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# Palynological and foraminiferal biostratigraphy of (Upper Pliocene) Nordland Group mudstones at Sleipner, northern North Sea

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## Abstract

The Nordland Group is an important stratigraphical unit within the upper Cenozoic of the northern North Sea. At its base lies the Utsira Sand, a dominantly sandy regional saline aquifer that is currently being utilized for carbon dioxide sequestration from the Sleipner gas and condensate field. A ‘mudstone drape’ immediately overlies the Utsira Sand, forming the caprock for this aquifer. The upper part of the Utsira Sand was recently dated as Early Pliocene, but the precise age of the overlying Nordland Group mudstones has remained uncertain. Dinoflagellate cyst, pollen and spore, foraminiferal and stable isotopic analyses have been performed on these mudstones from a conventional core within the interval 913.10–906.00 m (drilled depth) in Norwegian sector well 15/9-A-11. The samples lie closely above the Utsira Sand. Results give a Gelasian (late Late Pliocene) age for this interval, with a planktonic foraminiferal assemblage at 913.10 m indicating warm climatic conditions and an age between 2.4 and 1.8 Ma. An abundance of the cool-tolerant dinoflagellate cysts *Filisphaera filifera* and *Habibacysta tectata* at 906.00 m, along with evidence from pollen and foraminifera, points to deposition during a cool phase of the Gelasian. Dating the mudstone drape provides useful insights into depositional processes. It seems likely that the Utsira Sand, a basinal lowstand deposit, became progressively starved of clastic input as sea level rose and shorelines retreated. The mudstone drape is interpreted as a highstand deposit, perhaps including a maximum flooding surface. Overlying prograding wedges of the Nordland Group form a regressive succession, characterized by increased sedimentary input and rates of deposition of at least 25 cm per 1000 years, which is more than five times that of the Utsira Sand.

This is the first published study of a dinoflagellate cyst assemblage from the Upper Pliocene of the northern North Sea. The new dinoflagellate cyst species *Echinidinium nordlandensis* Head sp. nov. and *Echinidinium sleipnerensis* Head & Riding sp. nov. are formally described.

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**Keywords:** Dinoflagellate cysts; Foraminifera; Stable isotopes; Pliocene; North Sea

## 1. Introduction

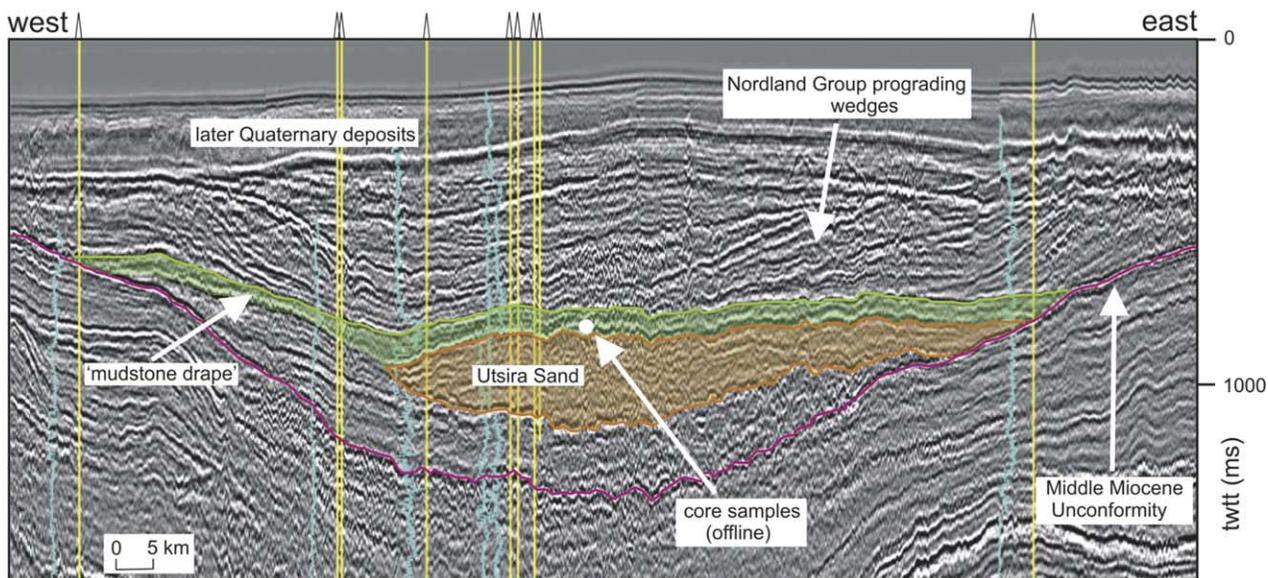
The world’s first industrial-scale carbon dioxide sequestration project is in progress at Sleipner in the Norwegian sector of the northern North Sea (Baklid, Korbøl, & Owren, 1996). Carbon dioxide (about 9%) separated from natural gas produced at Sleipner West, a Middle Jurassic gas and condensate field, is being injected into a subsurface saline aquifer, the Utsira Sand (Fig. 1), as an environmentally

preferable alternative to atmospheric venting. The CO<sub>2</sub> injection well is situated on the nearby Sleipner East, a Palaeocene gas and condensate field whose reservoir lies deep beneath the Utsira Sand. The international SACS (Saline Aquifer CO<sub>2</sub> Storage) project is studying the subsurface aspects of the CO<sub>2</sub> injection operation, and aims to monitor and predict the underground behaviour of the CO<sub>2</sub> plume.

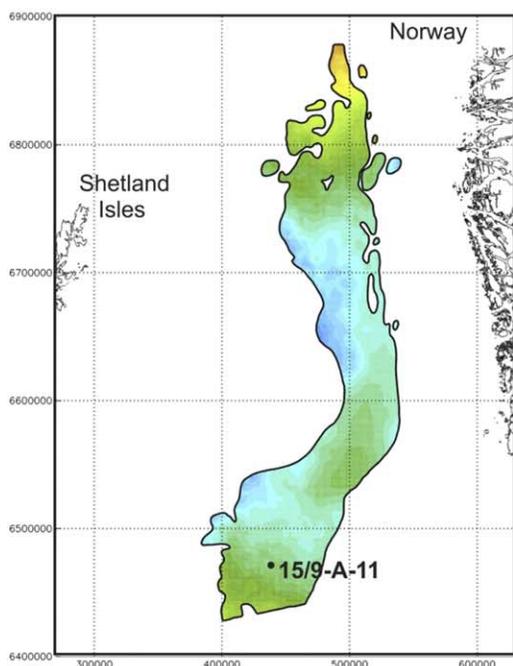
The Utsira Sand is overlain by dominantly argillaceous strata of the Nordland Group, which play a key role as the principal sealing unit. As part of the SACS studies, a conventional core was taken from within the Nordland Group in well 15/9-A-11 to test its sealing efficacy. The core was cut some 20–25 m above the Utsira Sand (Fig. 1A).

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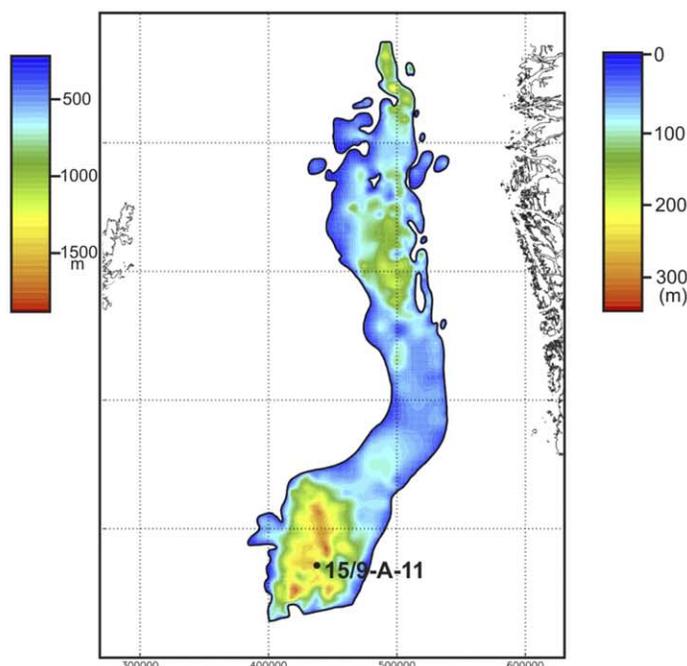
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A



B



C

Fig. 1. (A) Regional seismic line across the Cenozoic sag-basin of the northern North Sea, showing generalised stratigraphy and the position of core samples. The position of the Middle Miocene Unconformity is shown (Rundberg and Eidvin, unpublished). The vertical yellow lines represent well-bore profiles, and the vertical blue lines represent gamma-ray well-log traces (the Utsira Sand shows as a gamma-ray decrease, i.e. a leftward deflection in the log trace). (B) Depth contours to the top of the Utsira Sand. (C) Thickness of the Utsira Sand. Location of well 15/9-A-11 and other key wells also shown.

Four samples from the core, at drilled depths between 906.00 and 913.10 m (about 784–790 m true vertical depth below sea-level, TVDBSL), were analysed for palynomorphs and foraminifera. One sample from 906.00 m was analysed for palynomorphs, and three samples between 912.40 and 913.10 m were studied for foraminifera. The investigation aimed at determining the precise age and depositional environment of these caprocks to the Utsira Sand. The upper part of the Utsira Sand has been variously

dated as Late Miocene (Gregersen, Michelsen, & Sørensen, 1997, fig. 3; Isaksen & Tonstad, 1989), Early Pliocene (Eidvin & Rundberg, 2001; Piasecki, Gregersen, & Johanessen, 2002), or early Late Pliocene (Eidvin, Jansen, Rundberg, Brekke, & Grogan, 2000; Eidvin, Riis, & Rundberg, 1999; Eidvin, Rundberg, & Smelror, 2002). The base of the Nordland Group mudstones has been dated as Late Miocene (Gregersen et al., 1997, fig. 3) or early Late Pliocene (Eidvin et al., 1999). Establishing the precise age

of the base of the Nordland Group mudstones, and determining whether these deposits are synchronous across the basin, is necessary to gain insights into the depositional processes and sequence stratigraphy of the region.

The formal lithostratigraphic term Utsira Formation, as defined by Isaksen and Tonstad (1989), is not used in the present paper because difficulties have arisen over the definition of its base in the type well (Eidvin et al., 2002). Instead, the more descriptive term Utsira Sand is given as this represents an unambiguous unit in seismic sections in the Sleipner area. The timescales of Berggren et al. (1995a) and Berggren, Kent, Swisher, and Aubry (1995b) are adopted throughout, and ages cited in the earlier literature have been updated accordingly.

## 2. Geological background

Norwegian sector well 15/9-A-11 was drilled at 58° 22' 2.67" N, 1° 54' 30.04" E within the Sleipner Field in the Norwegian sector of the northern North Sea (Fig. 1). The northern North Sea Basin, along with the Viking Graben, has formed a rapidly subsiding epicontinental basin since early Mesozoic times. It was initiated during the Jurassic with continental lithospheric extension as its dominant structural feature (Evans, Graham, Armour, & Bathurst, 2003). Extension ceased in Early Cretaceous times, and the northern North Sea Basin subsequently subsided as a regional post-rift sag (Giltner, 1987), with deposition of a thick Cenozoic post-rift clastic succession. The British and Scandinavian land–shelf areas, which confined the post-rift northern North Sea Basin to the west and east, underwent as many as six phases of relative uplift during late Palaeogene and Neogene times (Galloway, Garber, Liu, & Sloan, 1993; Hansen, 1996; Japsen & Chalmers, 2000; Jordt, Faleide, Bjørlykke, & Ibrahim, 1995). These uplifts were followed by major episodes of siliciclastic sedimentation, principally during the Palaeocene, Eocene, Oligocene and Miocene, which Galloway et al. (1993) interpreted as onlap-defined megasequences.

In Miocene times, the northern North Sea Basin formed a shallow marine sag-basin with deposition of the mud-dominated Hordaland Group (Fig. 2). The group also includes three sand-dominated units, the Frigg, Grid and Skade formations (Isaksen & Tonstad, 1989, fig. 40). Within the Hordaland Group, the Middle Miocene Unconformity (Fyfe et al., 2003; Ziegler, 1981) is a regional feature particularly prominent on the eastern flank of the basin (Fig. 1A; Ghazi, 1992; Isaksen & Tonstad, 1989, fig. 40). The Nordland Group overlies the Hordaland Group and comprises the basal, dominantly sandy Utsira Sand, and overlying dominantly argillaceous units (unnamed). It is locally over 1500 m thick with strata ranging in age from late Middle Miocene through Holocene (Eidvin et al., 1999; Isaksen & Tonstad, 1989).

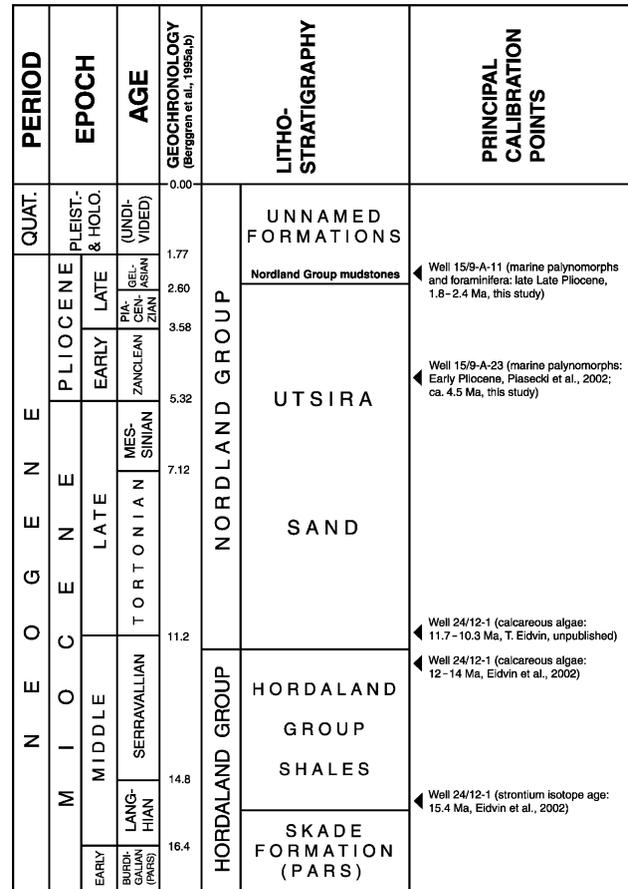


Fig. 2. A diagrammatic representation of the chronostratigraphy of the Nordland Group and the uppermost Hordaland Group in the Viking Graben, northern North Sea. The term Utsira Sand is used in preference to Utsira Formation for reasons given in the text. The principal calibration points are the present study of the lowermost Nordland Group mudstones of well 15/9-A-11, the palynological study of the Utsira Sand of well 15/9-A-23 by Piasecki et al. (2002) and the work on calcareous algae and strontium isotopes in well 24/12-1 by Eidvin et al. (2002) and Eidvin (unpublished data).

The Utsira Formation, first defined by Deegan and Scull (1977), forms an elongate, basin-restricted unit extending some 400 km from north to south and typically 50–100 km wide. The uppermost part of the formation is fine-grained, but by far its greater part comprises a dominantly sandy unit informally referred to as the Utsira Sand (Chadwick, Holloway, Kirby, Gregersen, & Johannessen, 2000; Chadwick et al., 2004). In the basin centre, the Utsira Sand overlies the uppermost Hordaland Group shales, but eastwards on the basin flank, it onlaps the Middle Miocene Unconformity (Fig. 1A). The Utsira Sand was deposited in two main depocentres, one around Sleipner where thicknesses range from 200 to 300 m, and the other near its northerly limits, with thicknesses around 200 m (Fig. 1C; Chadwick et al., 2000). It is believed to have been sourced largely from the uplifted East Shetland Platform to the west, with a significant component of Scandinavian-derived material in its northern part (Rundberg & Eidvin, 2002).

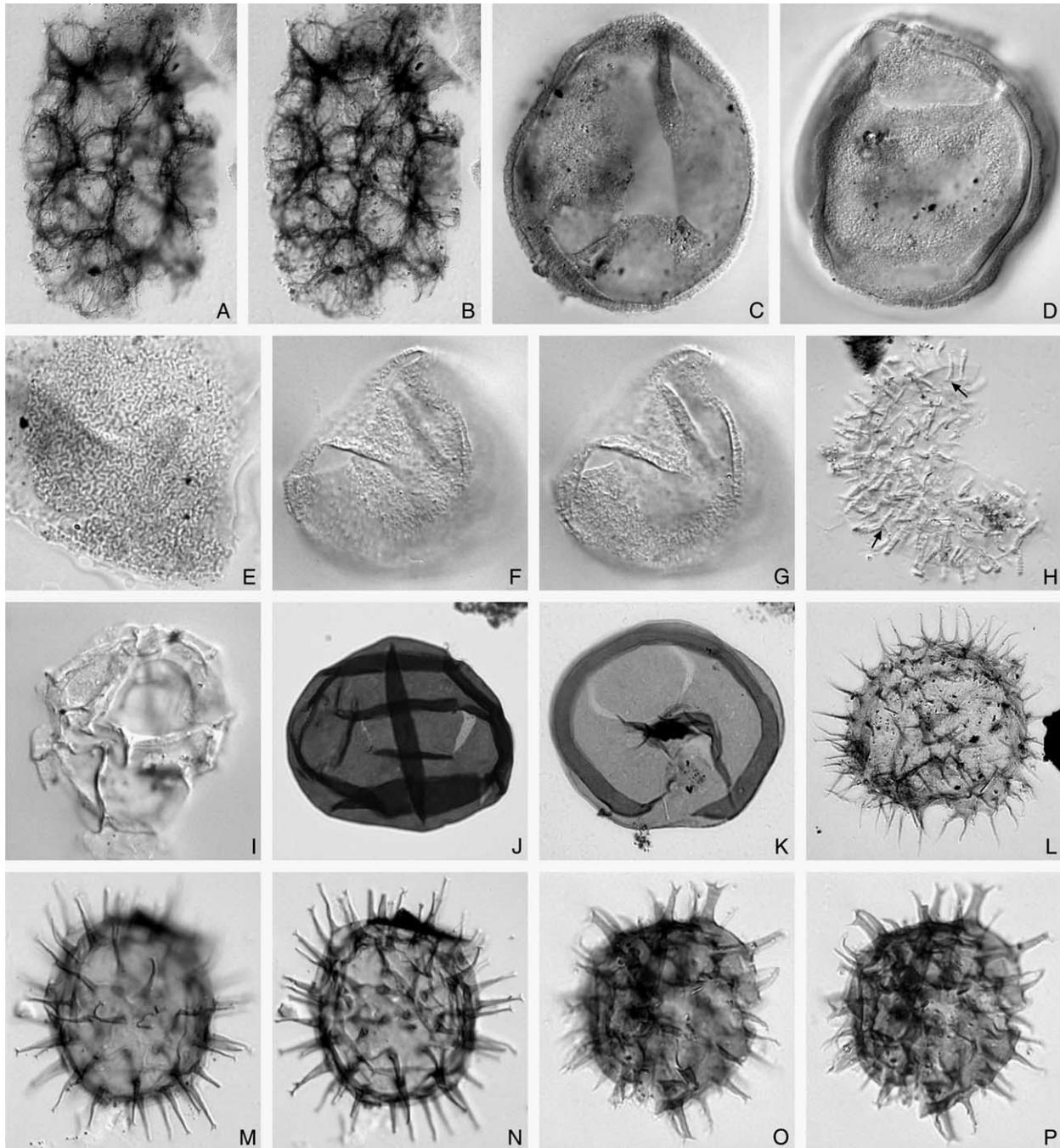


Fig. 3. Selected dinoflagellate cysts from the Nordland Group mudstone of Norwegian sector well 15/9-A-11 at 906.00 m depth. Various magnifications; an England Finder reference follows the slide number for each specimen. (A, B) *Polykrikos* sp. cf. *Polykrikos schwartzii*, equatorial view at upper (A) and mid (B) focal levels, showing fibrous and unusually high reticulation; maximum length including luxuria, 91  $\mu\text{m}$ ; specimen MPK 12786, slide 3, G20/4. (C) *Filisphaera filifera* subsp. *filifera*, dorsal view at mid focus showing high, microreticulate luxuria; maximum length, 62  $\mu\text{m}$ ; specimen MPK 12787, slide 3, W10/2. (D) *Operculodinium psilatatum*?, dorsal view of dorsal surface showing spongy luxuria of uneven thickness; maximum length, 62  $\mu\text{m}$ ; specimen MPK 12788, slide 3, W10/2. (E) *Bitectatodinium tepikiense* (vermiculate morphotype), external view of fragment showing details of wall ornament; height of figure, 36  $\mu\text{m}$ ; specimen MPK 12789, slide 1, G21/3. (F, G) *Habibacysta tectata*, right lateral view at upper (F) and slightly lower (G) focal levels showing the 1P archeopyle with rounded angles; maximum length, 38  $\mu\text{m}$ ; specimen MPK 12790, slide 1, W10/2. (H) *Nannobarbophora walldalei*, upper surface of torn specimen showing solid processes, some with root-like bases (e.g. as indicated by arrows); maximum diameter of central body, 37  $\mu\text{m}$ ; specimen MPK 12791, slide 1, F33/0. (I) *Impagidinium paradoxum*, ventral view at mid focus; maximum length including crests, 33  $\mu\text{m}$ ; specimen MPK 12792, slide 2, C14/3. (J) Round brown cyst, probably *Brigantedinium* sp., ventral view of dorsal surface; maximum diameter, 53  $\mu\text{m}$ ; specimen MPK 12793, slide 2, E09/0. (K) *Selenopemphix nephroides*, antapical view at mid focus; width, 59  $\mu\text{m}$ ; specimen MPK 12794, slide 3, H21/3. (L) *Selenopemphix quanta*, antapical view at mid focus; central body width, 54  $\mu\text{m}$ ; specimen MPK 12795, slide 1, C18/0. (M, N) '*Echinidinium aculeatum*', upper (M) and lower (N) focal levels; maximum diameter of central body, 27  $\mu\text{m}$ ; specimen MPK 12796, slide 1, D08/0. (O, P) *Echinidinium nordlandensis* Head sp. nov., holotype, upper (O) and lower (P) focal levels; central body maximum diameter, 30  $\mu\text{m}$ ; specimen MPK 12797, slide 1, F35/4.

The Utsira Sand is lithologically distinct from the surrounding dominantly argillaceous strata. It is readily recognizable by its characteristic well log signature (Piasecki et al., 2002, fig. 3), and on seismic data as a distinctive seismically transparent basin-restricted unit (Fig. 1A). Seismic and well data have been interpreted as showing the Utsira Sand as a composite fan-like body, comprising stacked, low-relief mounds of sand, with interspersed thin beds of shale (Gregersen et al., 1997). The lowermost sand mounds are located centrally around the basin axis with successive mounds progressively more extensive and onlapping to east and west. Three depositional models have been proposed for the Utsira Sand: firstly, a sand-ridge complex formed by marine currents, possibly tidal, flowing through a relatively narrow seaway where sand deposition was interrupted by periods of non-deposition and vigorous reworking (Eidvin et al., 2002; Rundberg, 1989; Rundberg & Eidvin, 2002); secondly, a geostrophic-induced, contourite drift complex (Galloway, 2002; Galloway et al., 1993); or thirdly, a possible turbiditic/massflow deposit sourced by the erosion and cannibalisation of updip shelf sands (Gregersen et al., 1997; Piasecki et al., 2002). Regardless of model, the unit is here interpreted as a lowstand deposit. A possible transgressive motif, particularly in the upper parts of the Utsira Sand, is suggested by the incoming of later glauconitic deposits, and, locally, an upwards increase in the thickness and frequency of the shale interbeds (see Section 7).

Mudstones, claystones and siltstones of the Nordland Group overlie the Utsira Sand and form its caprock. The lowest caprock unit was informally termed the ‘shale drape’ by Chadwick et al. (2000), but is here called the ‘mudstone drape’ to accord more accurately with its lithology. The mudstone drape (Fig. 1A) has a basin-restricted geometry similar to that of the underlying Utsira Sand, and generally overlaps it, such that eastwards it onlaps the Middle Miocene Unconformity, and westwards it onlaps pre-Utsira prograding wedges and in the far west, the Middle Miocene Unconformity (Fig. 1A). Cuttings samples from the mudstone drape, from both UK and Norwegian wells around Sleipner, show a soft grey silty mudstone (Chadwick et al., 2004). The core samples examined for this paper are from the mudstone drape, some 20–25 m above the Utsira Sand.

Above the mudstone drape, strata of the Nordland Group form a thick, generally regressive succession of sedimentary wedges, which coarsens both upwards and outwards away from the basin centre (Fyfe et al., 2003; Gregersen et al., 1997). The wedges prograde basinwards from the elevated massifs to east and west, thus westwards from the Scandinavian massif and eastwards from the east Shetland Platform (Fig. 1A). There is evidence of cyclicity, and sedimentation rates were thought to have been high (Martinsen, Bøen, Charnock, Mangerud, & Nøttvedt, 1999).

Major palaeoclimatic fluctuations also affected Late Cenozoic sedimentation in the northern North Sea, with most notably, glacial sediment transport westwards from Norway during the latest Pliocene and Quaternary.

### 3. Biostratigraphy of the Utsira Sand

The Utsira Sand comprises unconsolidated fine- to medium-grained quartz sand, locally with glaucony and shell fragments and minor lignite clasts (Piasecki et al., 2002), and the depositional environment was probably middle to outer neritic (Eidvin et al., 1999). This unit was stated to be Middle and Late Miocene in age by Deegan and Scull (1977), Isaksen and Tonstad (1989) and Gregersen et al. (1997, fig. 3). Based upon foraminifera from the Utsira Sand of Norwegian sector well 15/12-3 in the Sleipner area, this was revised to latest Middle Miocene to early Late Pliocene by Eidvin et al. (1999) and early Late Miocene to early Late Pliocene by Eidvin et al. (2000). This well has now been reanalyzed and the uppermost part of the Utsira Sand is of Early Pliocene age (T. Eidvin, unpublished data). The base of the Utsira Sand in the Sleipner area was considered to be no older than 12 Ma (Eidvin et al., 2002). However, an error in the original definition of the base of the Utsira Sand in the type area has complicated efforts to clarify the age of its base (Eidvin et al., 2002). The top of the Utsira Sand in its type area, in Norwegian sector well 16/1-1, has been correlated to the nearby well 24/12-1 (the type well for the Skade Formation) and dated as Early Pliocene (Eidvin et al., 2002; T. Eidvin, unpublished data). At its northern extent, at about 61° 30' N, the Utsira Sand is Late Miocene to Early Pliocene in age (Eidvin & Rundberg, 2001).

In Norwegian sector well 15/9-A-23, a 5-m interval in the upper middle part of the Utsira Sand was recently assigned to the Lower Pliocene (Zanclean) by Piasecki et al. (2002), based on dinoflagellate cysts (Fig. 2). Piasecki et al. (2002) subdivided their seven conventional core samples into assemblages 1 and 2. The lowermost five samples were placed in Assemblage 1 (Piasecki et al., 2002, fig. 4), and we agree that it is of Early Pliocene age and note that Cyst type I of de Vernal and Mudie (1989a) is restricted to this assemblage. This acritarch has a restricted range between subchrons C3n2r and C3n1n (ca. 4.7–4.2 Ma) within the Lower Pliocene of Deep Sea Drilling Project (DSDP) Hole 603C in the western North Atlantic (MJH, unpublished data), and has an approximately equivalent range in Ocean Drilling Program (ODP) Hole 646B in the Labrador Sea (de Vernal & Mudie, 1989a). It has also been recorded in the southern North Sea Basin, where it appears to be restricted to the Lower Pliocene of Belgium (Louwye, Head & De Schepper, 2004). *Reticulosphaera actinocoronata* is also restricted to Assemblage 1 (Piasecki et al., 2002), and has a range top at about 4.4 Ma within the Lower Pliocene of DSDP Site 611 in the northern North Atlantic (as *?Cannosphaeropsis* sp. 1 in Baldauf et al., 1987; Mudie, 1987). The two uppermost samples comprise Assemblage 2 of Piasecki et al. (2002) and, in the present authors' opinion, are of somewhat less demonstrable Early Pliocene age. However, we note that the presence of *Invertocysta lacrymosa*, if in situ, indicates an age no younger than early Late Pliocene

(Piacenzian). According to Versteegh (1995, 1997), this species has a well defined highest occurrence at 2.75 Ma in the Upper Pliocene of southern Italy and the North Atlantic. In higher latitudes this range top is somewhat earlier, at 2.8 Ma in ODP Hole 646B in the Labrador Sea (de Vernal & Mudie, 1989b) and at 2.84 Ma in DSDP Hole 400A in the Bay of Biscay (as *Thalassiphora delicata* in Harland, 1979) (Versteegh, 1995, 1997).

To summarise, we agree with Piasecki et al. (2002) that the upper middle part of the Utsira Sand, at least within the narrow interval containing their Assemblage 1, is of Early Pliocene age. We place this interval between about 4.7 and 4.2 Ma, using the stratigraphic range of Cyst type I of de Vernal and Mudie (1989a) in the North Atlantic. This estimate is consistent with an Early Pliocene age recently established for the top of the Utsira Sand based on foraminifera (Eidvin et al., 2002; T. Eidvin, unpublished data).

Also recorded from the Utsira Sand were *Filisphaera filifera* (as *Bitectatodinium tepikiense* in Piasecki et al., 2002, pl. 2, figs. 9 and 10) and a cyst that appears to be *Bitectatodinium arborichiarum* Louwey 1999 (as *Habibacysta tectata* in Piasecki et al., 2002, pl. 2, figs. 7 and 8). The latter species is known only from the Middle Miocene of the Netherlands (as 'cf. *Habibacysta* sp.' in Head, 1994b) and the Upper Miocene of Belgium (Louwey, 1999, 2002). If present in the Utsira Sand and if not reworked, it will extend the range of *Bitectatodinium arborichiarum* upwards into the Lower Pliocene.

#### 4. Material and methods

Four samples of conventional core were analysed: one at 906.00 m (ca. 784.00 m TVDBSL) for palynology, and three at 912.40, 912.80 and 913.10 m (ca. 789.50, 789.90 and 790.10 m TVDBSL) for foraminifera. Isotopic analyses were also performed on the benthic foraminifera from all three samples. The lowest sample (913.10 m) is 20.5 m TVDBSL above the top of the Utsira Sand.

##### 4.1. Palynology

The single sample from 906.00 m analysed for palynology is a dark green clay with a crude fabric of laminations and no visible microfossils. It was registered in the BGS micropalaeontology collection as sample number MPA 51092 and prepared using the conventional mineral acid digestion technique including sieving at 10 µm (Wood, Gabriel, & Lawson, 1996). The organic residue was not oxidized, in order to preserve a complete dinoflagellate cyst association. Neogene and Quaternary heterotrophic dinoflagellate cysts, such as *Brigantedinium*, are known to be much more susceptible to oxidation than autotrophic forms (Dale, 1976; Head, 1996a; Zonneveld, Versteegh, & De Lange, 1997). Furthermore, amorphous organic material,

Table 1

Abundances of palynomorph taxa at 906.00 m. Dinoflagellate cysts are the most important group, both numerically and biostratigraphically. These are listed first, and are arranged alphabetically within their respective families and subfamilies, followed by acritarchs, freshwater algae, angiosperm pollen, gymnosperm pollen, embryophyte spores, miscellaneous palynomorphs and reworked palynomorphs

1. DINOFLAGELLATE CYSTS:	
Division DINOFLAGELLATA (Bütschli, 1885) Fensome et al., 1993	
Subdivision DINOKARYOTA Fensome et al., 1993	
Class DINOPHYCEAE Pascher, 1914	
Subclass GYMNODINIPHYCIDAE Fensome et al., 1993	
Order GYMNODINIALES Apstein, 1909	
Suborder GYMNODINIINEAE (autonym)	
Family POLYKRIKACEAE Kofoid and Swezy, 1921	
<i>Polykrikos</i> sp. cf. <i>Polykrikos schwartzii</i>	5
Subclass PERIDINIPHYCIDAE Fensome et al., 1993	
Order GONYAULACALES Taylor, 1980	
Suborder GONYAULACINEAE (autonym)	
Family GONYAULACACEAE Lindemann, 1928	
Subfamily CRIBROPERIDINIOIDEAE Fensome et al., 1993	
<i>Habibacysta tectata</i>	87
<i>Lingulodinium machaerophorum</i> subsp. <i>machaerophorum</i>	+
<i>Operculodinium centrocarpum</i> sensu Wall and Dale, 1966	2
<i>Operculodinium centrocarpum</i> s.s./ <i>Operculodinium israelianum</i>	6
<i>Operculodinium giganteum</i>	1
<i>Operculodinium pilatum?</i>	13
<i>Operculodinium tegillatum</i> (reworked)	+
Subfamily GONYAULACOIDEAE (autonym)	
<i>Achomosphaera andalusiensis</i> / <i>Spiniferites septentrionalis</i>	+
<i>Bitectatodinium raedwaldii</i>	+
<i>Bitectatodinium tepikiense</i> (columellate morphotype)	11
<i>Bitectatodinium tepikiense</i> (vermiculate morphotype)	4
<i>Corrudinium labradori?</i>	1
<i>Filisphaera filifera</i> subsp. <i>filifera</i>	19
<i>Filisphaera filifera</i> subsp. <i>pilosa</i>	2
<i>Filisphaera microornata</i>	1
<i>Impagidinium paradoxum</i>	+
<i>Nematosphaeropsis labyrinthus</i>	2
<i>Spiniferites</i> spp. indet.	18
Family PERIDINIACEAE Balech, 1988	
Calcareous dinoflagellate cyst of Dale (1983, fig. 28)	*
Family PROTOPERIDINIACEAE Balech, 1988	
<i>Barssidinium graminosum</i> (reworked?)	+
<i>Brigantedinium simplex</i>	+
<i>Capillicysta fusca</i>	3
' <i>Echinidinium aculeatum</i> '	+
<i>Echinidinium euaxum</i> (reworked?)	+
<i>Echinidinium nordlandensis</i> Head sp. nov.	4
<i>Echinidinium sleipnerensis</i> Head and Riding sp. nov.	+
<i>Echinidinium?</i> sp. 1	4
<i>Lejeunecysta catomus</i>	+
<i>Lejeunecysta</i> sp.	+
<i>Lejeunecysta</i> sp. cf. <i>Lejeunecysta fallax</i>	+
Round brown, smooth cysts (mostly <i>Brigantedinium</i> )	120
<i>Selenopemphix nephroides</i>	5
<i>Selenopemphix quanta</i>	3
<i>Trinovantedinium glorianum</i>	+
TOTAL DINOFLAGELLATE CYSTS	311
2. ACRITARCHS:	
Algal cyst sp. 1 of Head (1996b)	16
<i>Cymatiosphaera?</i> <i>invaginata</i>	4

(continued on next page)

Table 1 (Continued)

<i>Nannobarbophora walldalei</i>	7
<i>Cyclopsiella granosa</i> (reworked?)	1
3. FRESHWATER ALGAE:	
<i>Gelasinicysta</i> sp.	+
<i>Pediastrum</i> spp.	3
<i>Botryococcus braunii</i>	4
<i>Tasmanites</i> sp.	1
4. ANGIOSPERM POLLEN:	
<i>Alnus</i>	2
Ericales	26
Gramineae	1
Lactuceae	+
<i>Polypodium persicaria</i> type	+
<i>Pterocarya</i>	1
5. GYMNOSPERM POLLEN:	
<i>Abies</i>	1
<i>Cedrus</i>	3
<i>Picea</i>	6
<i>Pinus</i>	63
<i>Sciadopitys</i> (reworked?)	2
<i>Taxodium</i> (reworked?)	7
<i>Tsuga</i>	+
6. EMBRYOPHYTE SPORES:	
<i>Lycopodium</i> sp.	3
<i>Osmunda</i> sp.	2
Other Filicales	16
<i>Sphagnum</i> spp.	6
7. MISCELLANEOUS PALYNOMORPHS:	
Trochospiral foraminiferal linings	7
Uniserial foraminiferal linings	5
8. REWORKED PALYNOMORPHS:	
Reworked dinoflagellate cysts (undifferentiated)	4
Reworked pollen and spores (undifferentiated)	8

Quantitative data are given only for the first ca. 300 dinoflagellate cysts enumerated; the counts are in the right hand column. Dinoflagellate cyst taxa indicated by a cross (+) were recorded outside the count. The organic lining of a 'so far unidentified' calcareous dinoflagellate cyst illustrated by Dale (1983) probably represents the cyst of *Scrippsiella crystallina* Lewis, 1991 ex Head, 1996a (Lewis, 1991, p. 104) and is marked by an asterisk (\*) in our records. This cyst lining is apparently common in our sample, but could not be counted consistently owing to its thin wall and variable preservation.

which may occlude palynomorphs and can be removed by oxidation, is rare in this sample. Three microscope slides were produced and all palynomorph groups were counted at  $\times 1250$  magnification until approximately 300 dinoflagellate cysts had been enumerated. Subsequently, all three slides were scanned at low magnification for rare specimens not encountered during the main count. The number of specimens counted and the presence of rare taxa are listed in Table 1. The Appendix systematically details five dinoflagellate cyst species, two of which are described as new. For one of these species, *Echinidinium nordlandensis* Head sp. nov., samples from DSDP Hole 603C, western North Atlantic, were examined for comparative purposes.

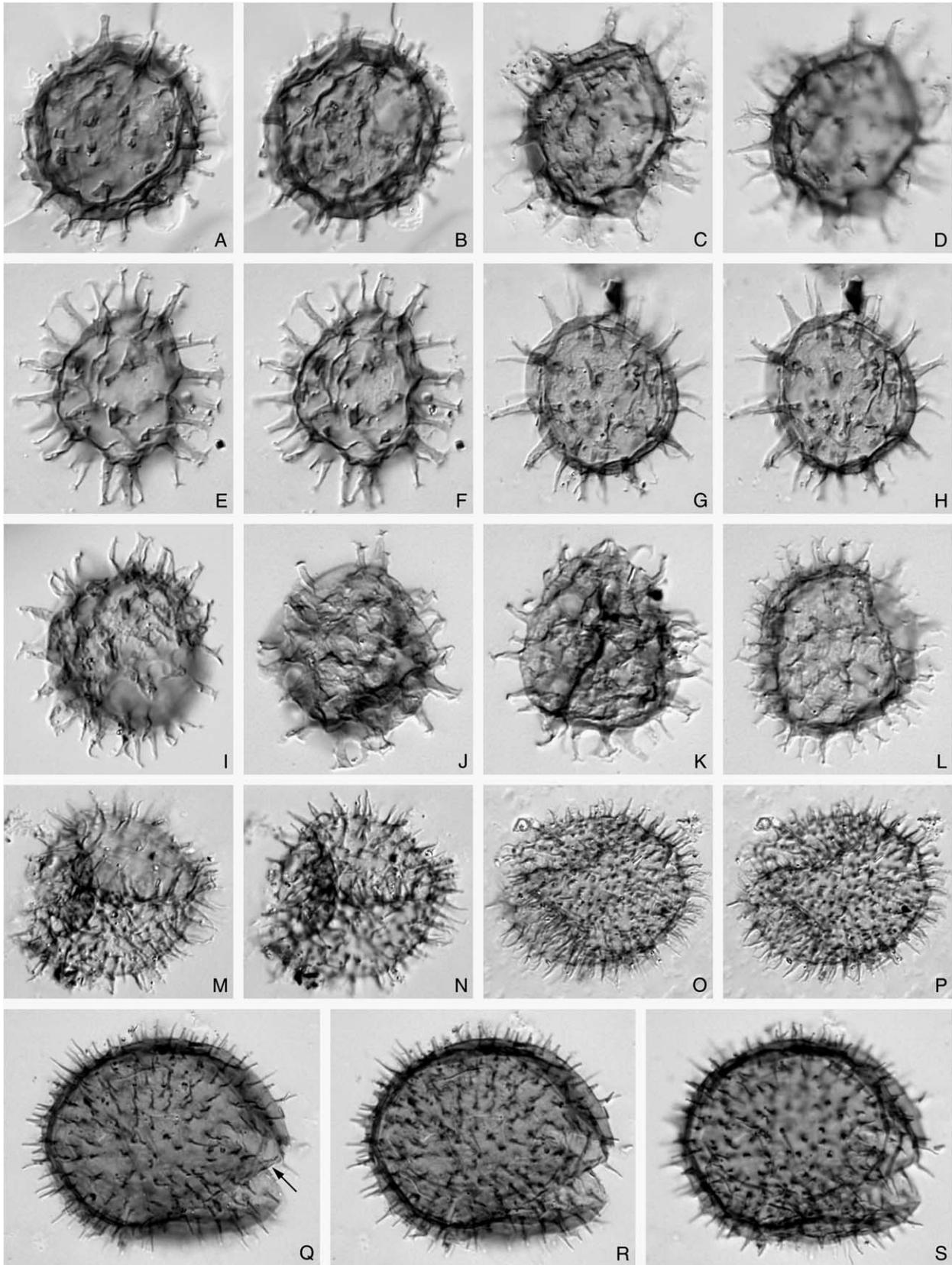
Dinoflagellate cyst species of particular interest are shown in Figs. 3–5. The dinoflagellate cyst nomenclatural index of Williams, Lentin, and Fensome (1998) is followed here, except where stated, and the suprageneric classification of dinoflagellate cysts used in Table 1 is largely based on Fensome et al. (1993). The remaining rock sample, organic residue and all slides and figured specimens from the Nordland Group mudstone are curated in the collections of the British Geological Survey, Keyworth, Nottingham NG12 5GG, UK. Specimens from DSDP Hole 603C (Fig. 4E–L) are deposited in the Invertebrate Section of the Department of Palaeobiology, Royal Ontario Museum, Toronto, Canada, under the catalog numbers ROM 56681 (sample 603C-8-5, 100–102 cm, slide 2), ROM 56682 (sample 603C-8-2, 100–102 cm, slide 1), ROM 56683 (sample 603C-7-2, 85–87 cm, slide 3) and ROM 56684 (sample 603C-5-5, 100–102 cm, slide 2).

#### 4.2. Foraminifera

The three samples at 912.40, 912.80 and 913.10 m analysed for foraminifera were 50–100 g in weight and disaggregated with water without using a disaggregating agent. They were each soaked in water overnight, then mechanically agitated prior to washing through a 63  $\mu\text{m}$  sieve. The >63  $\mu\text{m}$  residue was then dried overnight in an oven at <60 °C. The foraminifera were identified from the 106–500  $\mu\text{m}$  fraction and approximately 300 individuals were picked from each sample. The small (63–106  $\mu\text{m}$ ) and large (>500  $\mu\text{m}$ ) fractions were also examined. The taxa recorded, together with semiquantitative data, are listed in Fig. 6.

#### 4.3. Isotopic analyses of foraminifera

Specimens were placed into glass vials, crushed and soaked in approximately 0.5 ml of a 3% solution of hydrogen peroxide for 30 min. Acetone (AR) was added and the sample ultrasonicated for 30 s to detach fine particles of sediment. The liquid was carefully drawn off using a tissue. Samples were then oven dried at 50 °C overnight. The vials were sealed with a screw cap holding a septum and PCTFE washer to make a vacuum seal, and the samples reacted with 100% orthophosphoric acid at 90 °C using a Micromass Multicarb Sample Preparation System. The carbon dioxide produced was dried and transferred cryogenically into a VG PRISM mass spectrometer for isotopic analysis. Results are reported with reference to the international standard VPDB calibrated through the NBS19 standard (Coplen, 1995), and the precision is better than  $\pm 0.06\text{‰}$  for  $^{12}\text{C}/^{13}\text{C}$  and better than  $\pm 0.08\text{‰}$  for  $^{16}\text{O}/^{18}\text{O}$ . Results are given in Table 2. Analyses were conducted by the Godwin Laboratory, University of Cambridge.



## 5. Palynology of the ‘mudstone drape’ of the Nordland Group

### 5.1. The nature of the palynomorph association

The palynomorphs from 906.00 m are generally compressed but not flattened, although the preservation varies significantly. A total of 34 dinoflagellate cyst taxa were recorded, of which round, brown, smooth cysts overwhelmingly dominate (Table 1). These vary considerably in preservational state and largely represent species of *Brigantidium*, but also include globular protoperidiniacean species with reduced horns. Thin-walled specimens representing the organic inner linings of an unidentified calcareous dinoflagellate cyst (Dale, 1983, fig. 28), probably that of *Scrippsiella crystallina* Lewis, 1991 ex Head, 1996a, are common, but could not be reliably counted due to their thin walls and variable preservation. Pollen and spores are much less abundant than dinoflagellate cysts and are dominated by *Pinus* (Table 1). This genus is readily transported long distances and therefore is over-represented in many marine settings. Other pollen and spores are present in low numbers. Biostratigraphical, palaeoecological and palaeoclimatological interpretations are given below.

### 5.2. Palynomorph biostratigraphy

The absence of key taxa whose range tops are in the Lower Pliocene, such as *Batiacrasphaera* spp., *Corrudinium devernaliae*, *Leiosphaera rockhallensis*, *Quadrina condita*, *Reticulatosphaera actinocoronata* and *Selenopemphix armageddonensis*, precludes an Early Pliocene age for the base of the Nordland Group mudstones (de Vernal & Mudie, 1989a; Head & Norris, 2003; Mudie, 1987; M.J.H., unpublished data). The single recorded specimen of *Operculodinium tegillatum* is considered to have been reworked because this species is common in Lower Pliocene strata of the North Sea (Head, 1997; Louwye et al., 2004) and the Labrador Sea (as *Operculodinium crassum* in de Vernal & Mudie, 1989a). Additionally, the low proportion of thermophilic dinoflagellate cyst species in the Nordland Group mudstone sample suggests that this deposit postdates

the onset of glaciation in the North Atlantic at ca. 2.5 Ma, although the possibility of correlation to a cold climatic stage within the Piacenzian cannot be excluded.

The Nordland Group mudstone assemblage exhibits strong similarities to floras from the latest Pliocene (Gelasian) deposits in eastern England, particularly with respect to the co-occurrences of *Bitectatodinium tepikiense*, *Filisphaera filifera*, *Habibacysta tectata*, *Nannobarbophora walldalei*, *Trinovantedinium glorianum* and morphotypes of *Operculodinium israelianum/centrocarpum* sensu stricto (Head, 1994a, 1996b, 1998).

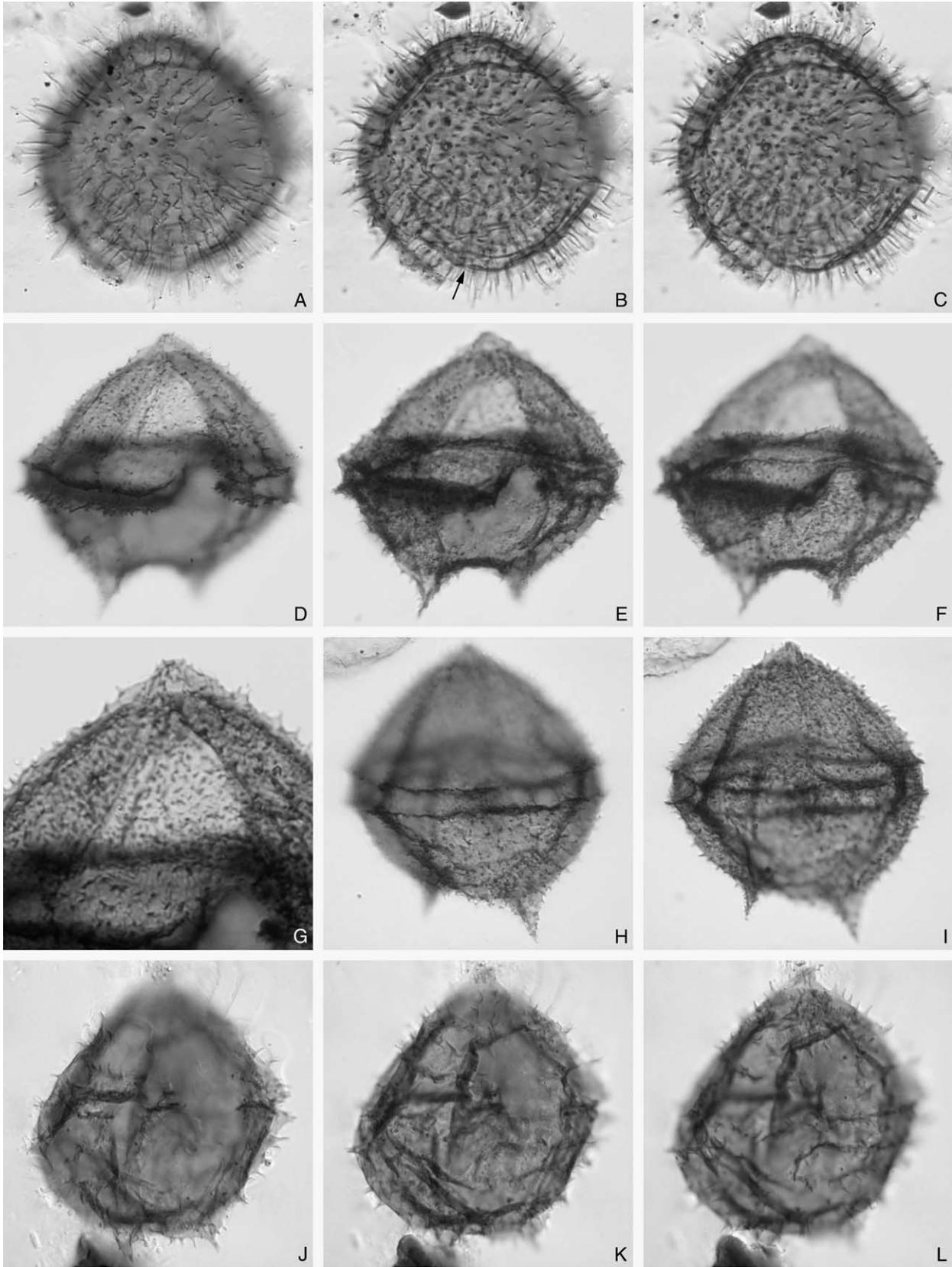
*Filisphaera filifera* (Fig. 3C) is known from Lower Pleistocene deposits throughout the North Atlantic, and has a range top near the Lower–Middle Pleistocene transition (Mudie, 1989). An upper Middle Pleistocene record of *Filisphaera filifera* from ODP Site 986, western Svalbard margin (Smelror, 1999) is here thought to represent reworking.

*Habibacysta tectata* (Fig. 3F and G) has a stratigraphically highest common occurrence at the base of the Olduvai Subchron in DSDP Hole 603C in the western North Atlantic (MJH, unpublished data) and at the Reunion event of both DSDP Hole 610A in the eastern North Atlantic (MJH, unpublished data) and ODP Hole 644A in the Norwegian Sea (as *Dinocyst* sp. 1 in Mudie, 1989). Rare higher occurrences at all these sites and elsewhere in the Norwegian Sea (Mudie, 1989) may be attributable to reworking. Elsewhere this species has a highest common occurrence in the Piacenzian of ODP Site 646 in the Labrador Sea (as *Tectatodinium* sp. I in de Vernal & Mudie, 1989a) and near the Pliocene–Pleistocene boundary in ODP Site 645 in Baffin Bay (as *Tectatodinium* sp. I in de Vernal & Mudie, 1989b). *Habibacysta tectata* therefore has a confirmed highest occurrence in the uppermost Pliocene, with the sporadic and rare higher occurrences considered to represent possible reworking.

The acritarch *Nannobarbophora walldalei* (Fig. 3H) is a frequent constituent of upper Neogene assemblages in the North Atlantic. It is known from the Lower Pleistocene of both DSDP Hole 610A in the eastern North Atlantic and DSDP Hole 603C in the western North Atlantic, but has not been reported from younger deposits (Head, 2003a).

*Trinovantedinium glorianum* (Fig. 5J–L) has been reported frequently from mid to high northern latitude

Fig. 4. Selected dinoflagellate cysts from the Nordland Group mudstone of Norwegian sector well 15/9-A-11 at 906.00 m depth (A–D and M–S) and from DSDP Hole 603C, western North Atlantic (E–L). Various magnifications; an England Finder reference follows the slide number for each specimen. (A–L) *Echinidinium nordlandensis* Head sp. nov. (A, B) Upper (A) and lower (B) focal levels; central body maximum diameter, 27 µm; well 15/9-A-11, specimen MPK 12798, slide 1, U09/1. (C, D) Upper (C) and lower (D) focal levels; central body maximum diameter, 26 µm; well 15/9-A-11, specimen MPK 12799, slide 2, X17/2. (E, F) upper surface at high (E) and slightly lower (F) focal levels; central body maximum diameter, 22 µm; DSDP Hole 603C, sample 5-5, 100–102 cm, slide 2, G34/4; ROM 56684. (G, H) Upper surface at high (G) and slightly lower (H) focal levels; central body maximum diameter, 25 µm; DSDP Hole 603C, sample 7-2, 85–87 cm, slide 3, V32/4; ROM 56683. (I) Upper surface; central body maximum diameter, 28 µm; DSDP Hole 603C, sample 8-2, 100–102 cm, slide 1, V10/3; ROM 56682. (J) upper surface; central body maximum diameter, 25 µm; DSDP Hole 603C, sample 8-5, 100–102 cm, slide 2, D25/0; ROM 56681. (K) Upper surface; central body maximum diameter, 25 µm; DSDP Hole 603C, sample 8-5, 100–102 cm, slide 2, H25/1; ROM 56681. (L) Upper surface; central body maximum diameter, 24 µm; DSDP Hole 603C, sample 8-5, 100–102 cm, slide 2, M44/0; ROM 56681. (M, N) *Echinidinium* sp. 1, upper (M) and lower (N) focal levels; central body maximum diameter, 28 µm; well 15/9-A-11, specimen MPK 12800, slide 2, B34/4. (O, P) *Echinidinium* sp. 1, upper (O) and lower (P) focal levels; central body maximum diameter, 30 µm; well 15/9-A-11, specimen MPK 12801, slide 3, J10/1. (Q–S) *Echinidinium sleipnerensis* Head and Riding sp. nov., upper surface (Q), mid focus (R) and lower surface (S); the theropylic archeopyle is indicated by an arrow in Q; central body maximum diameter, 42 µm; well 15/9-A-11, specimen MPK 12802, slide 2, C31/2.



Upper Pliocene strata (Bennike et al., 2002; Head, 1996b and references therein; Louwey et al., 2004; Smelror, 1999). It has a highest confirmed occurrence within the Olduvai Subchron in DSDP Hole 603C in the western North Atlantic (MJH, unpublished data).

The presence of *Capillicysta fusca* (Fig. 5D–I; Appendix) deserves mention as this species has not been reported above the Lower Pliocene elsewhere (Matsuoka, Bujak, & Shimazaki, 1987; Zevenboom in Head, 1994b), and there are no known records for the North Sea Basin (Zevenboom in Head, 1994b). *Capillicysta fusca* is considered in place in the Nordland Group mudstone sample because, although comprising only 1% of the dinoflagellate cyst assemblage (Table 1), a total of 16 generally well-preserved specimens were recorded. Confirmed reworking of dinoflagellate cysts is rare (just 1%) in the Nordland Group mudstone sample.

*Echinidinium nordlandensis* sp. nov. (Figs. 3O and P, 4A–L, 7; Appendix) is known elsewhere only from the western North Atlantic in DSDP Hole 603C, where it is restricted to the uppermost Pliocene (Gelasian).

An additional significant species in the Nordland Group mudstone sample is the acritarch *Cymatiosphaera? invaginata* which was described from Upper Miocene strata of the Labrador Sea (Head, Norris, & Mudie, 1989). It is a common component of oceanic Pliocene sites in the North Atlantic region and is also common in the Utsira Sand (Piasecki et al., 2002), so its rare presence in the Nordland Group mudstone sample indicates unfavourable ecological conditions or reworking. It has a range top within or near the Olduvai Subchron in ODP Sites 642 and 643 in the Norwegian Sea (as *Cymatiosphaera* sp. 1 in Mudie, 1989), DSDP Hole 603C in the western North Atlantic (MJH, unpublished data), and DSDP Hole 610A in the eastern North Atlantic. It has a similar range top near the Pliocene–Pleistocene boundary in ODP Site 646 in the Labrador Sea (as *Cymatiosphaera* sp. in de Vernal & Mudie, 1989a) and ODP Site 645 in Baffin Bay (as *Cymatiosphaera* sp. in de Vernal & Mudie, 1989b). Its range top therefore approximately corresponds to the Pliocene–Pleistocene boundary in the northern North Atlantic.

In summary, the Nordland Group mudstone sample is considered to be Late Pliocene in age based on acritarch and dinoflagellate cyst evidence. It corresponds to the cooler part of an unidentified climatic cycle (see below) and the dinoflagellate cysts have stronger affinities with Gelasian than Piacenzian assemblages elsewhere. The pollen is consistent with a Late Pliocene age, and mostly resembles

a Gelasian flora owing to the poor representation of warm temperate taxa that typify the Zanclean and Piacenzian.

### 5.3. Palynomorph palaeoecology

The oceanic dinoflagellate cyst species *Impagidinium paradoxum* (Fig. 3I) and the outer neritic to oceanic *Nematosphaeropsis labyrinthus*, although present in low numbers, clearly indicate the influence of oligotrophic (oceanic) water masses (Dale, 1996, p. 1260). The dinoflagellate cyst assemblage is, however, dominated by protoperidiniacean species. These are principally brown, smooth-walled forms with rounded outlines and often some indications of an archeopyle; they are listed as ‘round brown, smooth cysts’ in Table 1 (Fig. 3J). These cysts, and those of the gymnodinialean genus *Polykrikos* (Fig. 3A and B), were produced by heterotrophic dinoflagellates which are presumed to have lived on the inner shelf, where food and nutrients would have been locally abundant. River discharge is normally the source of nutrient input in nearshore environments, and evidence of river input in the sample at 906.00 m is provided by an abundance of partially degraded woody tissues that dominate the non-palynomorph kerogen macerals. The mudstones of the Nordland Group were deposited in open marine waters as indicated by the presence of oceanic dinoflagellate cysts. It hence follows that many of the heterotrophic cysts in the sample represent an allochthonous component transported from the inner shelf. Transport of cysts from the shelf into deeper waters is known in the Norwegian Sea today (Dale & Dale, 1992). The variable preservation seen in the heterotrophic component supports this contention and suggests that some reworking is also involved.

### 5.4. Palaeoclimate based on palynology

Of the heterotrophic dinoflagellate cysts, *Selenopemphix nephroides* (Fig. 3K), *Selenopemphix quanta* (Fig. 3L) and *Trinovantedinium glorianum* (Fig. 5J–L) are all known from high-latitude Pliocene sites (Bennike et al., 2002). *Selenopemphix nephroides* and *Selenopemphix quanta* have broad thermal tolerances (Dale, 1996), and *Selenopemphix quanta* is present in subpolar to temperate environments off Norway today (as *Protoperidinium conicum* in Dale, 1996; Grøsfjeld & Harland, 2001). A single specimen of the thermophilic species *Barssidinium graminosum* was recorded; this may be reworked because this species is

Fig. 5. Selected dinoflagellate cysts from the Nordland Group mudstone of Norwegian sector well 15/9-A-11 at 906.00 m depth. Various magnifications; an England Finder reference follows the slide number for each specimen. (A–C) *Echinidinium sleipnerensis* Head and Riding sp. nov., holotype, polar view showing the upper surface (A), mid focus (B) and lower surface (C), the theropylic archeopyle is indicated by an arrow in B; central body maximum diameter, 46 µm; specimen MPK 12803, slide 1, G30/0. (D–G) *Capillicysta fusca*, ventral view of the ventral surface (D), mid focus (E), dorsal surface (F), and enlargement of the ventral surface (G), showing the dense covering of hollow spinules and coni; length including horns, 63 µm; specimen MPK 12804, slide 1, G04/2. (H, I) *Capillicysta fusca*, dorsal view of the dorsal surface (H) and at mid focus (I); length including horns, 68 µm; specimen MPK 12805, slide 2, B31/4. (J–L) *Trinovantedinium glorianum*, ventral view of the ventral surface (J), mid focus (K), and dorsal surface (L); length including horns, 67 µm; specimen MPK 12806, slide 2, P17/1.

15/9-A-11				BENTHIC FORAMINIFERA		PLANKTONIC FORAMINIFERA	OTHER FOSSILS
Lithostratigraphic unit	Planktonic foraminiferal assemblages	Benthic foraminiferal assemblages	Depth (mRKB)				
NORDLAND GROUP	Undefined	<i>Cibicides grossus</i> assemblage	912.4	● ○ ● ○			
		<i>Cibicoides pachyderma</i> assemblage	912.8	● ● ● ○ ○ ○ ● ○ ○			
	<i>Neogloboquadrina atlantica</i> (dextrally coiled form) assembl.		913.1	● ● ○ ● ○ ○ ○ ○ ○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○		○ ○
				<i>Nonion affine</i> <i>Cibicides grossus</i> <i>Cassidulina teretis</i> <i>Epistominella</i> sp. <i>Lobatula lobatula</i> <i>Cibicoides pachyderma</i> <i>Quinqueloculina seminulum</i> <i>Angulogerina fluens</i> <i>Quinqueloculina</i> sp. <i>Cibicides scaldisiensis</i> <i>Dentalina</i> spp. <i>Elphidium groenlandicum</i> <i>Elphidium albumbilicatum</i> <i>Buccella tenerima</i> <i>Elphidium excavatum</i> <i>Oolina</i> sp. <i>Fronicularia</i> sp. <i>Fissurina</i> spp.  <i>Globigerina bulloides</i> <i>Neogloboquadrina pachyderma</i> (dextrally coiled form) <i>Turborotalia quinqueloba</i> <i>Neogloboquadrina atlantica</i> (dextrally coiled form) <i>Neogloboquadrina pachyderma</i> (sinistrally coiled form)			Mollusc fragments Fish teeth Pyritized clumps

Water depth: 82 m (msl)

● = Abundant ○ = Common ○ = Rare

Fig. 6. Range chart of benthic and planktonic foraminifera in the three samples taken from the cored section of well 15/9-A-11. Key: Rare = 0–5%. Common ≥ 5–20%. Abundant ≥ 20%. Metres below rig floor = mRKB and metres below mean sea level = mMSL.

common in the underlying Lower Pliocene Utsira Sand (Piasecki et al., 2002).

The autotrophic dinoflagellate cysts are dominated by the extinct *Habibacysta tectata* (Fig. 3F and G), which is a neritic, cool-tolerant species and *Filisphaera filifera* (Fig. 3C), a moderately cool-tolerant species known only from northern mid- and high-latitude sites in the Pliocene and Pleistocene (Bennike et al., 2002; Head, 1994a, 1996b). The presence of *Bitectatodinium tepikiense* (Fig. 3E) is particularly significant as this species is typical of the present day transition between subpolar and temperate zones (Dale, 1996). Warm-water species are generally absent, with the exception of the algal incertae sedis *Nannobarbophora walldalei* (Fig. 3H), which occurred in warmer intervals during the Pliocene (Head, 1996b, 2003a), and a single specimen of *Lingulodinium machaerophorum* subsp. *machaerophorum*. The autotrophic component therefore indicates cool-temperate surface-water conditions during deposition of the Nordland Group mudstone sample.

Overall the dinoflagellate cyst assemblage is characterised by an abundance of cool-tolerant species and a sparse representation of warm-water species, and this is reflected in the low species diversity. Cool-temperate surface-water

Table 2  
Benthic foraminiferal isotope ratios  $^{12}\text{C}/^{13}\text{C}$  and  $^{16}\text{O}/^{18}\text{O}$  of samples at 912.40, 912.80 and 913.10 m from the Norwegian sector well 15/9-A-11

Sample no.	Depth (m)	Species	No. of specimens	VPDB	
				O	C
M03/2103	912.40	<i>Nonion affine</i>	26	3.81	−0.59
M03/2101	912.40	<i>Cassidulina teretis</i>	30	3.27	0.41
M03/2100	912.80	<i>Nonion affine</i>	23	3.36	−1.45
M03/2099	912.80	<i>Cassidulina teretis</i>	20	4.02	−0.87
M03/2098	913.10	<i>Cibicoides pachyderma</i>	17	3.21	0.85
M03/2097	913.10	<i>Nonion affine</i>	32	3.12	−1.43
M03/2096	913.10	<i>Cassidulina teretis</i>	32	3.24	−1.35

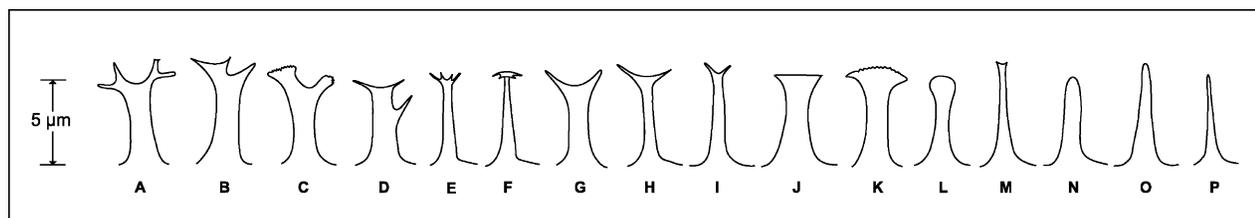


Fig. 7. Variation in process morphology for *Echinidinium nordlandensis* Head sp. nov. Heterogenous process morphology is a characteristic feature of this species, each specimen bearing several types of processes.

conditions evidently prevailed during deposition of the Nordland Group mudstone sample.

The spores and pollen exhibit low relative abundance and diversity (Table 1). They are generally poorly preserved, making reworking difficult to assess. These limitations, combined with taphonomic effects, substantially reduce the utility of these palynomorphs for palaeoecological and biostratigraphical interpretations. Nevertheless, the presence of *Abies* and *Pinus*, and the occasional presence of *Alnus* (representatives of the boreal forest flora), together with *Ericales* and *Sphagnum* (open heathland) are consistent with a northern-temperate to boreal vegetation, which accords with the cool-temperate surface waters deduced from the dinoflagellate cysts.

## 6. Foraminiferal micropalaeontology of the 'mudstone drape' of the Nordland Group

### 6.1. The nature of the foraminiferal associations

Eighteen calcareous benthic and five planktonic foraminiferal taxa were recorded. Fish teeth and mollusc fragments were also recorded in the two lowermost samples (Fig. 6). Most foraminiferal tests have a fresh, unworn appearance, but some are broken and might be reworked. Biostratigraphical, palaeoecological and palaeoclimatological interpretations are given below.

### 6.2. Foraminiferal assemblages and correlation

In the three samples studied, one planktonic and two benthic foraminiferal assemblages were recognised. The boundary between benthic assemblages is based on last appearance datums (LADs). Benthic assemblages are correlated with King's (1989) micropalaeontological zonation for the Cenozoic of the North Sea. The planktonic foraminiferal assemblage is compared with the zonation of Spiegelger and Jansen (1989) for ODP Hole 644A in the Norwegian Sea, and that of Weaver and Clement (1986) for the mid- to high-latitude North Atlantic.

#### 6.2.1. Planktonic foraminiferal assemblage

*Neogloboquadrina atlantica* (dextral) assemblage.

**Definition.** The occurrences of *Globigerina bulloides*, *Neogloboquadrina atlantica* (dextrally coiled form), *Neogloboquadrina pachyderma* (dextrally coiled form), and *N. pachyderma* (sinistrally coiled, non-encrusted variety).

**Material.** One conventional core sample at 913.10 m.

**Age.** Latest Pliocene.

**Correlation.** The upper *N. atlantica* (dextral) Zone of Spiegelger and Jansen (1989) or *N. pachyderma* (dextral) Zone of Spiegelger and Jansen (1989).

**Description.** Planktonic foraminifera are relatively sparse in this sample, although *G. bulloides*, *N. pachyderma* (dextrally coiled form), *N. atlantica* (dextrally coiled form), *N. pachyderma* (sinistrally coiled form) and *Turborotalia quinqueloba* were recorded (Fig. 6).

**Remarks.** Spiegelger and Jansen (1989) describe a lower *N. atlantica* (dextral) Zone from Upper Miocene deposits in the Norwegian Sea and an upper *N. atlantica* (dextral) Zone from Upper Pliocene strata in the same area. In the Upper Pliocene, *N. atlantica* (dextral form) is persistent in the Norwegian Sea only from 2.4 Ma, implying an age of 2.4 Ma or younger for the Nordland Group mudstone assemblage. The absence of *N. atlantica* (sinistral form), which has a highest occurrence at 2.4 Ma and characterises the *N. atlantica* (sinistral) Zone of Spiegelger and Jansen (1989), appears to confirm that the Nordland Group mudstone assemblage is no older.

Absence of the encrusted variety of *N. pachyderma* (sinistral) probably indicates an age no younger than 1.8 Ma (top of Olduvai Subchron) since this form suddenly dominates assemblages in the Norwegian Sea from then onwards (Spiegelger & Jansen, 1989, fig. 7). This evidence restricts the assemblage to the *N. atlantica* (dextral) Zone (2.4–1.9 Ma) or *N. pachyderma* (dextral) Zone (1.9–1.8 Ma) of Spiegelger and Jansen (1989).

The presence of *G. bulloides* and *N. atlantica* (dextral) implies assignment to the upper *N. atlantica* (dextral) Zone. Although the presence of *N. pachyderma* (dextral) would appear to contradict such an assignment as it ranges no lower than the superjacent *N. pachyderma* (dextral) Zone, it should be noted that the forms *N. pachyderma* (dextral) and *N. atlantica* (dextral) are difficult to distinguish in the Upper Pliocene of the Norwegian Sea (Spiegelger, pers.

commun. to TE). Moreover, *N. pachyderma* (dextral) extends throughout the Upper Pliocene in the North Atlantic (Weaver & Clement, 1986), and its range base may not be a reliable marker in the Sleipner Field. Nevertheless, it is not possible to differentiate unambiguously the *N. atlantica* (dextral) Zone from the *N. pachyderma* (dextral) Zone based on our sample. Therefore, we accept an age range of 2.4–1.8 Ma for our assemblage as this encompasses both zones. It should be noted that a younger age within this interval is suggested by the presence of *N. pachyderma* (sinistral, non-encrusted). This form was reported to have a range base in the North Atlantic at about 1.85 Ma within the Olduvai Subchron (Weaver & Clement, 1986), although sporadic occurrences are now known throughout the Pliocene in the northern North Atlantic (Flower, 1999).

### 6.2.2. Benthic foraminiferal assemblages

#### 6.2.2.1. *Cibicidoides pachyderma* assemblage.

**Definition.** The top of this assemblage is defined at the stratigraphically highest occurrence of *Cibicidoides pachyderma*; the base of the assemblage is undefined.

**Material.** Two conventional core samples at 913.10 and 912.80 m.

**Age.** Late Late Pliocene.

**Correlation.** Subzone NSB 15a of King (1989).

**Description.** This unit contains a moderately rich benthic assemblage of calcareous foraminifera. *Cassidulina teretis*, *Cibicidoides pachyderma* and *Nonion affine* occur most frequently. Other characteristic taxa include *Angulogerina fluens*, *Lobatula* (al. *Cibicides*) *lobatula*, *Cibicides scaldisiensis*, *Elphidium albiumbilicatum* (lower sample only) and *Elphidium groenlandicum* (lower sample only) (Fig. 6).

**Remarks.** Correlation to King's (1989) Subzone NSB 15a from Upper Pliocene strata in the North Sea is based on the presence of *Cibicidoides pachyderma*, and on the absence of the early Late Pliocene species *Monspeliensina pseudotepida* (index species for Subzone NSB 14b) and *Cibicidoides limbatosuturalis* (index species for Subzone NSB 14a). According to King (1989), *Elphidium albiumbilicatum* has only a very short overlap with *Cibicidoides pachyderma* in the top of Subzone NSB 15a.

#### 6.2.2.2. *Cibicides grossus* assemblage.

**Definition.** The occurrence of *Cibicides grossus*.

**Material.** One conventional core sample at 912.40 m.

**Age.** Late Late Pliocene.

**Correlation.** Subzone NSB 15b of King (1989).

**Description.** The sample contains a sparse benthic assemblage of calcareous foraminifera. *Cassidulina teretis* and *Nonion affine* are common. *Cibicides grossus* is also relatively numerous. *Epistominella* sp. was also recorded (Fig. 6).

**Remarks.** In the southern and south-central parts of the North Sea, the LAD of *Cibicides grossus* lies close to

the Pliocene–Pleistocene boundary (King, 1989). Farther north in the central North Sea, this species has its highest occurrence close to the Olduvai Subchron (Eidvin et al., 1999), indicating a latest Pliocene or earliest Pleistocene age.

### 6.3. Foraminiferal biostratigraphy

The *Cibicidoides pachyderma* benthic foraminiferal assemblage recorded at 913.10 and 912.80 m and the *Cibicides grossus* assemblage at 912.40 m are, respectively, assignable to Subzone NSB 15a and Subzone NSB 15b of King (1989). Of these North Sea subzones, NSB 15a is late Late Pliocene in age whereas the superjacent NSB 15b may extend into the earliest Pleistocene (Eidvin et al., 1999; King, 1989). The presence of *Elphidium albiumbilicatum* at 913.10 m suggests that this lowest sample correlates with the upper part of Subzone NSB 15a.

The single planktonic foraminiferal assemblage at 913.10 m is assigned to the *N. atlantica* (dextral) Zone (2.4–1.9 Ma) or the *N. pachyderma* (dextral) Zone (1.9–1.8 Ma) of the Norwegian Sea (Spiegler & Jansen, 1989) and is therefore dated between 1.8 and 2.4 Ma (late Late Pliocene, Gelasian). This agrees with a late Late Pliocene age indicated by benthic foraminifera and is consistent with a probable Gelasian age based on dinoflagellate cyst biostratigraphy.

### 6.4. Foraminiferal palaeoecology

The benthic foraminifera provide evidence of palaeobathymetry. According to King (1989) and Skarbø and Verdenius (1986), *Cibicides grossus* inhabited both shallow and deep water. The modern geographical distributions of *Cassidulina teretis*, *Nonion affine* and *Quinqueloculina seminulum* largely comprise the upper part of the continental slope and the outer shelf, although these species may also occur on the middle and inner shelf in smaller numbers. *Lobatula lobatula* inhabits the inner to outer continental shelf (Mackensen, Sejrup, & Jansen, 1985; Sejrup et al., 1981). *Angulogerina fluens*, *Cibicides scaldisiensis* and *Elphidium excavatum* all inhabit both deep and shallow water, whereas *Elphidium albiumbilicatum* and *Elphidium groenlandicum* are shallow marine species (Feyling-Hanssen, 1983; Sejrup et al., 1981; Skarbø & Verdenius, 1986). However, oceanic water masses, implying relatively deep waters, are indicated by the occurrence of planktonic foraminifera in the lowermost sample at 913.10 m. Hence, those benthic foraminiferal faunas indicative of shallow and intermediate water depths may have been transported from their original habitats into a more offshore setting.

### 6.5. Palaeoclimate based on foraminifera

With the exception of *Cibicides grossus* and *Cibicidoides pachyderma*, all the foraminifera are extant species.

The benthic faunas largely comprise boreal species including *Cassidulina teretis* and *Elphidium albiumbilicatum* (Feyling-Hanssen, 1983). *Elphidium excavatum* and *Elphidium groenlandicum* were the only polar species recorded.

The planktonic foraminifera are represented by cold- and temperate-water forms. *N. pachyderma* (sinistrally coiled) is a cold water form that dominates the planktonic foraminiferal faunas of most Norwegian Sea surface sediments (Kellogg, 1976). However, *N. pachyderma* (dextrally coiled) and *G. bulloides* are warmer-water forms that occur most abundantly in Norwegian Sea surface sediments close to the Norwegian current (Kellogg, 1976). Indeed, during the last 450,000 years, only the last interglacial (i.e. the Eemian) and Holocene saw substantial numbers of the planktonic foraminifera *G. bulloides* and *N. pachyderma* (dextrally coiled form) colonise the Norwegian Sea (Kellogg, 1977).

#### 6.6. Foraminiferal stable isotope analyses

Isotopic analyses were obtained on benthic foraminifera from three samples, at 912.40, 912.80 and 913.10 m (Table 2). Although planktonic foraminifera were picked from the sample at 913.10 m, specimens were insufficiently numerous to analyse. The deep-ocean benthic foraminiferal  $\delta^{18}\text{O}$  record is known to reflect global sea-ice volume and hence global climate (Shackleton, Hall & Pate, 1995b), and this has been used to create a standard marine isotope timescale (Shackleton, Crowhurst, Hageberg, Pisias, & Schneider, 1995a). Although the three samples used in the present study are too few and too widely spaced to attempt precise correlation to the marine isotope timescale, their analysis provides some indication of changing climatic conditions.

Oxygen isotope results of *Cassidulina teretis* indicate significant changes, from a lighter value of 3.24 at 913.10 m to a heavy value of 4.02 at 912.80 m, and return to a lighter value of 3.27 at 912.40 m. Results of *Nonion affine* vary from a lighter value of 3.12 at 913.10 m to a slightly heavier value of 3.36 at 912.80 m, to an even heavier value of 3.81 at 912.40 m. The lowest sample, at 913.10 m, evidently represents the warmest (isotopically lightest) interval of the three samples, likely explaining why planktonic foraminifera are present in this sample and not the others. However, precise comparison with the standard isotope curve of Shackleton et al. (1995a,b) is hampered by the unavailability of correction factors for *Cassidulina teretis* and *Nonion affine*. The relatively high negative values of  $\delta^{13}\text{C}$  in this sample (Table 2) suggest increased organic productivity consistent with a warm phase. The sample at 912.80 m appears to represent a cold climatic phase given the very heavy value of 4.02 for *Cassidulina teretis*.

It should be noted that the three samples are not necessarily part of the same climate cycle (i.e. marine isotope stage), and that the sample analysed for palynology at 906.00 m presumably belongs to a different climate cycle

assuming fairly uniform sedimentation rates, although isotope analyses are not available for this sample.

## 7. Discussion and conclusions

Samples of conventional core within the Nordland Group mudstone drape immediately overlying the Utsira Sand in Norwegian sector well 15/9-A-11 have yielded planktonic and benthic foraminifera and marine palynomorphs. These microfossils collectively indicate a late Late Pliocene (Gelasian) age, with evidence from planktonic foraminifera placing the lowest sample between 1.8 and 2.4 Ma. This age is younger than previous estimates between Late Miocene (Gregersen et al., 1997, fig. 3) and early Late Pliocene (Eidvin et al., 1999), and it constrains the maximum age of the overlying prograding wedges of the Nordland Group which are about 500 m thick (probably originally thicker than this given the likelihood of significant Quaternary erosion). Given a time span of about 2.0 Myr, these prograding wedges have an average sedimentation rate of at least 25 cm per 1000 years.

The age of our Nordland Group mudstone drape samples also tightly constrains that of the Utsira Sand. These samples are just 20 m above the top of the Utsira Sand and seismic data show the uppermost sandy units of the Utsira Sand to interfinger with the lowermost units of the mudstone drape (Chadwick et al., 2004). This indicates that the Utsira Sand and the mudstone drape formed a depositional continuum, characterised by an upward transition from sand-dominated to mud-dominated sedimentation. The rates of deposition for the Utsira Sand can now be estimated.

The Utsira Sand is about 300 m thick in the Sleipner area. Its base has been considered latest Middle Miocene (Eidvin et al., 1999) and no older than 12 Ma (Eidvin et al., 2002). In well 24/12-1, recognition of a *Bolboforma fragori* assemblage at the base of the Utsira Sand (Eidvin et al., unpublished) gives an age of 11.7–10.3 Ma, based on the schemes of Müller and Spiegler (1993) and Spiegler and Müller (1992). Taking the base of the Utsira Sand at 11.7 Ma, and our mudstone drape samples at ca. 2.1 Ma, the resulting time span of 11.7–2.1 Ma gives an average sedimentation rate of 3.3 cm per 1000 years for the entire Utsira Sand plus its transition into the Nordland Group mudstones.

The interval analysed by Piasecki et al. (2002) allows the sedimentation rate for the lower two-third of the Utsira Sand to be estimated. This interval is about 202.5 m (corrected depth) above the base of the Utsira Sand, and is dated as Early Pliocene at about 4.5 Ma (Piasecki et al., 2002; and herein, see Biostratigraphy of the Utsira Sand). Again, taking the base of the Utsira Sand at 11.7 Ma, this gives an average sedimentation rate for the lower two-thirds of the Utsira Sand at 2.8 cm per 1000 years. Similarly we can estimate an average sedimentation rate of 4.9 cm per 1000

years for the upper third of the Utsira Sand plus its transition into the Nordland Group mudstones.

Average figures such as these are clearly not representative of actual rates of sedimentation, where ‘pulsed’ influxes of sediment were likely deposited more-or-less instantaneously, and possibly subsequently re-worked, but they do provide a useful measure of the overall rate of sediment supply to the depositional system. Depositional rates calculated for the lower two-thirds of the Utsira Sand are lower than for the upper third (plus Nordland Group mudstone transition) despite deposition becoming increasingly argillaceous upwards. This presents something of a paradox. It is perhaps best explained as reflecting a strongly random component in the preservation of strata in a turbiditic or tidal-current setting. The uppermost part of the Utsira Sand is dated as Early Pliocene (Eidvin & Rundberg, 2001; Eidvin et al., 2002) based on cuttings samples whose depth in the borehole necessarily cannot be known with the precision of conventional coring. Nonetheless, a significant interval of at least 1.1 Myr appears to exist between the uppermost part of the Utsira Sand (Early Pliocene) and our Nordland Group mudstone samples (late Late Pliocene). This either reflects the incompleteness of the sedimentary record within the uppermost part of the Utsira Sand, or it represents a considerable reduction in sedimentation rate at the Utsira Sand–Nordland Group mudstone transition.

Whether the Utsira Sand is interpreted to have been deposited as a sand-ridge complex in a seaway, as a contourite drift, or as a possible turbidite complex (see Section 2), its transition into the overlying argillaceous mudstone drape is suggestive of progressively deepening water and/or a more distal situation as sea level started to rise and shorelines retreated. Continued transgression would have led to progressive submergence of the previously eroded updip shelfal areas, a consequent decrease in the coarse clastic supply and a declining rate of sedimentation. The mudstone drape can perhaps be viewed as the final, most argillaceous unit of the transgressive systems tract, characterised by complete coarse clastic shutoff and very low rates of sedimentation, and perhaps forming part of a maximum flooding surface. This is supported by the presence of planktonic foraminifera and oceanic dinoflagellates which, although rare, point to the incursion of oceanic waters at this site. Nonetheless, the dominance of heterotrophic protoperidiniacean dinoflagellate cysts, which characterize nearshore settings, as well as the abundance of partially degraded woody tissues in the palynological assemblage, suggests that transport from the shelf remained a major influence on sedimentation at this site.

The mudstone drape is overlain by downlapping toe-sets of the prograding wedges of the Nordland Group. These signaled the onset of a regressive systems tract,

which was characterised by much higher rates of sedimentation and an overall upwards coarsening and shallowing trend. Average sedimentation rates of the prograding wedges may have been more than five times those of the Utsira Sand (see above).

The foraminiferal assemblage at 913.10 m within the mudstone drape indicates warm climatic conditions, as indicated by the presence of the warm-water planktonic forms *G. bulloides* and *N. pachyderma* (dextrally coiled form) and by isotopic analyses of the benthic foraminifera yielding high positive values of  $\delta^{18}\text{O}$  and high negative values of  $\delta^{13}\text{C}$ . The foraminiferal assemblages at 912.80 and 912.40 m represent cooler phases of the same or a different climatic cycle.

The dinoflagellate cyst assemblage at 906.00 m contains relatively few thermophilic species and is dominated by cool-tolerant species, indicating deposition during a cool phase of a presumably younger climatic cycle within the late Late Pliocene. The scarcity of warm-temperate pollen taxa seems to support a cool climate. An absence of ice-rafted material in the cored section of well 15/9-A-11 may indicate that iceberg-related transport started later in the 15/9-A-11 area, or may have been less prevalent than farther north. According to Fronval and Jansen (1996) and Jansen and Sjøholm (1991), a large increase in the supply of ice-rafted material to the Norwegian Sea (Vøring Plateau) after about 2.8 Ma reflects the marked expansion of northern European glaciers.

The present study offers a unique glimpse into the Upper Pliocene dinoflagellate cyst record of the northern North Sea. The species *Echinidinium nordlandensis* Head and *Echinidinium sleipnerensis* Head and Riding are described as new, and *Capillicysta fusca* is reported for the first time both from the North Sea basin and from deposits as young as Late Pliocene.

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#### Appendix. Systematic palaeontology (MJH and JBR)

This Appendix comprises the systematic treatment of five dinoflagellate cyst species. Two of these, *Echinidinium nordlandensis* and *Echinidinium sleipnerensis*, are new species. The species treated are arranged alphabetically within genera.

Division DINOFLAGELLATA (Bütschli, 1885) Fensome et al., 1993

Subdivision DINOKARYOTA Fensome et al., 1993

Class DINOPHYCEAE Pascher, 1914

Subclass PERIDINIPHYCIDAE Fensome et al., 1993

Order PERIDINIALES Haeckel, 1894

Suborder PERIDINIINEAE (autonym)

Family PROTOPERIDINIACEAE Balech, 1988

Subfamily PROTOPERIDINIOIDEAE Balech, 1988

Genus *Capillicysta* Matsuoka & Bujak in Matsuoka et al., 1987

*Capillicysta fusca* Matsuoka & Bujak in Matsuoka et al., 1987

Fig. 5D–I

*Discussion.* Sixteen mostly well-preserved specimens of *Capillicysta fusca* were encountered and correspond well to the description of the type material from the Miocene and Pliocene of Japan (Matsuoka and Bujak in Matsuoka et al., 1987). Specimens are brown in colour, biphragmal, cornucavate, and are characterised by a dense distribution of spinules and coni formed from the outer wall layer. Both wall layers are pigmented, the inner wall layer being light brown. The spinules and coni may be hollow and thickened distally, or solid for most of their length and with hollow bases. The spinules and coni have rounded or pointed tips (Fig. 5G). These details are not observable on the Japanese type material, which has suffered corrosion (Head, 1994b). The spinules occur along and between low sutural crests or ridges on the epicyst and hypocyst, and along the cingular margins. *Capillicysta fusca* differs from *Trinovantedinium glorianum* (Fig. 5J–L), which occurs less frequently in the sample studied, in its dense distribution of spinules between the sutural crests, and in the shorter length of the spinules. In our material, these are approximately 1.0–2.0  $\mu\text{m}$  long for *Capillicysta fusca* and up to 4.5  $\mu\text{m}$  in *Trinovantedinium glorianum*. The presence of *Capillicysta fusca* in the Upper Pliocene Nordland Group

mudstone sample extends the stratigraphical range of this species, previously considered to range no higher than the Lower Pliocene of Japan (Matsuoka et al., 1987), and represents its first record in the North Sea Basin.

Subfamily PROTOPERIDINIOIDEAE Balech, 1988

or

Subfamily DIPLOPSALIOIDEAE Abé, 1981

Genus *Echinidinium* Zonneveld, 1997 ex Head et al., 2001

*Discussion.* See Head (2003b) for a list of the currently accepted species of *Echinidinium*.

'*Echinidinium aculeatum*' Zonneveld 1997

Fig. 3M and N

*Discussion.* Five well-preserved specimens were found, having a maximum central body diameter of 20 (25.6) 28  $\mu\text{m}$  and a maximum process length of 5.5 (6.3) 7.0  $\mu\text{m}$ . Processes may be more numerous than for the type material from the Holocene of the Arabian Sea (Zonneveld, 1997), varying from about 43 processes for the smaller specimens to about 67 for the larger ones (e.g. Fig. 3M and N), compared with less than 50 processes for the type material. The holotype and paratype of '*Echinidinium aculeatum*' both have thin, faint lines of thickening between process bases on the central body wall, forming a polygonal pattern over part of the central body (MJH, personal observation; see also Zonneveld, 1997, pl. 3, fig. 5). Specimens from the Nordland Group mudstone do not appear to show this feature. They have a more-or-less smooth central body wall, with occasional scattered granules.

This species has not been reported previously from deposits older than Holocene and Late Pleistocene (Zonneveld, 1997). The name '*Echinidinium aculeatum*' was not validly published in Zonneveld (1997) because a Latin diagnosis had not been provided, a requirement because the type specimen is a modern cyst (Head, Harland, & Matthiessen, 2001; Head, 2003b).

*Echinidinium nordlandensis* Head sp. nov.

Figs. 3O and P, 4A–L and 7

*Diagnosis.* A species of *Echinidinium* with a smooth to scabrate central body surface bearing numerous processes of heterogenous morphology. Processes are hollow, with broad and narrow processes occurring on the same specimen. Likewise, process tips may be evexate, flared, bulbous, aculeate, acuminate or bifid, with or without secondary branching; one or two forms usually predominating on each specimen. Archeopyle therapylic, consisting of a short straight split. No other expression of tabulation.

*Description.* Spheroidal central body with thin wall (less than 0.3  $\mu\text{m}$ ) that shows no stratification under light microscopy except at process bases. Both central body

and processes are light to medium brown. Processes are randomly distributed over the surface and distinguished by their heterogenous morphology (Fig. 7), with several forms occurring on each cyst although usually with one or two forms predominating, e.g. bifid and acuminate process tips on the holotype. Processes have a smooth surface and may be open or closed distally. The archeopyle is presumed to be theropylic, based on a short, straight split seen on occasional specimens.

**Measurements.** Holotype: central body diameter  $30 \times 26 \mu\text{m}$ , maximum process length  $6.5 \mu\text{m}$ . Range (DSDP Hole 603C): maximum central body diameter 21 (24.3)  $28 \mu\text{m}$ , maximum process length 3.5 (5.06)  $7.0 \mu\text{m}$ . Eighteen specimens were measured. Range (Nordland Group mudstone): maximum central body diameter 21 (26.5)  $30 \mu\text{m}$ , maximum process length 4.0 (5.81)  $7.0 \mu\text{m}$ . Thirteen specimens were measured.

**Etymology.** Named after the Nordland Group mudstones, which serve as the type stratum for this species.

**Holotype.** Fig. 3O and P. BGS specimen MPK 12797, slide 1, England Finder reference F35/4. Sample MPA 51092 at 906.00 m depth in Norwegian sector well 15/9-A-11. Curated at the British Geological Survey, Nottingham, UK.

**Occurrence.** Nordland Group mudstone, northern North Sea. Also restricted to the Gelasian (upper Upper Pliocene) of western North Atlantic DSDP Hole 603C, in four samples (core, section, interval) from the study of Head and Norris (2003): 8-5, 100–102 cm; 8-2, 100–102 cm; 7-2, 85–87 cm; and 5-5, 100–102 cm.

**Comparison.** *Echinidinium nordlandensis* differs from all known species of the genus in the heterogenous morphology of its processes.

*Echinidinium sleipnerensis* Head and Riding sp. nov.  
Figs. 4Q–S and 5A–C

**Diagnosis.** A species of *Echinidinium* whose smooth central body surface bears long, densely distributed, acuminate processes. Processes generally have hollow, expanded bases, and are solid for most of their length; occasional processes are solid throughout. Processes are circular in transverse section. Archeopyle theropylic consisting of a straight split extending at least half-way around the cyst. No other expression of tabulation.

**Description.** Central body surface smooth, but may bear sparsely scattered spinules and granules less than  $0.3 \mu\text{m}$  in diameter. The central body wall is thin (less than  $0.3 \mu\text{m}$ ) and shows no stratification under light microscopy except at process bases. Both central body and processes are light to medium brown. Processes are numerous and distributed over entire surface, adjacent processes being separated by about  $1.5\text{--}3.0 \mu\text{m}$  at their base. Processes are solid for most of length but bases, generally  $1.0\text{--}1.5 \mu\text{m}$  in diameter, are usually hollow and expanded. Occasional thin processes have solid bases that are only weakly expanded. All processes

have a smooth surface and taper to a fine point. The archeopyle (indicated by an arrow in Figs. 4Q and 5B), possibly following a cingular margin, consists of a straight or nearly straight split extending at least half-way around the cyst.

**Measurements.** Holotype: central body diameter  $46 \times 43 \mu\text{m}$ , maximum process length  $8 \mu\text{m}$ . Range: maximum central body diameter 41 (44.3)  $48 \mu\text{m}$ , maximum process length 5 (6.2)  $8 \mu\text{m}$ . Six specimens were measured.

**Etymology.** Named after the Sleipner Field area, northern North Sea, which serves as the type locality for this species.

**Holotype.** Fig. 5A–C. BGS specimen MPK 12803, slide 1, England Finder reference G30/0. Sample MPA 51092, at 906.00 m depth in Norwegian sector well 15/9-A-11. Curated at the British Geological Survey, Nottingham, UK.

**Comparison.** The apiculocavate and acuminate nature of the processes on *Echinidinium sleipnerensis* together distinguish this species from all others of the genus. *Echinidinium zonneveldiae* Head, 2003b and '*Echinidinium transparentum*' Zonneveld (1997) both differ in having processes that are solid and colourless to pale brown, and in having some processes with rectangular basal cross-sections. *Echinidinium?* sp. 1 of this study is similar to *Echinidinium sleipnerensis* but is smaller (a central body diameter of  $25\text{--}32 \mu\text{m}$ ), and has an uncertain style of archeopyle. *Islandinium minutum* (Harland and Reid in Harland, Reid, Dobell & Norris, 1980) Head et al., 2001, although superficially similar to *Echinidinium sleipnerensis* in size and process morphology, has a granulate central body surface and apical archeopyle.

*Echinidinium?* sp. 1  
Fig. 4M–P

**Discussion.** These cysts are small and light brown in colour with a spheroidal central body and a dense covering of mostly solid processes. The central body wall is less than  $0.3 \mu\text{m}$  thick and has a smooth surface. Processes taper to acuminate tips and may have expanded process bases. Specimens have a maximum central body diameter of 25 (27.5)  $32 \mu\text{m}$  and a maximum process length of 3 (3.9)  $5 \mu\text{m}$ , based on 15 specimens. The nature of the archeopyle could not be determined but apparently represents a simple split or rupture of the wall. This species is not formally described because the archeopyle style is uncertain.

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