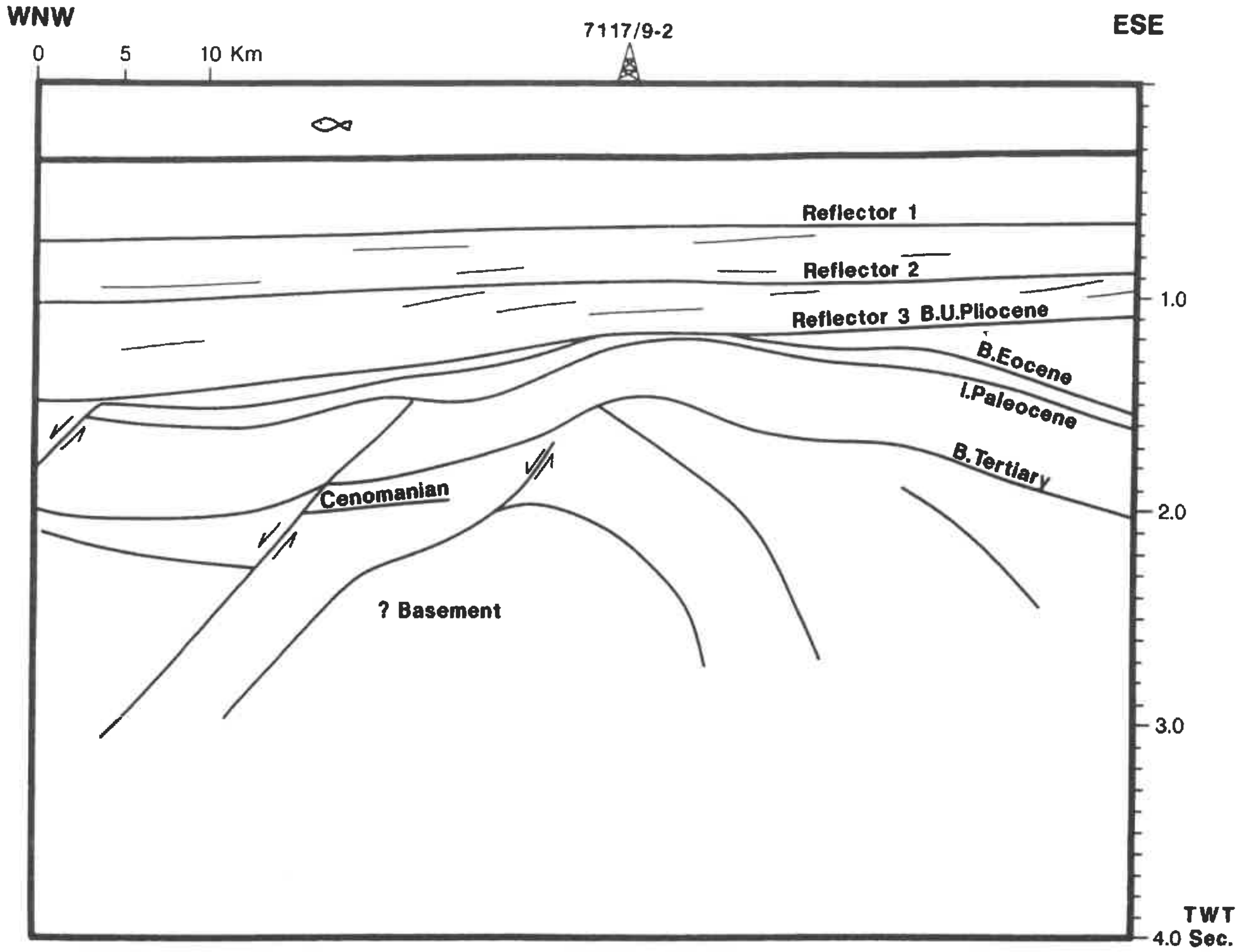

Fig. 7. Geoseismic section through Hole 7119/9-2.

unlikely that this is the case should the Plio-Pleistocene assemblages be a result of random downfall.

We define these zones as follows:

Zone A: Neogloboquadrina pachyderma *(sinistral)*–Islandiella islandica *Zone*

Definition: Frequent occurrence of *N. pachyderma* sin. encrusted form and common occurrence of *I. islandica* (Figs. 9, 10 and 12).

The zone ranges from 350 to 610 m in Hole 7117/9-1 and from 360 to 600 m in Hole 7117/9-2. The zone covers the sediments above Reflector 1 in both holes (Fig. 3).

N. pachyderma sin. which is common to frequent in this zone, is the dominant foraminifer species, defining the last 1.7 Ma interval in DSDP/ODP holes from the Norwegian Sea and the northernmost North Atlantic. The first frequent occurrence of this species in its encrusted variety is at 1.7 Ma, and it is only occurring very sporadically before this time (Weaver and Clement, 1986; Spiegler and Jansen, 1989). This indicates that Zone A is younger than 1.7 Ma.

The benthic calcareous foraminifers of this zone are all species known from Plio-Pleistocene deposits. None are extinct. All samples contain mixtures of arctic and boreal forms, probably mixed from levels representing different climatic states within glacial–interglacial sequences. Each sample represents 10 m of drilling and will include a mixture of what was represented in that interval, hence mixing of different paleoenvironmental indicators

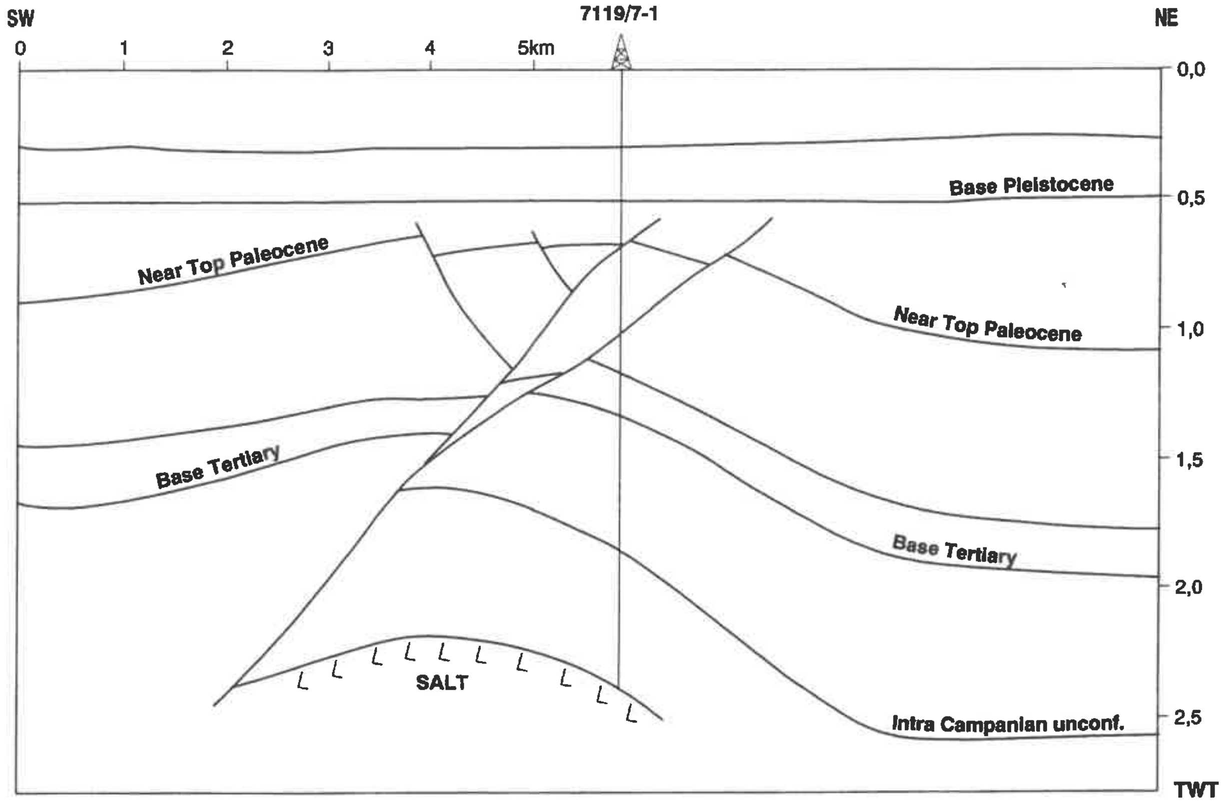

Fig. 8. Geoseismic section through Hole 7119/7-1.

is highly possible. The samples were taken so as to represent as closely as possible an average of the drilled sequence. *I. islandica*, which is limited to this zone, is described from Pleistocene deposits from Arctic Canada (Feyling-Hanssen, 1986) further indicating a Pleistocene age for the zone.

The Cretaceous–Eocene fossils found in the zone are believed to be redeposited during the erosion phases that led to fan formation. This is supported by the worn and fragmented appearance of these fossils.

Zone B: Cibicides grossus *Zone*

Definition: Common occurrence of *C. grossus* (Figs. 9, 10 and 12).

The zone ranges from 610 to 900 m in Hole 7117/9-1 and 600 to 880 m in Hole 7117/9-2. It covers the sediments between Reflector 2 and 1 in both holes (Fig. 3).

Common occurrence of *C. grossus* is almost exclusively limited to this zone and it occurs systematically throughout the zone. According to King (1989), this species is found in late Pliocene deposits in the southern North Sea where it became extinct just before the Pliocene/Pleistocene boundary. Further to the north in the North Sea it may have become extinct somewhat later, perhaps slightly above the Pliocene/Pleistocene boundary (King, 1989). Upper Pliocene deposits from Arctic Canada also contain *C. grossus* (Feyling-Hanssen, 1986). As for Zone A, the remaining Plio-Pleistocene calcareous foraminifers are all extant and mixtures of species of arctic and boreal affinities.

N. pachyderma sin. appears only sporadically in the zone. This is the same pattern of appearance which is noted in late Pliocene sediments from the Vøring Plateau (Spiegler and Jansen, 1990).

In contrast to Zone A, agglutinated foraminifers are more common in Zone B. Most particularly we find *Spiroplectammina spectabilis* and *Reticulophragmium amplectens*. According to King (1989) *S. spectabilis* is found in Paleocene and

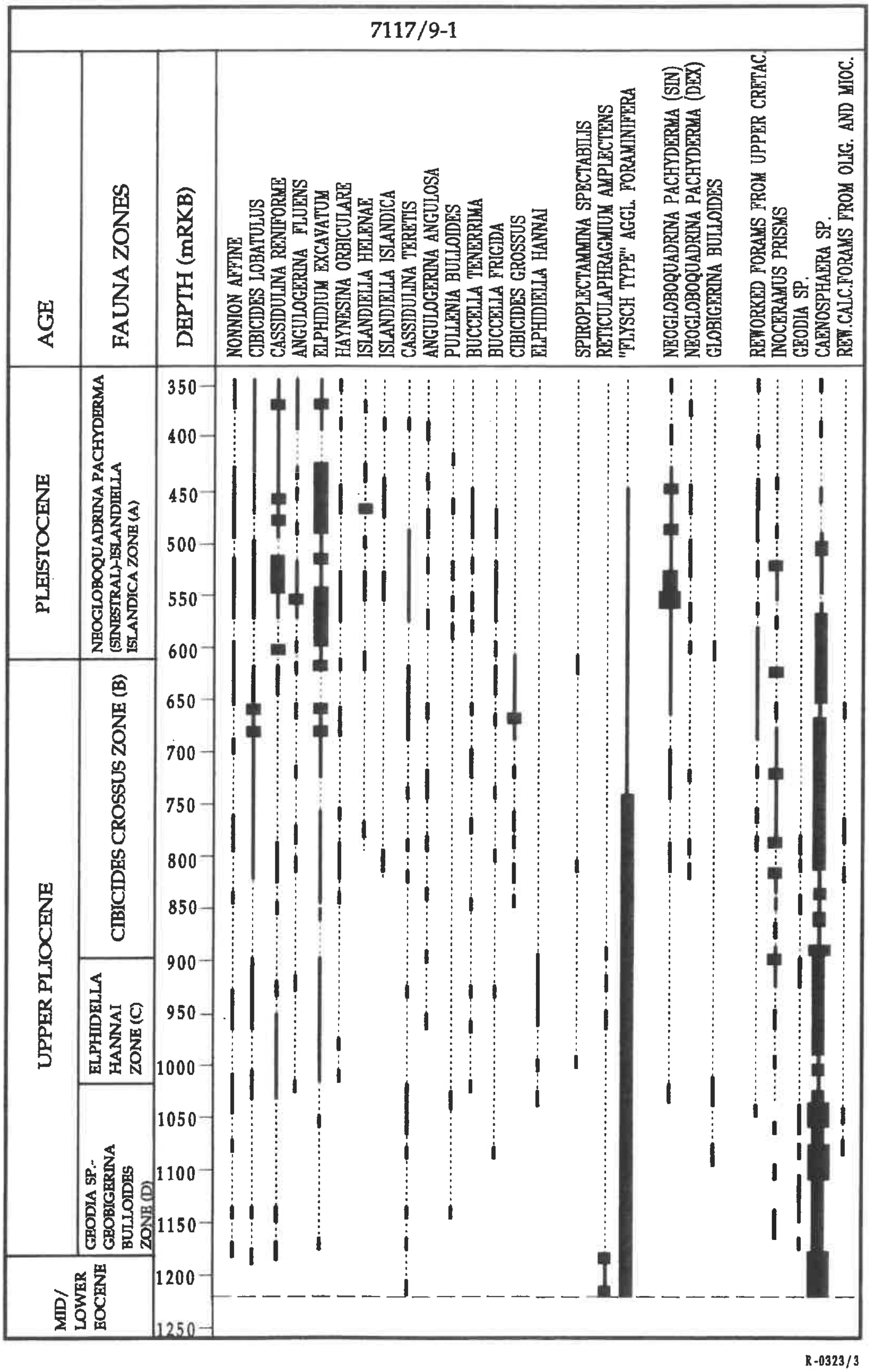

Fig. 9. Biostratigraphic range chart for Hole 7117/9-1.

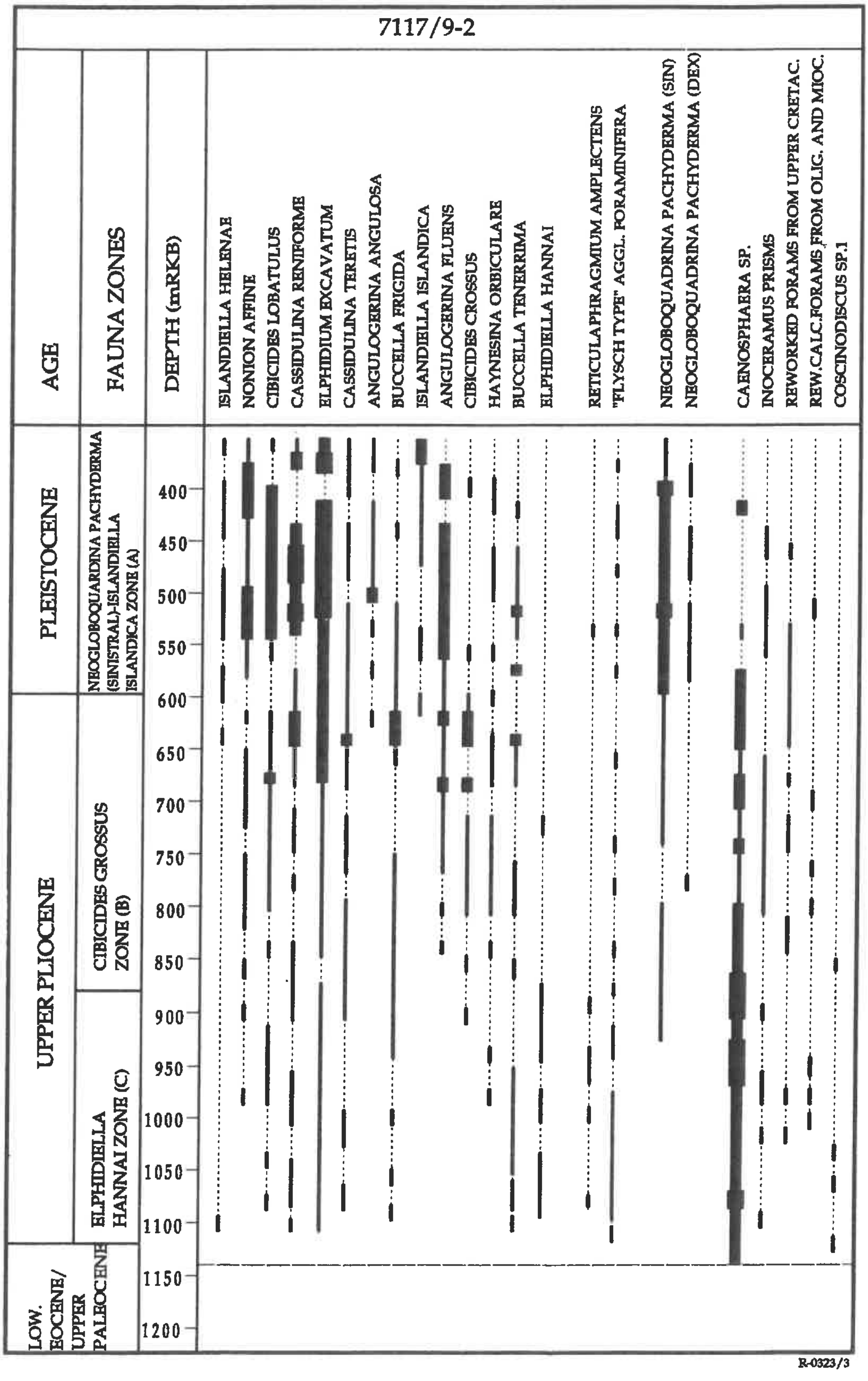

Fig. 10. Biostratigraphic range chart for Hole 7117/9-2.

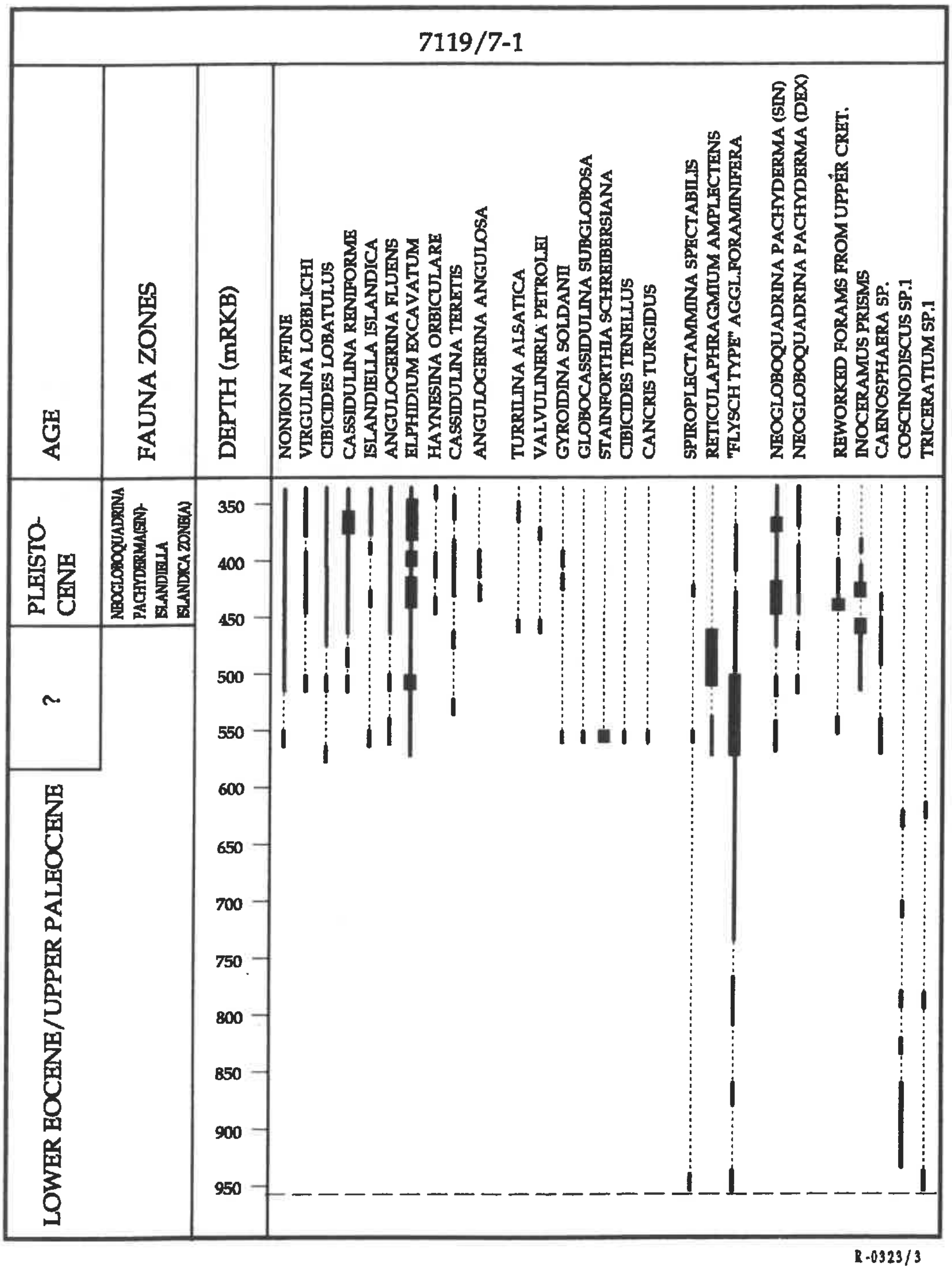

Fig. 11. Biostratigraphic range chart for Hole 7117/7-1.


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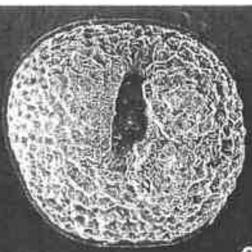
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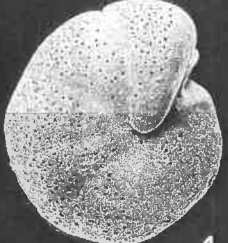
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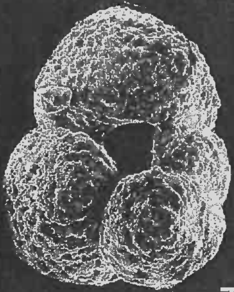
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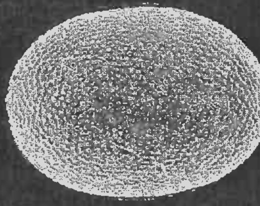
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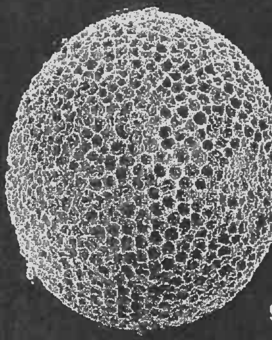
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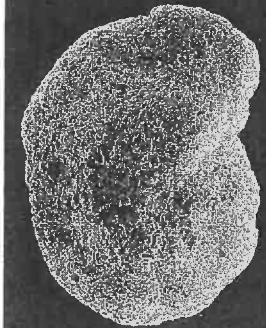
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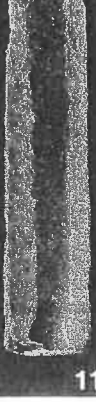
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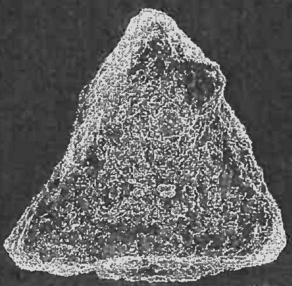
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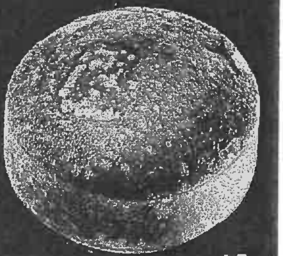
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lower/middle Eocene deposits in the North Sea. *Reticulophragmium amplectens* is found in lower/-middle Eocene deposits in the North Sea (King, 1989). The remaining agglutinated foraminifers are long ranging taxa of mainly lower Tertiary affinity. The agglutinated specimens are highly corroded and fragmented and we believe they were redeposited along with Eocene radiolarians of the genus *Caenosphaera* and a suite of foraminifer species ranging in age from Jurassic to Miocene.

The *C. grossus* Zone, as mentioned above, covers the same part of the sedimentary column in both holes. It also fits nicely in age below the overlying zone in both holes. From this evidence we conclude that it indicates a young, late Pliocene, age for the sediments. The uppermost part of the zone may represent the lowermost Pleistocene, based on the known time of extinction for *C. grossus*. Seismic data indicate a minor unconformity between faunal Zones A and B (Figs. 3, 6 and 7, Reflector 1) This is the Upper Regional Unconformity of Vorren et al. (1990).

Zone C: Elphidiella hannai *Zone*

Definition: Common occurrence of *E. hannai* (Figs. 9, 10 and 12).

The zone ranges from 900 to 1020 m in Hole 7117/9-1 and 880 to 1120 m in Hole 7117/9-2. It is found beneath Reflector 2 (Fig. 3). The occurrence of *E. hannai* is limited to this zone. In the North Sea *E. hannai* has a distribution range from the upper Pliocene to the lower Pleistocene (King, 1989). The same age is inferred from studies of Pliocene deposits from Arctic Canada, Alaska and Northern Greenland (Feyling-Hanssen, 1986). The remaining Plio-Pleistocene foraminifers are similar to those found in the overlying zones and consist of extant arctic and boreal species. *N. pachyderma* sin. is only found in a few scattered levels.

Our conclusion is that these foraminifers are in situ and do not represent downhole contamination due to the following arguments: *E. hannai* has not been found in any overlying sediment. The highest occurrence of this species is found at roughly the same sub-bottom depth in both holes. Above this zone a 20-inch casing which limits downfall, was placed. Should the fossils represent downfall, we should expect also to see *C. grossus* which is common in the overlying zone. This species is absent. Based on the occurrence of *E. hannai* we assign a late Pliocene age to this zone.

We find the same kinds of agglutinated foraminifers in this zone as in Zone B. Also here they are fragmented and wear signs of reworking. The common occurrence of early/middle Eocene radiolarians and late Cretaceous *Inoceramus* prisms as well as Cretaceous–Miocene benthic foraminifers represents redeposition from shelf erosion of Miocene, Paleogene and Mesozoic strata.

Zone D: Geoida *sp.–*Globigerina bulloides *Zone*

Definition: Common occurrence of *Geoida* sp. and *G. bulloides* (Figs. 9, 10 and 12).

The zone is only found in Hole 7117/9-1 and covers the interval 1020–1180 m. Seismically it corresponds to the sequence just above Reflector 3 which defines the lower boundary of fan deposits.

Geoida sp. (sponge spicule) is found in scattered samples also in other zones, but is here found commonly. In the North Sea and mid-Norwegian continental shelf this species is found throughout most of the Tertiary. The planktonic foraminifer *G. bulloides* is found today along the Norwegian margin further south. In Pliocene deposits drilled by ODP Leg 104 from the Vøring Plateau there is a strong dominance of this species together with *Neogloboquadrina atlantica* before 2.3 Ma (Spiegler and Jansen, 1990). Throughout the last 2.3 Ma *G. bulloides* is only rarely found in the warmest interglacials of the last 1 Ma, i.e. corresponing to Zone

Fig. 12. Scanning micrographs documenting the main index fossils. 1. *Islandiellea islandica*, × 133, 7117/9-1, 560 m; 2. *Neogloboquadrina pachyderma* (sinistral), × 233 7117/9-1, 450 m; 3. *Neogloboquadrina pachyderma* (sinistral), ("Encrusted" form), × 233, 7117/9-1, 450 m; 4. *Cibicides grossus*, × 100, 7117/9-1, 660 m; 5. *Cibicides grossus*, × 100, 7117/9-1, 660 m; 6. *Elphidiella hannai*, × 133, 7117/9-2, 1070 m; 7. *Globigerina bulloides*, × 233, 7117/9-1,1080 m; 8. *Geodia* sp., × 333, 7117/9-1, 1110 m; 9. *Cenosphaera* sp., × 233, 7117/9-1, 900 m; 10. *Cyclammina amplectens*, × 100, 7117/9-2, 1180 m; 11. *Inoceramus* prism, × 67, 7117/9-1, 900 m; 12. *Triceratium* sp., × 333, 7117/9-1, 910 m; 13. *Coscinodiscus* sp. 1 (Bettenstaedt et al., 1992), × 100, 7117/9-1, 885 m.

A. Thus, common occurrence of this species at high latitudes, probably relates to its maximum abundance zone defined at the Vøring Plateau south of the Bjørnøyrenna Fan (Fig. 1). We did not find *N. atlantica* associated with *G. bulloides* which is the case on the Vøring Plateau. Data from the mid-Norwegian Shelf landward of the Vøring Plateau (Eidvin and Riis, 1991) and from the northern North Sea (Eidvin and Riis, 1992) indicate, however, that there is a tendency of *N. atlantica* to stay away from more coastal areas in the Pliocene. We believe that this explains the absence of *N. atlantica* from coeval sediments from the Barents Sea holes. Based on this correlation, Zone D must be older than 2.3 Ma. A maxiumum abundance zone of *G. bulloides* is also described in North-Atlantic records from DSDP Leg 94 (Weaver and Clement, 1987), and was assigned an age of 2.4–2.1 Ma based on paleomagnetic data. The onset of strong *G. bulloides* occurrence took place in the lower normal polarity interval in the Gilbert Chron at about 4.4 Ma on the Vøring Plateau (Jansen and Spiegler, 1990; Bleil, 1990). This gives a maxium age of early Pliocene for Zone D. Based on sedimentological evidence (see below) we prefer to correlate Zone D to the upper part of the 4.4 to 2.3 Ma interval of high *G. bulloides* content in the Vøring Plateau record. This is now supported by new Ar/Ar data on volcaniclastics in sediments below the fan west of Bjørnøya, dating pre-fan sediments at 2.2–2.35 Ma (Mørk et al., 1993).

Our conclusion is therefore that the zone contains sediments of Pliocene age, probably slightly older than 2.3 Ma. The same mixed assemblage of Mesozoic, Paleogene and Miocene microfossils we found in the upper zones is also represented here. They are believed to be redeposited as a result of the erosion which led to the formation of the fan.

Below Zone D in Hole 7117/9-1 we record a microfossil fauna entirely consisting of agglutinated foraminifers and reticulate radiolarians (*Caenospaera* sp.). In contrast to the overlying zones they are not worn and fragmented, but appear fresh. No appearance of younger fossils is observed. The presence of *Reticulophragmium amplectens* and *Caenospaera* sp. indicates that these are lower/middle Eocene sediments correlatable to faunal Zones NSA 4 and NSP 6 in the North Sea zonation (King, 1989). Since these fossils are unfragmented and do not appear worn, and the sediments contain no mentionable amounts of younger fossils, we conclude that the sediments below Zone D are in situ Eocene deposits.

Below Zone C in Hole 7117/9-2 we observe a pure diatom microfossil flora with pyritized specimens. Among these we find *Coscinodiscus* sp. 1 (Bettenstedt et al., 1962) which indicates upper Paleocene–lower Eocene sediments. This corresponds to faunal Zone NSP 4 in the North Sea (King, 1989). We conclude that these sediments also are in situ Eocene deposits.

Based on the total absence of younger sediments and the common presence of Paleogene microfossils we propose that the lower zones of the wedge are directly underlain by in situ late Paleocene to middle Eocene deposits in the two holes on the Senja Ridge.

Hole 7119/7-1

This hole was drilled eastward of the Fan (Fig. 1) and contains a different biostratigraphic sequence than the two other holes to the west (Fig. 11).

360–460 m: The upper sedimentary section has a nearly identical fossil assemblage as Zone A in the two other holes and contains common *N. pachyderma* sin. (both encrusted and non-encrusted varieties). Dextrally coiling *N. pachyderma* is rare. Scattered late Cretaceous foraminifers are present.

460–590 m: This section contains a highly mixed assemblage. Agglutinated foraminifers such as *Reticulophragmium amplectens* and reticulate radiolarians indicating an early/middle Eocene age (King, 1989) predominate. Scattered Plio-Pleistocene foraminifers are also found. In addition to these, rare Oligocene–Miocene foraminifers occur in higher abundance than in the overlying interval. There is a lithologic boundary at 460 m in this hole. Above this level, distinct unconsolidated sediments are observed, while below are consolidated mudstones and scattered limestone layers. It is possible that the consolidated sediments are Eocene in age, and that the younger fossils represent downfall. No distinct zonation markers are found in the unit. It is also possible that some material was deposited by slides. A fault which may have caused such disturbance crosses the unit at about 0.7 s (Fig. 8).

590–885 m: This section is very fossil poor, and contains scattered agglutinated foraminifers and pyritized diatoms of the genus *Coscinodiscus* sp. According to King (1989) faunal Zones NSB 2 and NSP 4 from the North Sea are characterized by co-occurring diatoms of the genus *Coscinodiscus* sp. 1 and sp. 2 (Bettenstedt et al., 1962), representing the late Paleocene–early Eocene. We use this as the best age assignment for this sequence in the Barents Sea.

885–950 m: The section contains common *Coscinodiscus* sp. 1 which places the sediments in the late Paleocene–early Eocene (King, 1989).

Sediments corresponding to Zones B, C and D which define the Bjørnøyrenna Fan sequence are missing from this hole, as was also evident in the seismic record, documenting that fan sedimentation was limited to the areas west of this location.

Biostratigraphic conclusions

Previous studies of these sediment sections concluded that the sediments covering Zones B, C and D were in-situ Eocene–Miocene sediments. Younger fossils were considered to represent downfall, and the older considered redeposited in the Eocene (unpubl. industry reports). Spencer et al. (1984) contend that the section containing Zones B, C and D in Hole 7117/9-1 is of Oligocene to Pliocene age. Our biostratigraphic study indicates that these conclusions most likely are wrong, and that the whole fan sequence is younger, due to the following reasons:

(1) There is a well defined zonation of Plio-Pleistocene assemblages in both holes. The zonation represents a reasonable chronological succession which can be correlated to the mid-Norwegian Shelf and the North Sea. The boundaries between the zones are found at similar depths in both holes, making downhole contamination an unlikely reason for the appearance of young microfossils. The zonal boundaries correspond to marked reflector horizons (Fig. 3).

(2) The upper occurrence of the Pliocene foraminifer *E. hannai* is found at large sediment depth. Above this depth a 20-inch casing was mounted, thus making it highly unlikely that the reason it was found so deep originates from downfall. The likely reason is that the sediments are late Pliocene in age, documenting extremely high Plio-Pleistocene sedimentation rates.

(3) Surface textures of fossils older than the Plio-Pleistocene show clear signs of redeposition.

(4) In the sediments below the assemblage zones, i.e. below the fan, we find no Plio-Pleistocene fossils, indicating that downhole contamination is a minor problem. Redeposition of Jurassic–Paleogene microfossils higher in the section was probably very common due to the erosive processes that formed the fans.

(5) Recent Ar/Ar data on volcaniclastic debris in sediments below the fan in the area west of Bjørnøya, give ages of 2.20–2.35 ± 0.12 Ma (Mørk et al., 1993), thereby confirming our conclusion of a young (late Pliocene and younger) age for the formation of the fans.

Strontium isotope results

Strontium isotope analyses of calcareous material (mollusc fragments) were performed at selected levels in holes 7117/9-1 and -2 (Fig. 13). Age information from the $^{87}Sr/^{86}Sr$-ratio can be gained by comparison to global strontium isotope curves (Palmer and Elderfield, 1985; DePaolo and Ingram, 1985; Koepnick et al., 1985; DePaolo, 1986; Hess et al., 1986). The results are shown in Fig. 13 and Table 1, and document the spread in ages we expect from the mixed microfossil assemblages which includes both autochtonous and allochtonous fossils, thus the age information from the Sr-isotope analyses is not conclusive. However, viewed in the context of the erosive processes responsible for the fan formation, they may be taken as support for our age inference. The main result is that material interpreted to be in-situ Plio-Pleistocene shows systematic changes in age which supports the age interpretation based on the biostratigraphic zones. These are the younger ages given in Fig. 13. Material from Zone C gives late

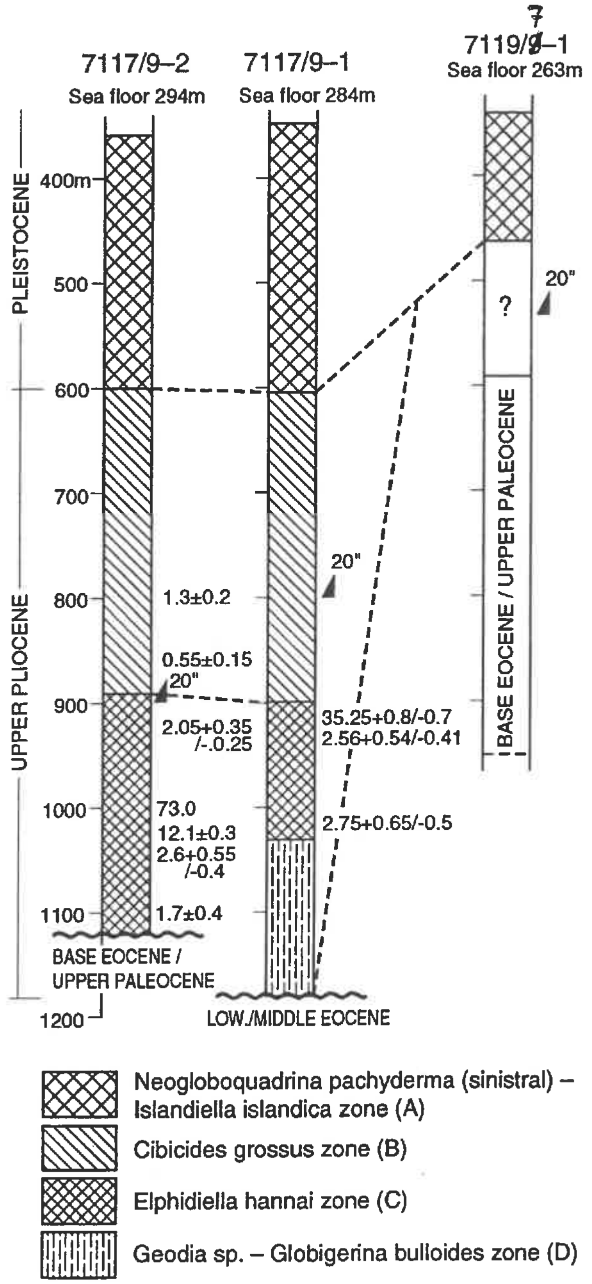

Fig. 13. Correlation of faunal zones between the holes studied. Also shown is the relationship between faunal zones and Sr ages and the position of the 20-inch casing.

Pliocene ages (2.05–2.75 Ma). The Sr age of material from Zone B is somewhat younger than the biostratigraphic determined age (Samples Sr 1 and Sr 2, Table 1). This discrepancy may be due to the inaccuracy of the Sr-method or downfall.

TABLE 1

Strontium isotope analyses of the mollusc fragments

Sample	Depth (m RKB)	$^{87}Sr/^{86}Sr$	$^{87}Sr/^{86}Sr$ (normalised)	Date (Ma)	Uncertainty (Ma)
Hole 7117/9-1					
Sr 1	800	0.709021	0.709005	1.30	+0.2/−0.2
Sr 2	860	0.709054	0.709038	0.55	+0.15/−0.15
Sr 3	940	0.708996	0.708980	2.05	+0.35/−0.25
Sr 4	960	0.708611	0.708595	16.00	
Sr 5	1000	0.707633	0.707617	73.00	
Sr 6	1020	0.708786	0.708770	12.10	+0.3/−0.3
Sr 7	1040	0.708981	0.708965	2.60	+0.55/−0.4
Sr 8	1100	0.709007	0.708991	1.70	+0.4/−0.4
Hole 7117/9-2					
Sr 9	810	0.707314	0.707298	109, 117, 140	
Sr 10	920	0.707809	0.707793	35.25	+0.8/−0.7
Sr 11	945	0.708942	0.708966	2.56	+0.54/−0.41
Sr 12	1015	0.708978	0.708962	2.75	+0.65/−0.5
Sr 13	1115	0.707501	0.707485	80, Jur. Perm.	

Paleoenvironmental indicators

The presence of planktonic foraminifers in near-coast/shelf regions indicates open marine environments, high salinity and absence of low salinity coastal waters. Planktonic foraminifers are common in the upper Zone D and in Zone A, indicating relatively deep waters under the deposition of these zones. *E. hannai* is by many workers believed to be a shallow-water indicator (Feyling-Hanssen, 1986; Skarbø and Verdenius, 1986; King, 1989), indicating rather shallow water during the formation of Zone C. Some influx of planktonic foraminifers and the deeper dwelling *C. grossus* (Feyling-Hanssen, 1986; Skarbø and Verdenius, 1986; King, 1989) in Zone B indicates that the water depth increased again after the deposition of Zone C.

Ice rafted material

The sediments recovered from Zones A–D consist mainly of unconsolidated material. Common to them is the frequent presence of gravel sized rock fragments. These are angular to sub-angular, a majority of these fragments consists of sedimentary rocks typical for the Barents Shelf, while a significant contribution comes from crystalline rock fragments (see example in Fig. 14). The significant presence of sub-angular gravel is interpreted to result from ice-transport either as ice-rafted material (IRD) or directly deposited by ice-sheets.

ODP Leg 104 holes from the Vøring Plateau provide a nearly continuous record of IRD-deposition over the last six million years in the eastern Norwgeian Sea (Fig. 15; Jansen and Sjøholm,

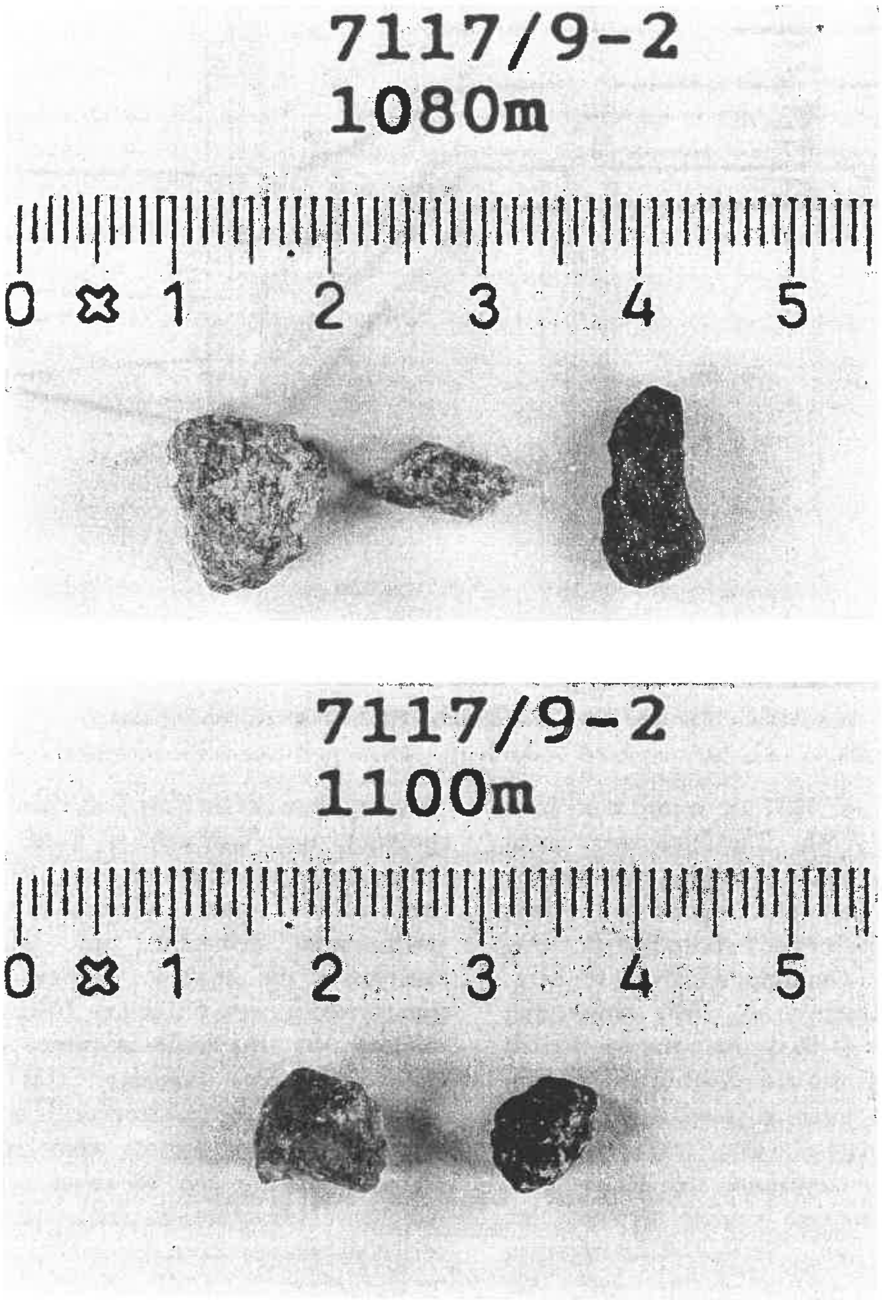

Fig. 14. Pictures of common sub-angular rock fragments of believed glacial origin. Scale in centimeters.

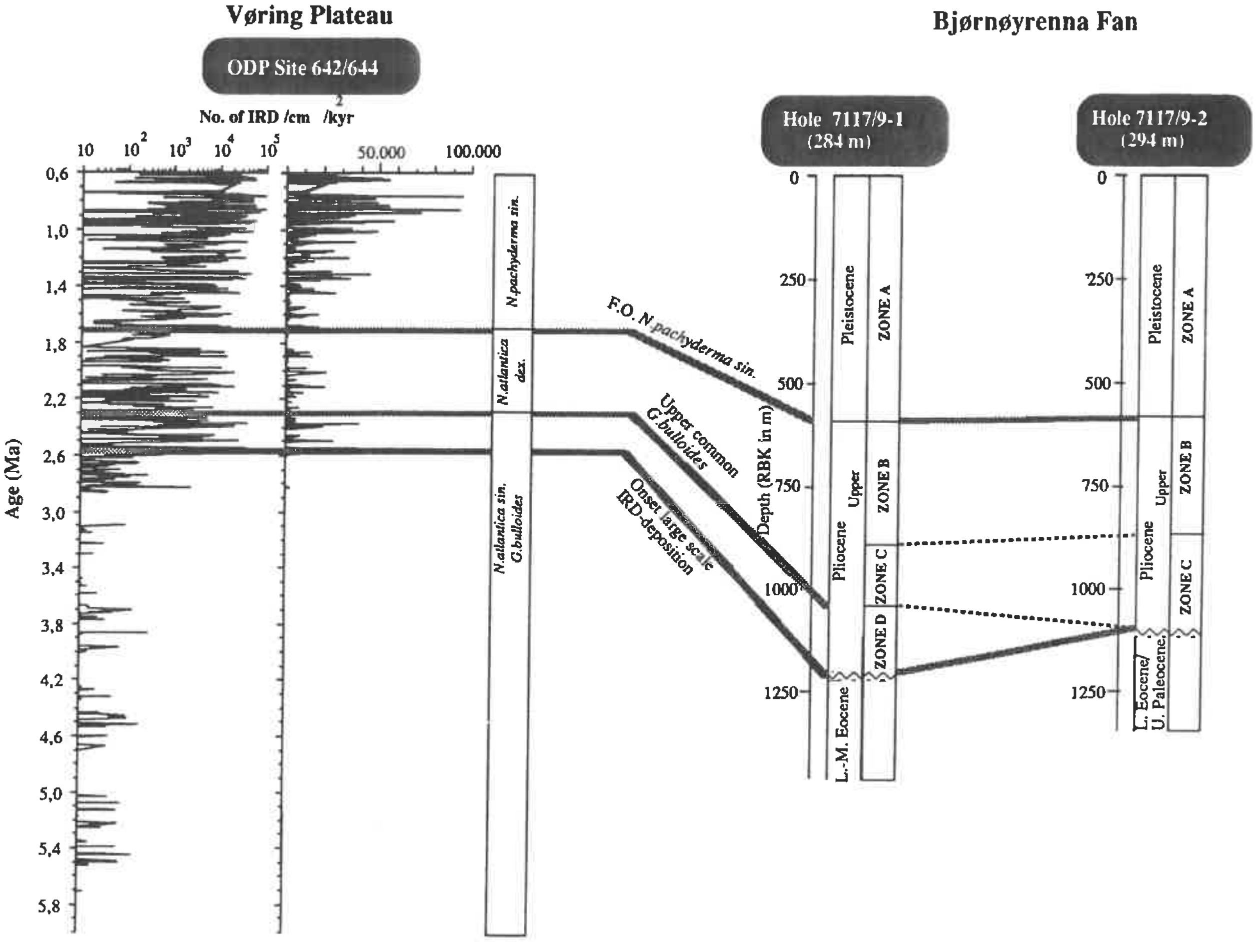

Fig. 15. Correlation of Vøring Plateau ODP sites (Jansen and Sjøholm, 1991) and Barents Sea stratigraphy.

1991). Small fluxes of IRD are recorded in sediments as old as 5.5 Ma. The fluxes were small until 2.56 Ma, when IRD-deposition increased by several orders of magnitude, signalling the time when large ice sheets formed in Scandinavia, being able to spread large quantities of calving ice-bergs over the ocean (Jansen et al., 1990; Jansen and Sjøholm, 1991). It is likely that the ice-derived material of the fans was deposited in conjunction with this phase of enhanced glaciation and thus postdates approximately 2.6 Ma. This corresponds well with the above contention that Zones D–A are of late Pliocene and younger age and the correlation of the Vøring Plateau biostratigraphy with the holes investigated in this study. We illustrate this relationship in Fig. 15.

DSDP Site 344 drilled during Leg 38 of DSDP is located east of the Knipovitch Ridge in the distal portions of the Storfjord Fan (Fig. 1). A sill, probably near basement, is dated at 3 Ma by potassium/argon (Talwani et al., 1976). The sediment column contains mixtures of turbidites and glaciomarine sediments, and biostratigraphic analyses of the sequence (Talwani et al., 1976) interpreted in view of the Leg 104 biostratigraphy indicate that the whole sequence postdates the Miocene/Pliocene boundary. This indicates a young age also for the Storfjord Fan.

Oxygen isotope records which reflect the late Tertiary cooling and the onset of large scale Northern Hemisphere glaciation document a series of glacial phases superimposed on a cooling trend in the period 3.5–2.3 Ma (Shackleton et al., 1984; Keigwin, 1987; Raymo et al., 1989; Sarnthein and Thiedemann, 1992; Jansen et al., in press). While the onset of large scale IRD-deposition appears like a sudden step (Fig. 15), the oxygen isotope records indicate a trend toward stronger glaciation during this period. Commencement of glacial erosion and deposition on the Barents Shelf most likely happened as a part of this evolution. The signs of IRD on the Vøring Plateau in the Messinian at 5.5 Ma probably represents a maximum age for the deposition of glacial debris off the Barents Shelf. The low flux before 2.56 Ma indicates, however, that significant glacial erosion on the shelf areas off northern Europe commenced after this time. Hence, the time when glacial processes were intense enough to build large fans probably was after 2.6 Ma. An intensification of glaciation and a shift to dominant 100-kyr cyclicity in ice-volume fluctuations took place after 1 Ma. This is clearly documented by the increased IRD-flux shown in Fig. 15, and in oxygen isotope records (Shackleton et al., 1984; Raymo et al., 1989; Ruddiman et al., 1989). It is likely that this also marked an intensification of glacial erosion in the Barents Sea. We suggest that this period corresponds to the sequence deposited during most of Zone A in the Bjørnøyrenna Fan. Since the zone is bounded by a lower unconformity according to seismic data, it is not clear how long the period represented by the zone really is. The biostratigraphic resolution is also not sufficient to accurately date the base of Zone A.

Discussion

Trough mouth fans of variable sizes are found off a number of formerly glaciated shelves both off the North Sea, off Greenland, off Spitzbergen, in the Arctic Ocean and in Antarctica, in addition to the ones off the Barents Sea. It appears that particularly active sediment transport takes place in shelf areas with localized troughs. While it is uncontroversial that the fans partly are formed due to glacial erosion and deposition, the onset of fan build-up and the time needed to produce them is more problematic to assess.

The young age for the Bjørnøyrenna Fan advocated for in this paper indicates that glaciation on shelves is a highly active erosion agent, capable of retransporting vast sediment quantities. A number of processes probably interacted to produce this result: direct glacial erosion by ice-sheets based in the Barents Sea. Most of the Barents Sea was ice covered during the last glacial maximum (Vorren et al., 1989, 1990; Elverhøi et al., 1988), and we presume this was the case also in a number of earlier glaciations. The deep erosional channels related to the base of the wedge in the Bjørnøya area (Sættem et al., 1992) indicate that the ice margin was located very close to these localities as early as the late Pliocene. Given the 2.6 Ma age for the onset of repeated strong glaciations in Scandinavia (Jansen et al., 1990; Jansen and Sjøholm, 1991) it is likely that the shelf was covered by ice during a major part of this period. The rapid shifts of regressions/transgressions due to the combination of glacio-eustatic sea-level variations and glacio-isostatic compensation also contributed to sediment removal and redistribution.

The high rates of erosion in the Barents Sea, particularly in the late Pliocene, may possibly be related to a topography different from the present one. Purely theoretical considerations indicate that the isostatic effect of removing a sheet of 1000 m of sediments with a density slightly above 2 g/cm^3, will be a lowering of the surface of approximately 500–600 m (Riis and Fjeldskaar, in press; Vågnes and Faleide, in press). Thus, the Barents Sea may have been elevated above sea level prior to the onset of the Pliocene erosion phase.

From bore-holes it is also known that the Stappen High in the Barents Sea and the Svalbard orogenic belt were strongly affected by tectonic movement, mainly in Eocene times (Gabrielsen et al., 1990; Wood et al., 1990). Compression tectonics probably related to this phase is described from the northern Barents Sea (Gabrielsen et al., 1990). We suggest that these tectonic movements caused uplift which preconditioned the area for glaciation due to the increased altitude.

This suggests that in the northwestern and northern parts of the Barents Sea, much of the observed erosion can be related to Paleogene tectonic uplift, while in the central Barents Sea, Tertiary tectonic effects were weak. Here, the main erosion can be related to glacial processes, and the uplift can be interpreted mainly as an isostatic compensation to the erosion.

The Barents Sea stratigraphy contains excellent source rocks and reservoirs for hydrocarbons. So far, however, prospecting has resulted only in a limited number of gas discoveries. In most prospects, residual oil is abundant, while significant quantities of movable oil are reported from one field only (Snøhvit). Apparently none of the discovered fields are filled to the spill point. It can be argued that the hydrocarbon traps were affected by intense Neogene erosion in a number of ways, causing leakage and redistribution of gas and oil (Skagen, 1993; Riis, in press). The most important effect is suggested to be the cooling related to the removal of overburden which stopped hydrocarbon generation in mature Triassic and Jurassic source rocks in the large platform areas of the Barents Sea. Thus, in most of the traps, no gas was being created to replace the gas that was leaking out of the traps during the last 1–2 million years.

Acknowledgements

Special thanks are due to O. Skarbø for sharing results and to S. Olafsen, B. Ruus, R. Williams and J. Ellingsen for technical assistance. We also thank K.R. Bjørklund, P. Blystad, W. Fjeldskaar, D. Helliksen, E. Mearns, F. Moe, Aa. Moe and P. van Veen for contributing in different ways to this study. GECO is thanked for providing seismic lines.

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