Newsletters on Stratigraphy
Vol. **43/1:** 33–48, June 2008

Late Pliocene and Pleistocene biostratigraphy of the Nordic Atlantic region

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With 3 figures and 1 appendix

Abstract. The lack of primary and secondary GSSP correlative markers in Plio-Pleistocene deposits of the North Sea, Nordic seas and northern North Atlantic creates a challenge for the biostratigrapher. This study highlights the closest biostratigraphic approximations in this region to the standard chronostratigraphic boundaries of the Gelasian Stage and Lower, Middle and Upper Pleistocene. Via correlations to key Ocean Drilling studies and unambiguous magnetostratigraphies in the region, the age of shallower deposits of the North Sea has been better constrained. The closest biostratigraphic approximations to these chronostratigraphic boundaries in the region are presented, together with a framework of calibrated events according to sub-basin. The best approximating boundary events at any given location in this region depends upon both the paleoceanographic and paleobathymetric settings. In the Nordic Atlantic region only three GSSP correlative marker events have been identified in the 15 Ocean Drilling Program sites discussed. At lower neritic to bathyal water depths, the first common occurrence of *Neogloboquadrina pachyderma* (sinistrally-coiled morphotype) allows for direct correlation with the base Pleistocene GSSP in Italy. The occurrence of the benthic foraminifer *Cibicides grossus* appears to have been bathymetrically controlled, with a youngest stratigraphic occurrence at upper bathyal depths. At lower neritic depths in the central and northern North Sea the last occurrence of *C. grossus* coincides with the base of the Pleistocene. Diachroneity of a number of Nordic high-latitude bioevents may be primarily due to differences in surface water masses and paleobathymetry.

Key words. North Sea, Norwegian Sea, Foraminifera, calibrations, Quaternary, Pliocene

1. Introduction

This study aims to improve the temporal resolution of the established Plio-Pleistocene biostratigraphy of the Nordic Atlantic region, through multi-fossil calibrations to the standard geologic time scale with its Global boundary Stratotype Section and Point (GSSP) definitions in the Mediterranean. The definitions of the relevant Upper Cenozoic chronostratigraphic units, i.e. Gelasian Stage, Pleistocene Series, Neogene and Quaternary Systems follow Ogg et al. (in press); they are also available from the website of the International Commission on Stratigraphy (ICS) at www.stratigraphy.org. The orbitally tuned time scale is that of Lourens et al. (2004), which also re-calibrated the Berggren et al. (1995) biochronology.

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DOI: 10.1127/0078-0421/2008/0043-0033
0078-0421/08/0043-0001 $ 3.25

2. Regional setting and biostratigraphy

The "Nordic Atlantic region" is here defined as roughly the area stretching from immediately south of the Greenland-Scotland Ridge northwards, encompassing the North Sea and Nordic Seas (Norwegian Sea, Greenland Sea, Iceland Sea, West Barents Sea) to the Arctic Ocean Gateway and the Yermak Plateau (Fig. 1). In this region, the Upper Cenozoic biostratigraphy is based primarily upon foraminifers, calcareous nannoplankton and organic-walled dinoflagellate cysts. Marine diatoms and continental pollen sequences (van der Vlerk and Florschütz 1953, Zagwijn 1974) add paleontological age control across discrete time intervals. At these high latitudes, many of the standard 'global' markers present in the mid- to low-latitudes (including the Mediterranean region) are absent; these include most of the primary and secondary correlative events defining the relevant GSSPs.

Various abiotic and biotic expressions of late Cenozoic climatic change have been used for dating the onset of the Quaternary and Pleistocene in the Nordic Atlantic region. Marine isotopic trends and magnetic polarity reversals show near synchroneity across large geographic regions. However, these dating methods often require additional control to interpret an age, being inherently limited to two outcomes (e. g. either glacial/interglacial

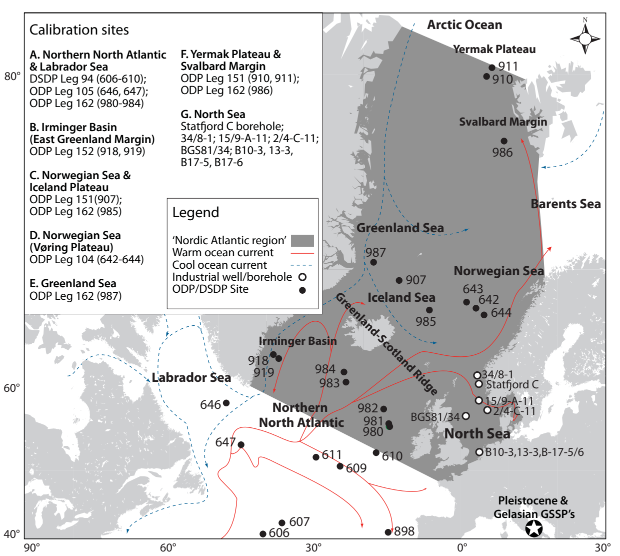


Fig. 1. Map showing the location of calibration points used in this study, including Deep Sea Drilling Project Sites, Ocean Drilling Program Sites, and industrial wells/boreholes. Locations are grouped according to region/basin and given a letter abbreviation.

or normal polarity/reversed polarity). This additional age control is often in the form of planktonic marker fossils that have been well-documented both spatially and temporally (planktonic foraminifera, calcareous nannoplankton, dinoflagellate cysts and siliceous microfossils). Where integration of data sets from a range of both abiotic and biotic proxies is possible (e. g. in deep-sea cores), well-constrained age models form the basis for a regional biostratigraphy.

High-resolution biostratigraphies have been constructed from Upper Cenozoic depositional sequences in Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) coreholes from the Mediterranean to the high Arctic. For the Nordic Atlantic region, the following planktonic foraminiferal zonation studies have been most utilised: Weaver and Clement (1986) and Weaver (1987) in the northern North Atlantic (DSDP Leg 94) and Spiegler and Jansen (1989) in the Norwegian Sea (ODP Leg 104). For the North Sea Basin, dominated by shallow neritic benthic foraminiferal assemblages, the deterministic zonation by King (1983, 1989) and the probabilistic zonation by Gradstein and Bäckström (1996) are most widely used. Their zonal boundaries are defined almost entirely upon last occurrence events (LOs) due to downhole contamination in industrial exploration well samples. Both schemes are based primarily on poorly constrained ranges of benthic foraminifera, with age interpretations strongly dependent upon the biomagnetostratigraphy of DSDP Leg 94 in the northern North Atlantic.

In response to high-frequency Quaternary climate change, benthic communities would have been forced to migrate repeatedly to more preferable environmental conditions. Benthic foraminifera are sensitive to water mass and substrate properties and therefore they often exhibit sedimentary facies dependency (Mackensen et al. 1985). They are therefore often unreliable markers, showing a high degree of diachroneity in their first and last appearances (Denne and Sen Gupta 1990). This is especially evident in the bathymetrically controlled last occurrence of *Cibicides grossus* (*C. lobatulus* var. *grossa*) in the North Sea (see Appendix 1).

Following ODP Leg 104, a number of new oceanic sites have been drilled as part of ODP Legs 151, 152 and 162 (Fig 1.). Calibration of the stratigraphy of these new sites to astronomical parameters has greatly increased Neogene temporal resolution (Lourens et al., 1996; Gradstein et al., 2004). These additional data points allow for a broader examination of the relationship between the geographic distribution and the degree of synchroneity/diachroneity of important northern high-latitude bioevents. A better understanding and quantification of the time-transgressive nature of key planktonic events from oceanic settings will help to improve the accuracy of Quaternary biostratigraphy and to better constrain benthic foraminiferal ranges in shallower shelf settings such as the North Sea.

High-resolution integrated stratigraphic data sets are rare in industrial exploration-well studies in the North and Norwegian seas. Here both quality of material and economic constraints limit the availability of paleomagnetic and isotopic data. Strontium isotope measurements may provide a limited degree of independent age control, but contamination has often rendered contradictory results (e.g. Eidvin et al. 1993). For latest Pleistocene deposits, amino-acid dating and optically stimulated luminescence (OSL) dating have proved useful, especially in areas where paleomagnetic data is ambiguous or unobtainable and where key planktonic markers are absent (e.g. Sejrup and Knudsen 1999). However, due to the strong dependency of amino-acid racemization rates on temperature, water concentration and alkalinity, uncertainties regarding conditions of preservation can obscure the results (Brown 1985).

3. Material and Methods: Mid- to high-latitude correlations

The location of Nordic ocean drilling sites and selected industrial petroleum wells with a reliable Plio-Pleistocene record is shown in Fig. 1. The sites have been organised from south to north, according to sub-basin. They have been divided into three correlation panels: 1) temperate to subpolar sites located south of the Greenland-Scotland Ridge (GSR) in the northeastern North Atlantic; 2) subpolar sites located north of the GSR in the Nordic Seas; 3) Arctic Sites in the Greenland Sea and on the Yermak Plateau (Figs. 2a–c). Most sites have a reliable magnetostratigraphy, allowing for direct calibration of bioevents via the Geomagnetic Polarity Time Scale (GPTS) to the standard chronostratigraphy of Gradstein et al. (2004). At a few sites, a Pleistocene oxygen-isotope stratigraphy allows for high-resolution calibrations to the marine oxygen isotope stages. In addition, a limited number of astronomically calibrated foraminiferal and calcareous nannoplankton bioevents (with ages according to Lourens et al. 2004) improve the stratigraphic resolution. In a few cases, new events have been identified from the raw fossil occurrence data in the respective publications. Each site record presented here is a composite of the results from the individual site coreholes. Where possible, the standard chronostratigraphic boundaries of the Late Pliocene – Pleistocene have been correlated between sites. This has facilitated a biostratigraphic comparison of sites at both a local level between sub-basins and at a more regional scale from temperate to polar latitudes.

It is only via the high-resolution data sets provided through these deep-sea cores that reliable stratigraphic relationships can be found between the Mediterranean stages and the Nordic Atlantic biostratigraphy. The reliability of these relationships or calibrations can be ranked according to the number of correlations necessary. First-order calibrations are those involving a direct and onsite stratigraphic link between the respective bioevent and the standard Geologic Time Scale. This has most often been achieved via an onsite stratigraphic tie to the GPTS or to selected astronomically calibrated events (Lourens et al. 2004). Second-order calibrations involved a correlation between the observed bioevent and another locality with a corresponding stratigraphic level which had a 1st order – calibrated age. Third-order calibrations involve two correlations. Updated ages have been calculated based on their relative positions between magnetosubchron and/or nannofossil zonal boundaries. For the majority of events, the age has been calculated for the depth originally quoted in the respective DSDP/ODP publications and given to one decimal place only. This is intended to account for low sample resolution, lack of continuous coring, and the often numerous occurrence of bracketing barren intervals.

4. Results: Late Pliocene – Pleistocene chronostratigraphic boundaries at Nordic high-latitudes

A critical assessment of the biostratigraphy and correlation of key deep-sea cores and industrial petroleum wells has resulted in the framework of calibrated bioevents for the Nordic Atlantic region presented in Appendix 1. Selected bioevents can be used for the identification of the standard chronostratigraphic boundaries of the Late Pliocene – Pleistocene in this region.

Four chronostratigraphic boundaries divide the Quaternary: Base Upper Pleistocene Subseries, Base Middle Pleistocene Subseries, Base Pleistocene Series, and Base Gelasian Stage. To date, the Pleistocene and Gelasian GSSPs have been ratified by the Interna-

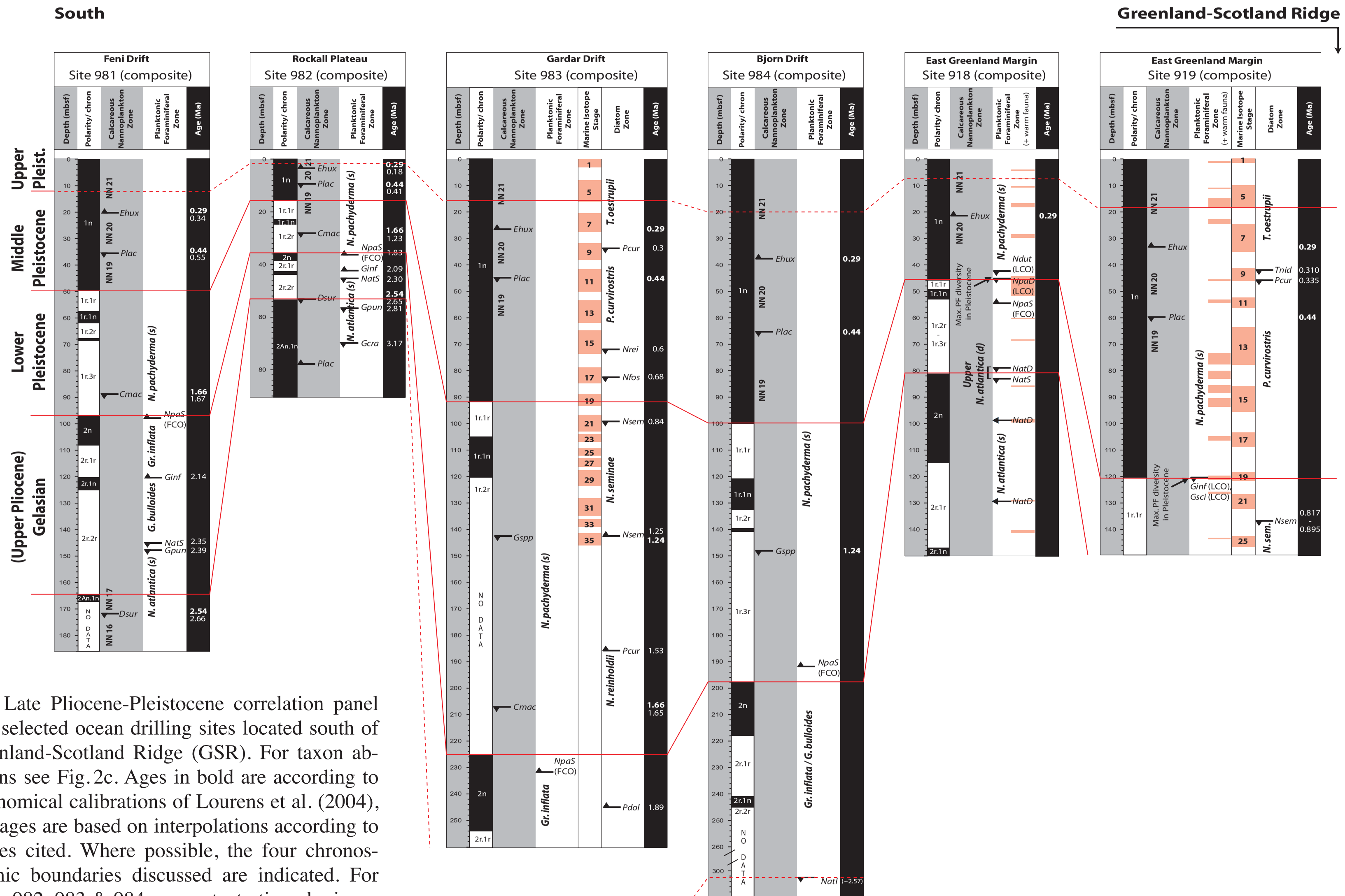


Fig. 2a. Late Pliocene-Pleistocene correlation panel showing selected ocean drilling sites located south of the Greenland-Scotland Ridge (GSR). For taxon abbreviations see Fig. 2c. Ages in bold are according to the astronomical calibrations of Lourens et al. (2004), all other ages are based on interpolations according to the studies cited. Where possible, the four chronostratigraphic boundaries discussed are indicated. For Sites 981, 982, 983 & 984: magnetostratigraphy is according to Channell and Lehman (1999); calcareous nannoplankton biostratigraphy is according to Shipboard Scientific Party (1996a); planktonic foraminiferal biostratigraphy is according to Flower (1999); marine diatom biostratigraphy and oxygen isotope stratigraphy is according to Koc et al. (1999). For Sites 918 and 919: magnetostratigraphy is according to Fukuma (1998); calcareous nannoplankton stratigraphy is according to Wei (1998); planktonic foraminiferal biostratigraphy is according to Spezzaferri (1998); marine diatom biostratigraphy and oxygen isotope stratigraphy is according to Koc and Flower (1998).

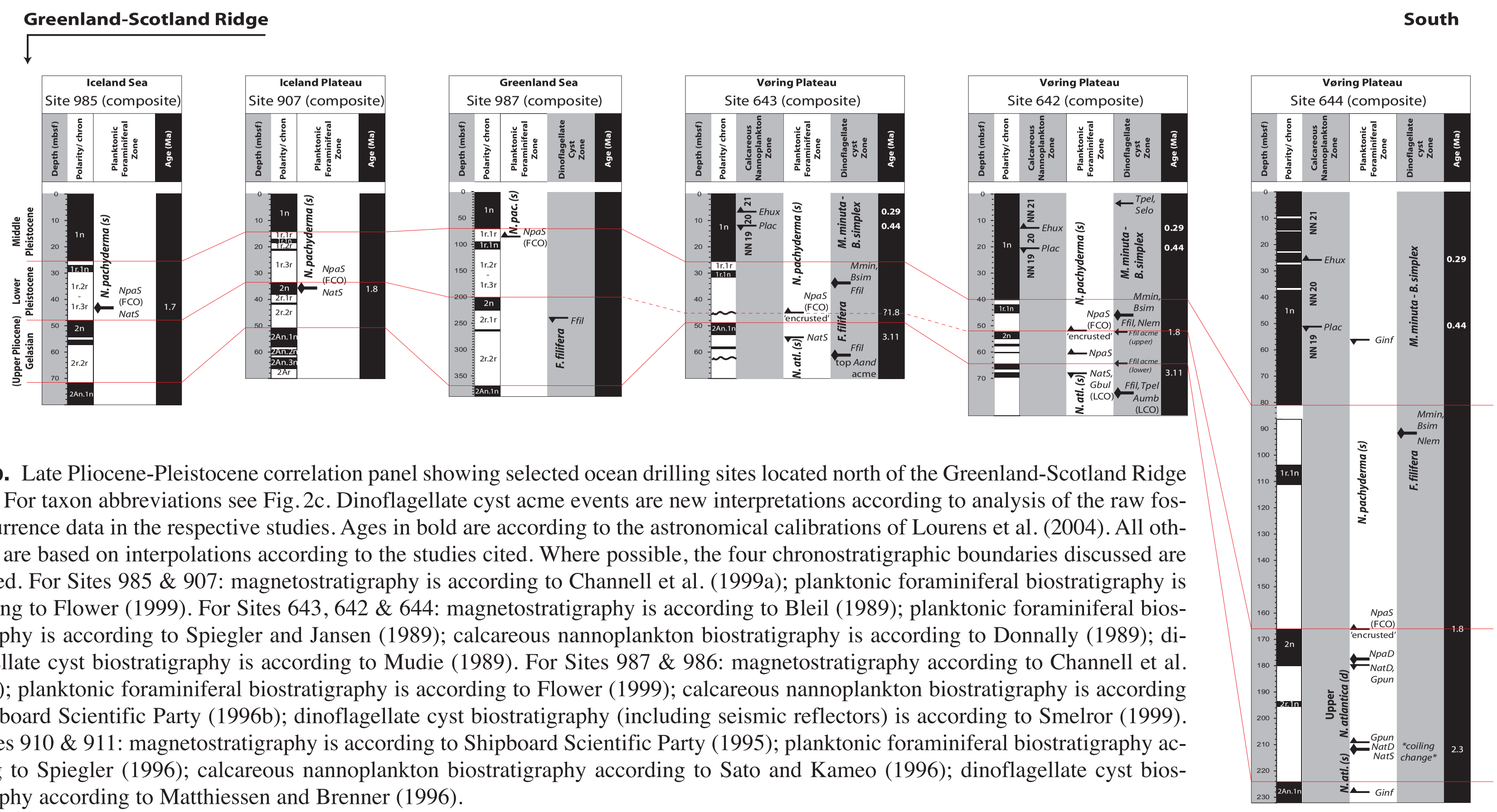
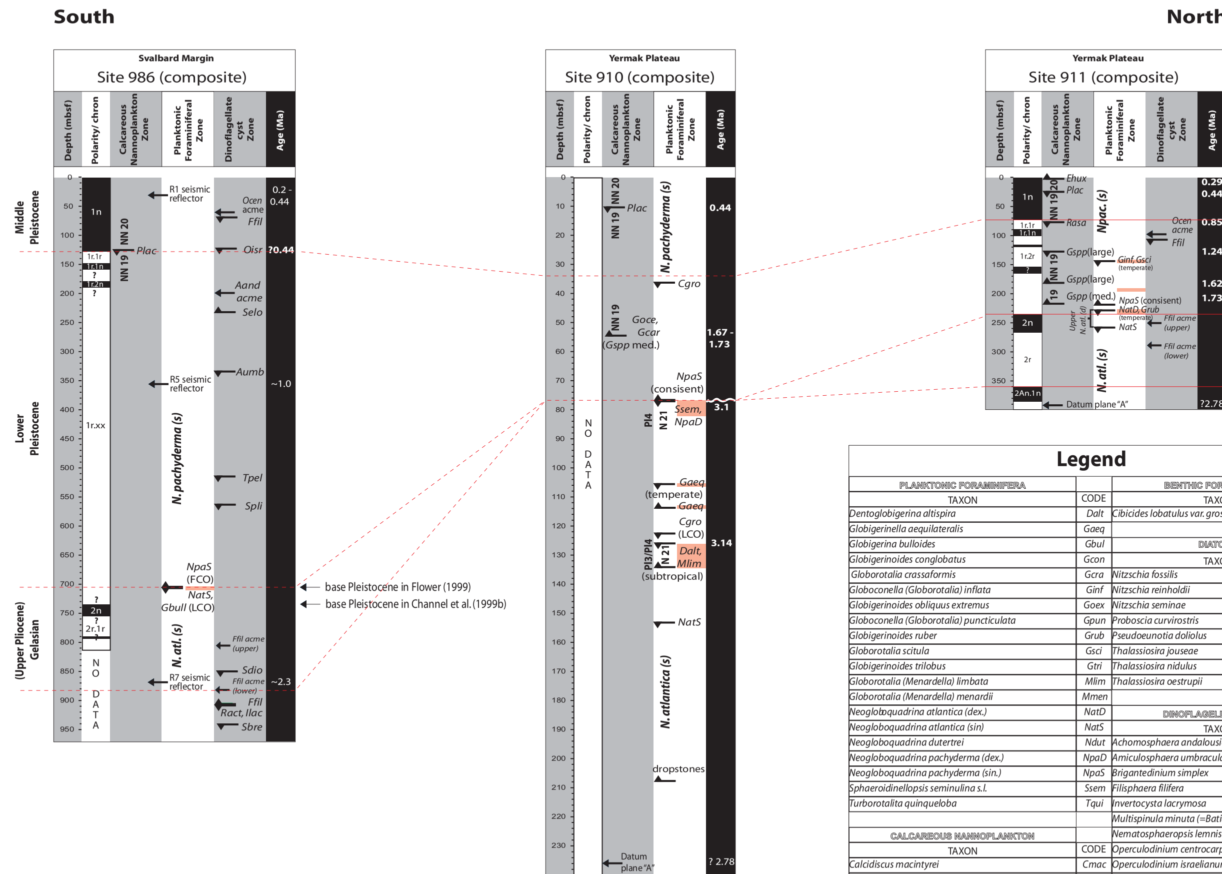


Fig. 2b. Late Pliocene-Pleistocene correlation panel showing selected ocean drilling sites located north of the Greenland-Scotland Ridge (GSR). For taxon abbreviations see Fig. 2c. Dinoflagellate cyst acme events are new interpretations according to analysis of the raw fossil occurrence data in the respective studies. Ages in bold are according to the astronomical calibrations of Lourens et al. (2004). All other ages are based on interpolations according to the studies cited. Where possible, the four chronostratigraphic boundaries discussed are indicated. For Sites 985 & 907: magnetostratigraphy is according to Channell et al. (1999a); planktonic foraminiferal biostratigraphy is according to Flower (1999). For Sites 643, 642 & 644: magnetostratigraphy is according to Bleil (1989); planktonic foraminiferal biostratigraphy is according to Spiegler and Jansen (1989); calcareous nannoplankton biostratigraphy is according to Donnally (1989); dinoflagellate cyst biostratigraphy is according to Mudie (1989). For Sites 987 & 986: magnetostratigraphy according to Channell et al. (1999b); planktonic foraminiferal biostratigraphy is according to Flower (1999); calcareous nannoplankton biostratigraphy is according to Shipboard Scientific Party (1996b); dinoflagellate cyst biostratigraphy (including seismic reflectors) is according to Smelror (1999). For Sites 910 & 911: magnetostratigraphy is according to Shipboard Scientific Party (1995); planktonic foraminiferal biostratigraphy according to Spiegler (1996); calcareous nannoplankton biostratigraphy according to Sato and Kameo (1996); dinoflagellate cyst biostratigraphy according to Matthiessen and Brenner (1996).



Legend

PLANKTONIC FORAMINIFERA TAXON	CODE
Dentoglobigerina altispira	Dalt
Globigerinella aequilateralis	Gaeq
Globigerina bulloides	Gbul
Globigerinoides conglobatus	Gcon
Globorotalia crassaformis	Gcra
Globoconella (Globorotalia) inflata	Ginf
Globigerinoides obliquus extremus	Goex
Globoconella (Globorotalia) puncticulata	Gpun
Globigerinoides ruber	Grub
Globorotalia scitula	Gsci
Globigerinoides trilobus	Gtri
Globorotalia (Menardella) limbata	Mlim
Globorotalia (Menardella) menardii	Mmen
Neogloboquadrina atlantica (dex.)	NatD
Neogloboquadrina atlantica (sin)	NatS
Neogloboquadrina dutertrei	Ndut
Neogloboquadrina pachyderma (dex.)	NpaD
Neogloboquadrina pachyderma (sin.)	NpaS
Sphaeroidinellopsis seminulina s.l.	Ssem
Turborotalita quinqueloba	Tqui

CALCAREOUS NANNOPLANKTON TAXON	CODE
Calcidiscus macintyrei	Cmac
Discoaster surculus	Dsur
Emiliania huxleyi	Ehux
Gephyrocapsa caribbeanica (Medium)	Gcar
Gephyrocapsa oceanica (Medium)	Goce
Gephyrocapsa spp. (Large)	Gspp
Pseudoemiliania lacunosa	Plac
Reticulofenestra asanoi	Rasa
Datum plane "A" of Sato & Kameo (1996)	-

MISCELLANEOUS TAXON/EVENT	CODE
Seismic reflector R1	R1
Seismic reflector R5	R5
Seismic reflector R7	R7

BENTHIC FORAMINIFERA TAXON	CODE
Cibicides lobatulus var. grossa (= C. grossus)	Cgro

DIATOMS TAXON	CODE
Nitzschia fossilis	Nfos
Nitzschia reinholdii	Nrei
Nitzschia seminae	Nsem
Proboscia curvirostris	Pcur
Pseudoeunotia doliolus	Pdol
Thalassiosira jouseae	Tjou
Thalassiosira nidulus	Tnid
Thalassiosira oestrupii	Toes

DINOFLAGELLATE CYSTS TAXON	CODE
Achomosphaera andalousiensis	Aand
Amiculosphaera umbracula	Aumb
Brigantedinium simplex	Bsim
Filisphaera filifera	Ffil
Invertocysta lacrymosa	Ilac
Multispinula minuta (=Batiacasphaera minuta)	Mmin
Nematosphaeropsis lemniscata	Nlem
Operculodinium centrocarpum	Ocen
Operculodinium israelianum	Oisr
Reticulatosphaera actinocoronata	Ract
Selenopemphix brevispinosa	Sbre
Selenopemphix dionaecysta	Sdio
Spiniferites elongatus	Selo
Sumatradinium pliocenicum	Spli
Tectatodinium pellitum	Tpel

Event (Zone)	last occurrence or last common occurrence (LCO)
Event (Zone)	first occurrence or first common occurrence (FCO)
Event	point occurrence or acme
(shaded)	'warm' assemblage
0.44 (bold)	age from interpolation based on Berggren et al. (1995)
0.44	age from Lourens et al. (2004)

Fig. 2c. Late Pliocene-Pleistocene correlation panel showing selected ocean drilling sites located in the Arctic region. Dinoflagellate cyst acme events are new interpretations according to analysis of the raw fossil occurrence data in the respective studies. Ages in bold are according to the astronomical calibrations of Lourens et al. (2004). All other ages are based on interpolations according to the studies cited. Where possible, the four chronostratigraphic boundaries discussed are indicated. For Site 986: magnetostratigraphy according to Channell et al. (1999b); planktonic foraminiferal biostratigraphy is according to Flower (1999); calcareous nannoplannkton biostratigraphy is according to Shipboard Scientific Party (1996b); dinoflagellate cyst biostratigraphy (including seismic reflectors) is according to Smelror (1999). For Sites 910 & 911: magnetostratigraphy is according to Shipboard Scientific Party (1995); planktonic foraminiferal biostratigraphy according to Spiegler (1996); calcareous nannoplankton biostratigraphy according to Sato and Kameo (1996); dinoflagellate cyst bio-stratigraphy according to Matthiessen and Brenner (1996).

tional Commission on Stratigraphy as formal global boundaries (Ogg et al. in press). The Base Upper Pleistocene Subseries is provisionally placed at the base of the Eemian Interglacial in Marine Isotope Stage (MIS) 5. The Base Middle Pleistocene Subseries is provisionally placed at the Brunhes-Matuyama magnetic reversal (Gibbard 2003). The identification of these chronostratigraphic boundaries outside of the Mediterranean type area is possible via first-order principal and secondary correlative events associated with the GSSPs (Aguirre and Pasini 1985, Rio et al. 1998). In the Nordic Atlantic region, only two secondary correlative marker events for the base Pleistocene GSSP at Vrica have been identified. These are the calcareous nannofossil last occurrence of *Calcidiscus macintyrei* (northern North Atlantic) and the first occurrence of medium *Gephyrocapsa* spp. (Yermak Plateau). For direct correlation to the base Gelasian GSSP, the last occurrence of *Discoaster surculus* was the only primary correlative event observed in the northern North Atlantic (Fig. 3). In addition to these relatively rare observations, the following microfossil markers best approximate the four main chronostratigraphic boundaries dividing the Late Pliocene – Pleistocene interval in this region (see Appendix 1 for details):

4.1 Base Upper Pleistocene (0.126 Ma)

Planktonic foraminifera
At all ODP sites in the Nordic Atlantic region where MIS 5e was identified, this level occurred within the *Neogloboquadrina pachyderma* (sinistral) Zone. In addition, it marks the base of a warm temperate planktonic foraminiferal assemblage at ODP Sites 918 and 919 (Spezzaferri 1998), consistent with the Eemian Interglacial.

Benthic foraminifera
This level coincides with a high-productivity benthic foraminiferal assemblage rich in *Bulimina marginata, Cassidulina laevigata* and *Bolivina* spp. in the North Sea (Knudsen and Sejrup 1988). It may coincide with the last common occurrence of *Elphidium ustulatum* in neritic deposits (see Appendix 1).

Calcareous nannoplankton
At ODP Site 983, on the Gardar Drift in the northern North Atlantic, the base of MIS 5 occurs approximately 15 metres below the seafloor (Koç et al. 1999), and ca. 10 metres above the first occurrence of *Emiliania huxleyi* (0.29 Ma in Lourens et al. 2004). The base of the Upper Pleistocene occurs at a level approximating to the middle of Calcareous Nannoplankton Zone NN21. The same is true for ODP Site 919 on the East Greenland margin (Koç and Flower 1998) and ODP Site 643 on the Vøring Plateau (Jansen et al. 1989).

Diatoms
Based on the oxygen isotope studies at ODP Sites 983 and 919, the boundary should be placed within the *Thalassiosira oestrupii* Zone of Koc et al. (1999). It can be identified more precisely as the base of the second and largest acme of *T. oestrupii*, as counted either uphole or downhole.

4.2 Base Middle Pleistocene (0.781 Ma)

Planktonic foraminifera
At ODP Site 919, on the East Greenland margin in the northern North Atlantic, the top of MIS 19 (warm stage) corresponds to the last common occurrence (LCO) of the 'warm-temperate' species *Globorotalia scitula* and *Globorotalia inflata* (new event identified in Flower 1998 and Spezzaferri 1998). Similarly, at neighbouring ODP Site 918 the last common occurrence of the 'cool-temperate' ('warm-subpolar') *Neogloboquadrina pachyderma* (dextral) and the slightly later LCO *N. dutertrei* occur close to the Brunhes-Matuyama boundary. This level is also marked by a maximum in Pleistocene planktonic foraminiferal species diversity at both East Greenland Margin ODP Sites 918 and 919 (Spezzaferri 1998), consistent with the top of the MIS 19 warm stage (Fig. 2a). North of the Greenland-Scotland Ridge, this 'cool-temperate' assemblage appears to be absent at this level with the LCO (consistent) *N. pachyderma* (dextral) occurring older, close to the Pliocene-Pleistocene boundary (Spiegler and Jansen 1989; Spiegler 1996). On the Yermak Plateau, the LCO (consistent) *N. pachyderma* (dextral) does, however, occur together with the last occurrence of a cool-temperate assemblage close to the Pliocene-Pleistocene boundary (Spiegler 1996). The lack of a clearly identifiable younger LCO *N. pachyderma* (dextral) and other "warmer species" at most sites north of the GSR may be attributed to a reduced impact of warmer interglacial surface currents at these higher latitudes.

Benthic foraminifera
At shallow neritic paleo-water depths in the North Sea, the base of the Middle Pleistocene corresponds to the top of a warm assemblage of abundant *Bulimina mar-*

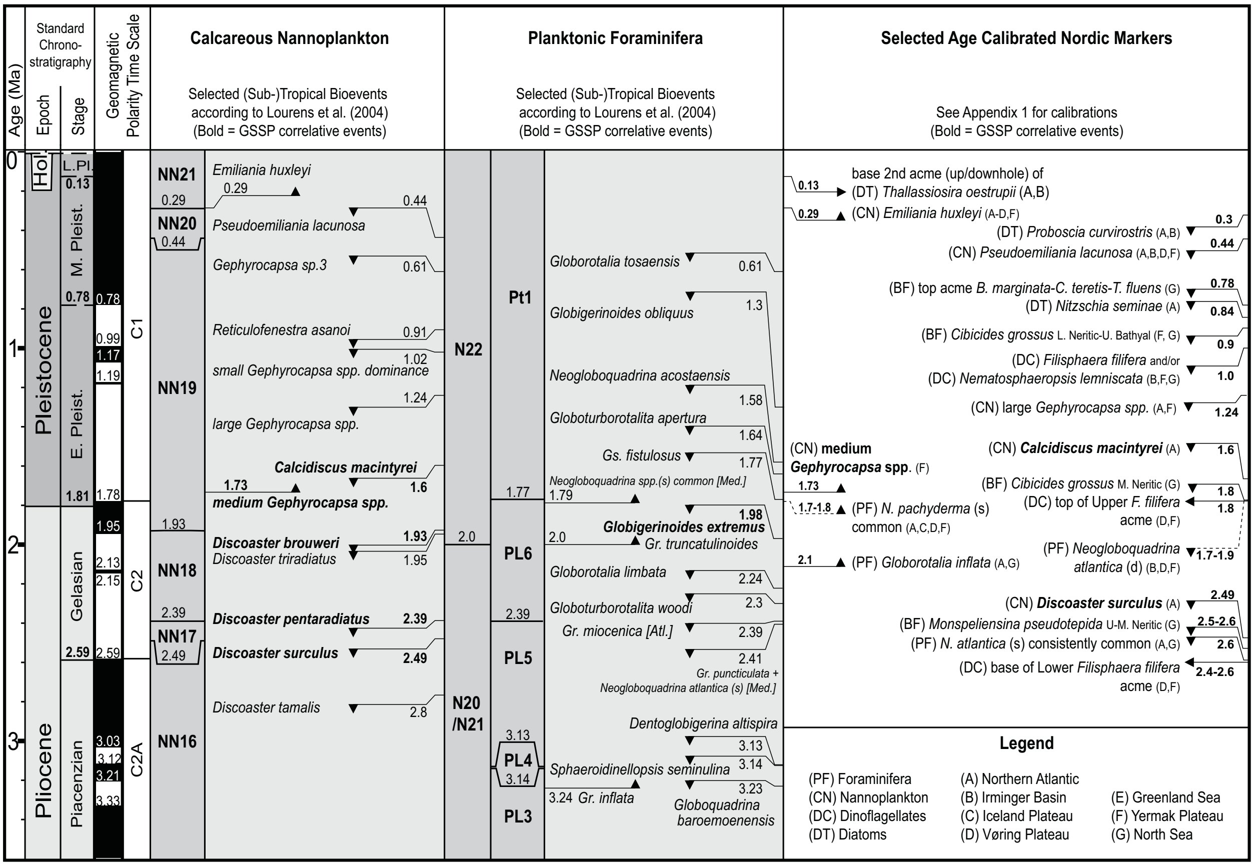


Fig. 3. Comparison of the low-latitude standard biozonations and important calibrated Nordic region bioevents. The geographic distribution of calibration points for each Nordic bioevent is indicated by the letters following its name (see Legend).

ginata, *Trifarina fluens* and *Cassidulina teretis* (Sejrup et al. 1987). This may coincide with the first common occurrence of the cold-indicator *Elphidium asklundi* (Knudsen and Asbjørnsdottir 1991). At Lower Neritic to Upper Bathyal depths the last occurrence of *Cibicides grossus* approximates the boundary (King 1989; Osterman 1996). At Lower Bathyal depths the Mid-Pleistocene saw the extinction of deep-sea benthic foraminifera with elongate, cylindrical tests and highly specialised apertures. The '*Stilostomella* Extinction' has been documented globally as occurring around the Brunhes-Matuyama boundary. This includes ODP Sites 980 and 982 in the northern North Atlantic, where the event was seen to culminate at ~0.694 Ma at Lower Bathyal water depths (Kawagata et al. 2005).

Calcareous nannoplankton

At ODP Site 911, on the Yermak Plateau, Sato and Kameo (1996) found the last occurrence of *Reticulofenestra asanoi* at 0.85 Ma. This species had its last common occurrence calibrated astronomically in the South Atlantic and Eastern Mediterranean to 0.9 Ma in Lourens et al. (2004). This is the only nannofossil marker for the base Middle Pleistocene in the Nordic Atlantic region and was only identified at this high-Arctic location. It is believed to have entered the Arctic through the Bering Strait.

Diatoms

South of the Greenland-Scotland Ridge, the best biostratigraphic approximation to the base of the Middle Pleistocene is the last occurrence of the diatom *Nitzschia seminae*. This event was dated to 0.84 Ma (MIS 21) at the northern North Atlantic ODP Site 983 (Koç et al. 1999) and 0.817–0.895 Ma (MIS 22–24) at ODP Site 919 on the East Greenland Margin (Koç and Flower 1998).

Dinoflagellate cysts

In the Norwegian Sea, Smelror (pers. comm.) placed the last occurrence of *Filisphaera filifera* at 1.4 Ma. This age is according to correlations with the nannoplankton stratigraphies of ODP Leg 151 (Poulsen et al. 1996). Mudie et al. (1990) placed the last occurrence of *F. filifera* in the Norwegian Sea and North Atlantic at slightly older than the base of the Middle Pleistocene (ca. 1 Ma). The dinoflagellate cyst stratigraphies for Norwegian Sea ODP Sites 643 and 642 place this event slightly older than the base of the Middle Pleistocene. At Arctic ODP Site 911 this event occurs at a level similar to the Norwegian Sea occurrence. At the Svalbard Margin ODP Site 986, it is significantly younger, occurring in the Upper Pleistocene (between 0.2 and 0.44 Ma). Whether this is due to reworking or true extinction events is not known. The last occurrence of *F. filifera*, according to these data, appears to be a rough approximation to the base of the Middle Pleistocene in the Norwegian Sea and possibly further south.

4.3 Base Pleistocene (1.806 Ma)

Planktonic foraminifera

None of the base Pleistocene primary or secondary GSSP markers are present in the Nordic deep-sea cores (with the exception of a rare occurrence of *Globigerinoides obliquus extremus* in discontinuous Upper Pliocene sediments of ODP Site 910), which usually offer most precise dating via direct correlation to the Geomagnetic Polarity Time Scale. However, examination of the microfossil data in the original definition of the Vrica GSSP (Aguirre and Pasini 1985) shows, in addition to the secondary markers mentioned, the first occurrence of *Neogloboquadrina pachyderma* (sinistral) occurring just above the boundary. In a later study of the Vrica Section, Lourens et al. (1996) astronomically calibrated the first common occurrence of *N. pachyderma* (s) to 1.799 Ma. The first common occurrence (FCO) of this species has also been recorded in ocean drilling cores throughout the Nordic Atlantic region as corresponding approximately to the top of the Olduvai Subchron: North Atlantic DSDP Sites 609, 610, 611 (Weaver and Clement 1986 recorded as a first occurrence of the "encrusted" morphotype); Northern North Atlantic ODP Site 985 (Flower 1999), Norwegian Sea ODP Sites 642, 643, 644 (Spiegler and Jansen 1989); Iceland Plateau Site 907 and Svalbard Margin ODP Site 986 (Flower 1999).

An additional planktonic foraminiferal event marking the boundary is the last occurrence of *Neogloboquadrina atlantica* (dextral), or the top of the Upper *N. atlantica* (dextral) Zone of Spiegler and Jansen (1989). It has been noted at ODP Sites 644 on the Vøring Basin, and 918 in the Irminger Basin. This event can also be described as the last occurrence of *N. atlantica* as a species including both coiling morphotypes. This was the case in the original range chart published by Aguirre and Pasini (1985) where they observed the last occurrence of *N. atlantica* just above the boundary at Vrica. It may sometimes occur together with the LCO *N. pachyderma* (dextral).

Benthic foraminifera

At upper neritic depths in the southern North Sea, the last common occurrence of the benthic foraminifer *Elphidiella hannai* occurs close to the Pliocene-Pleistocene boundary within the Olduvai Subchron (Kuhlmann 2004). At deeper lower neritic depths in the central and northern North Sea, the last occurrence of *Cibicides grossus* is a better approximation to the boundary (see Appendix 1).

Dinoflagellate cysts

The dinoflagellate cyst stratigraphy of Kuhlmann (2004) for the southern North Sea describes a first and second *'Filisphera/Habicysta/Bitectatodinium acme'* during the Olduvai normal event. A second or "upper *F. filifera* acme" is also evident in the raw fossil occurrence data of ODP Site 642 (see Mudie 1989) on the Vøring Plateau, and at ODP Site 911(see Matthiessen and Brenner, 1996) on the Yermak Plateau. At both sites this upper acme corresponds closely to the top of the Olduvai Subchron. On the Svalbard Margin, at ODP Site 986, this same acme event can be identified (see Smelror 1999), however, the ambiguous magnetostratigraphy in these samples obscures a reliable age estimate. It therefore appears that the upper *F. filifera* acme is the most reliable palynological marker for a level that is slightly younger than the base Pleistocene throughout much of the Nordic Atlantic region.

Calcareous nannoplankton

The calcareous nannoplankton stratigraphy of northern North Atlantic ODP Sites 981, 982 and 983 appears to be the most reliable biostratigraphy for this time interval, at least south of the GSR. At all three sites the last occurrence of *Calcidiscus macintyrei* occurs at the same level, above the Olduvai Subchron in C1r.3r. This datum was astronomically calibrated to 1.66 Ma according to Lourens et al. (2004) and occurs approximately 10 metres above the first common occurrence of *N. pachyderma* (s) at all three sites.

4.4 Base Gelasian (2.588 Ma)

Planktonic foraminifera

In the northern North Atlantic (DSDP Sites 609, 610, 611), Weaver and Clement (1986) and Weaver (1987) found the last occurrence (LO) *Neogloboquadrina atlantica* (sinistral) between the Gauss/Matuyama magnetic polarity boundary and the Olduvai Subchron. In the southern North Sea core study by Kuhlmann (2004), the last common occurrence (LCO) of *N. atlantica* was found just above the Gauss/Matuyama boundary. There may be exceptions to this age interpretation (see Discussion).

Benthic foraminifera

The benthic foraminiferal extinction of *Monspeliensina pseudotepida* in the Lower Neritic North Sea and offshore Mid-Norway corresponds approximately to the base of the Gelasian Stage (Kuhlmann 2004). This event was used by King (1989) to define his NSB 14/15 zonal boundary in the North Sea, which he placed close to the LO of *N. atlantica* (s) at 2.3 Ma (age according to Weaver and Clement 1986). The LO *Monspeliensina pseudotepida* also occurrs at a level with a strontium isotope date of 2.5–4.5 Ma in the central North Sea well 2/4-C-11 (Eidvin and Riis 1995).

Dinoflagellate cysts

In the southern North Sea, Kuhlmann (2004) found a first and a second acme of *Filisphera/Habicysta/Bitectatodinium*. The base of the first (or lower) acme corresponds closely to the Gauss-Matuyama magnetic reversal and therefore to the base of the Gelasian Stage. An analysis of the raw fossil occurrence data for ODP Sites 642 (Vøring Plateau), 986 (Svalbard Margin) and 911 (Yermak Plateau) reveals both an upper and a lower *F. filifera* acme. On the Vøring Plateau, the base of this acme approximately coincides with the Gauss/Matuyama boundary (see Mudie 1989). On the Svalbard Margin, it occurs slightly below the "R7 seismic reflector" (Smelror 1999), with a correlated age of ca. 2.3 Ma according to Faleide et al. (1996). While this suggests agreement with the Norwegian Sea age, this is not the case for the Yermak Plateau ODP Site 911, where the acme occurs much higher in the sequence. Further study is needed to ascertain the reliability of these acme events as regional markers.

A comparison between the key Nordic region bioevents and the standard (sub)tropical zonations is given in Fig 3.

5. Discussion: Synchroneity/diachroneity of selected planktonic foraminiferal datums

The age of the last occurrence of *Neogloboquadrina atlantica* (sinistral) in the Nordic Atlantic region has a history of conflicting interpretation. North Sea zonations have most often referred it to an age of 2.3 Ma, based on the temperate northern North Atlantic biomagnetostratigraphy of DSDP Leg 94 (Weaver and Clement 1986). This study shows this bioevent to be clearly time-transgressive across the region, but with three age clusters recorded at ca. 1.8 Ma, ca. 2.3 Ma and ca. 3.1 Ma (Appendix 1).

The oldest age assignment for the LO *N. atlantica* (s) of ca. 3.1 Ma was recorded at sites that show evidence of a significant Mid-Pliocene warm-water influx: Vøring Plateau ODP Sites 642 & 643 (?C2r.1r) and Yermak Plateau ODP Site 910 (slightly older than the standard Pl3/Pl4 planktonic foraminiferal zonal boundary of Berggren et al. 1995). The 'Mid-Pliocene global warmth' is evident here in the warm-temperate to subtropical planktonic foraminiferal assemblage at ODP Site 910 (including *Dentoglobigerina altispira* and *Globorotalia (Menardella) limbata*), and the acmes of *Globigerina bulloides* and the dinocyst *Achomosphaera andalousiensis* on the Vøring Plateau. Knies et al. (2002) identified a seasonally ice-free period in the eastern Arctic, contemporaneous with the 'Mid-Pliocene global warmth'.

The ca. 2.3 Ma age assignment for the LO *N. atlantica* (s) applies to the northern North Atlantic sites currently overlain by the warm surface waters of the North Atlantic Drift (ODP Sites 981, 982, ?984) and for the Vøring Plateau ODP Site 644, currently overlain by the warm Norwegian Coastal Current. At these locations the LO *N. atlantica* (s) occurs within the paleomagnetic Subchron C2r.2r.

The youngest age assignment for the LO *N. atlantica* (s) of ca. 1.8 Ma (straddling the Pliocene-Pleistocene boundary) was recorded at sites currently overlain by cold to mixed surface currents: Irminger Basin ODP Site 918 (upper C2n), Iceland Sea ODP Sites 985 (?C1r.3r) and 907 (mid C2n), Svalbard Margin ODP Site 986 (?C1r.3r) and Yermak Plateau ODP Site 911 (mid C2n). The complete absence of this bioevent and poor preservation encountered at Greenland Sea ODP Site 987 is probably due to dissolution as a result of the overlying cold East Greenland Current. The presence of this bioevent at the more northerly sites could be due to the contemporaneous inception of the warm Proto-Norwegian Current at ca. 1.9 Ma (Henrich et al. 2002). Poore and Berggren (1974) observed this event in the Labrador Sea at Deep Sea Drilling Project Site 113 as a very rare occurrence at the same level as the LO *Discoaster brouweri* (1.9 Ma astronomically calibrated age in Lourens et al. 2004). At other Labrador Sea sites, the event occurred lower in the Upper Pliocene, also possibly due to dissolution by the cold Labrador Current.

The age of the first common occurrence of *Neogloboquadrina pachyderma* (sinistral) appears to be largely synchronous across the region, ranging from 1.7–1.9 Ma (mid C2n to lower C1r.3r) in the majority of the sites investigated. The only exceptions to this record are the anomalously young ages of 1.0–1.1 Ma recorded at East Greenland ODP Site 918 (upper C1r.2r) and Greenland Sea ODP Site 987 (mid C1r.1r). Both sites are presently overlain by the cold East Greenland Current, which may have resulted in calcite dissolution of the lower parts of the *N. pachyderma* (s) acme. The inception of the warm Proto-Norwegian Current at ca. 1.9 Ma might have been responsible for this sudden acme event. Since these warmer-water incursions are believed to have been confined to the eastern and southern Nordic Seas, the Greenland Sea would not have experienced the same ameliorated surface-water conditions (Henrich et al. 2002). The anomalously younger age does, however, coincide with the globally synchronous first occurrence of the larger modern *N. pachyderma* (s) morphotype (Kucera and Kennett, 2002).

6. Conclusions

The correlation of deep-sea cores in the Nordic Atlantic region highlights the geographical extent and stratigraphic range of a number of high-latitude marker species. This has resulted in the identification of synchronous and diachronous bioevents, together with the best biostratigraphic approximations to the standard chronostratigraphic boundaries of this time period. Although many of these taxa have been know to show diachronous local ranges, this regional correlation allows for a better quantification of the degree of this diachroneity. This has resulted in identification of the best biostratigraphic approximations to the standard Late Pliocene – Pleistocene chronostratigraphic boundaries at these high latitudes. In addition, this study highlights biostratigraphic trends on both a regional scale and on a more local scale between subbasins.

Possible explanations for the diachronous record of the last occurrence *Neogloboquadrina atlantica* (sinistral) in the Nordic Atlantic region are: calcite dissolution under cold ocean currents (results in a depressed range); ice-rafting or other reworking (results in an artificially extended range); sites located under warm surface water from the Gulf Stream/North Atlantic Drift might have experienced unfavourable environmental conditions for this apparently cold-adapted, sinistrally-coiled *N. atlantica* morphotype (results in a depressed range). At locations dominated by cold or mixed ocean currents, the last occurrence of *Neogloboquadrina atlantica* (s) occurs together with the first common occurrence of *N. pachyderma* (s).

The first common occurrence of *N. pachyderma* (s) is a largely synchronous datum in the region, and a good biostratigraphic approximation for the base of the Pleistocene. The exception occurs at locations dominated by cold ocean currents such as the East Greenland Current, where only the uppermost part of the acme is present. The earlier onset of this acme event in the southern and eastern parts of the region may be related to the inception of the warm Proto-Norwegian Current (Henrich et al. 2002).

The continuing efforts of the Integrated Ocean Drilling Program (IODP) and further advances in amino-acid dating, OSL and isotope dating methods may improve linking these high-latitude microfossil records to the standard Neogene chronostratigraphic definitions of the Mediterranean.

Acknowledgements. This study, under the supervision of Felix M. Gradstein, is part of an ongoing project at the Natural History Museum in Oslo (Norway) to calibrate Nordic Upper Cenozoic biozones relative to the standard global time scale. Support comes from the Natural History Museum, University of Oslo and the Norwegian Interactive Lithostratigraphic Lexicon (NORLEX Project).

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Manuscript received: March 13, 2008, rev. version received: April 8, 2008, accepted for print: April 9, 2008.

Age or [average] in Ma	Bioevent[a]	Fossil group[b]	Calibration[c]	Calibrated Ages by Region/Basin (Ma): A. Northern Atlantic	B. Irminger Basin	C. Iceland Platea	D. Vøring Plateau	E. Greenland Sea	F. Yermak Plateau	G. North Sea	References
0.12	Acme of high-productivity 'warm stage' benthic foraminifers, including *Bulimina marginata, Cassidulina laevigata & Bolivina* spp. [At neritic paleo-waterdepths]	BF	1st order: Marine Isotope Stage (MIS) 5e based on amino acid dating of *E. excavatum & B. marginata* (isoleucine epimerization ratios between 0.08 and 0.115) from various interglacial deposits, including Statfjord C borehole in northern North Sea							0.12	G. Knudsen & Sejrup (1988), Sejrup et al. (1999)
0.13	base 2nd up/downhole acme of *Thallassiosira oestrupii*	DT	1st order: Base of MIS 5 based on stable isotopes (Site 983 & 919)	0.126	0.126						A. Koc et al. (1999); B. Koc & Flower (1998)
[0.27]	LCO *Elphidium ustulatum* [At neritic paleo-waterdepths]	BF	2nd order: Approximates the base of warm stage MIS 11 in North Sea 'Josephine' borehole, correlated to within magnetochron C1n (in nearby well BGS 81/34), below second downhole interglacial fauna; 2nd order: as young as MIS 5e (Eemian) warm stage (IGS borehole SLN 75/33)							0.13 - 0.40	G. Knudsen & Asbjørnsdottir (1991), Gregory & Bridge (1979)
0.29	FO *Emiliania huxleyi*	CN	1st order: Near base of MIS 7 (Sites 983 & 919); occurs within the upper third of the C1n (Brunhes) magnetochron (Sites 981, 982, 983, 984, 918, 919, 642, 643, 644, 911); global event with astronomically calibrated age	0.29	0.29	0.29	0.29		0.29		A. Shipboard Scientific Party (1996a); B. Wei (1998); C. Shipboard Scientific Party (1996b); D. Donnally (1989); F. Sato & Kameo (1996); Global: Lourens et al. (2004)
[0.32]	LO *Proboscia curvirostris*	DT	1st order: Upper MIS 9 (Site 983) to base MIS 9 (Site 919), at a level within the upper half of the C1n (Brunhes) magnetochron	0.3	0.34						A. Koc et al. (1999); B. Koc & Flower (1998)
0.44	LO *Pseudoemiliania lacunosa*	CN	1st order: Within MIS 11 (Sites 983); occurs approximately midway within C1n (Sites 981, 982, 983, 984, 919, 642, 643, 644, 986, 910, 911); global event with astronomically calibrated age	0.44	0.44		0.44		0.44		A. Shipboard Scientific Party (1996a); B. Wei (1998); D. Donnally (1989); F. Sato & Kameo (1996); Global: Lourens et al. (2004)
[0.69]	LO *Pleurostomella alternans* ('*Stilostomella* Extinction') [At middle to lower bathyal paleo-waterdepths]		1st order: Slightly above the C1n/C1r.1r (Brunhes-Matuyama) magnetochron boundary (Sites 980 & 982); global deep-sea event	0.68 - 0.70							A. Kawagata *et al.* (2005); Global: Hayward (2001)
0.78	Top of acme of high-productivity 'warm stage' benthic foraminifers *Bulimina marginata, Cassidulina teretis & Trifarina fluens* [At neritic paleo-waterdepths]	BF	2nd order: In North Sea 'Josephine' borehole, correlated to C1n/C1r.1r (Brunhes-Matuyama) magnetochron boundary (in nearby borehole BGS 81/34), corresponding to the global MIS 19 warm stage							0.78	G. Knudsen & Asbjørnsdottir (1991)
[0.9]	LO *Cibicides grossa* [At lower neritic to upper bathyal paleo-waterdepths]	BF	1st order: Approximately halfway between the LO *P. lacunosa* and FO medium *Gephyrocapsa* spp. (Site 910), i.e. mid. NN19. Occurs at a similar level in West Barents Sea wells 7117/9-1 & 7117/9-2 (Eidvin et al.,1993). 2nd order: In the deeper parts of the North Sea it occurs above FO *N. pachyderma* (s) to the Mid-Pleistocene according to King (1989)						~1.0	0.78 - 1.0	F. Osterman (1996); G. King (1989)
[0.87]	LO *Nitzschia seminae*	DT	1st order: MIS 21- 22, and middle of magnetosubchron C1r.1r (Sites 983 & 919)	0.84	0.82 - 0.90						A. Koc et al. (1999); B. Koc & Flower (1998)
0.9	LO *Reticulofenestra asanoi*	CN	1st order: Middle of subchron C1r.1r (Site 911); MIS 22/23 (Mediterranean Sites 976 & 963); global event with astronomically calibrated age						0.9		F. Sato & Kameo (1996); Mediterranean: Reale & Monechi, 2005; Global: Lourens et al. (2004)
[1.0]	LO *Filisphaera filifera* +/- LO *Nematosphaeropsis lemniscata*	DC	1st order: Within C1r.1r (Site 644, 611). Within C1r.1n (Site 607). Slightly below the base of C1r.1n (Site 642, 643 & 911). Between base of C1r.1n and LO *C. macintyrei* (Site 646 & 647). The LO *F. filifera* was recorded coincident with an acme of the species within C2r.1r (Site 987). This observation probably correlates to the older "top of upper/first acme of *F. filifera*" event	0.9 - 1.1			0.9- 1.1	"2.0"	1.1		A. de Vernal & Mudie (1985), Mudie (1987); D. Mudie (1989); E. Smelror (1999); F. Matthiessen & Brenner (1996)
[1.05]	FO Holocene (modern) dinocyst assemblage composition including shift in dominance of *Operculodinium israelianum* to *O. centrocarpum*	DC	1st order: Event marked by acme of *O. centrocarpum* within C1r.1n (Site 911); Coincident with P2/P1 palynomorph zonal boundary and nannofossil LO large *Gephyrocapsa carribeanica* (mid-latitude Site 898 Iberia Abyssal Plain)	1.15					1		A. McCarthy et al. (2000); F. Matthiessen & Brenner (1996); Iberia Abyssal Plain: McCarthy et al.(2000)
1.24	LO large *Gephyrocapsa* spp.	CN	1st order: MIS 35 (Site 983); upper part of subchron C1r.2r (Sites 983 & 911); global event with astronomically calibrated age	1.24					1.24		A. Shipboard Scientific Party (1996a); F. Sato & Kameo (1996); Global: Lourens et al. (2004)
1.66	LO *Calcidiscus macintyrei*	CN	1st order: Lower part of subchron C1r.3r (Site 981) and above C2n (Sites 982 & 983); global event with astronomically calibrated age	1.66							A. Shipboard Scientific Party (1996a);Global: Lourens et al. (2004)
1.73	FO medium *Gephyrocapsa* spp.	CN	1st order: Lower part of subchron C1r.3r (Site 911); global event with astronomically calibrated age						1.73		F. Sato & Kameo (1996); Global: Lourens et al. (2004)
[1.8] or "0.8-1.1"	FCO *Neogloboquadrina pachyderma* (sinistrally-coiled)	PF	1st order: approximates top C2n (Olduvai) magnetochron (Sites 985, 907, 642, 643, 644, 986). 1st order: approximates top C2n (Sites 609, 610, 611), coincident with the first occurrence of the "encrusted" morphotype. 1st order: first consistent occurrence is slightly below FO medium *Gephyrocapsa* spp. (Site 911). King (1989) observed a downhole change from left-coiling to predominantly right-coiling *N. pachyderma* in North Sea wells, with the age according to the magnetostratigraphy of Weaver & Clement (1986);Astronomically calibrated at the Mediterranean GSSP to 1.799 Ma. The event is anomalously younger in the Irminger Basin (East Greenland Margin) and in the Greenland Sea, possibly due to the cold paleo ocean current here.	1.7 - 1.8	"1.1"	1.7- 1.8	1.8	"0.8"	1.7		A. Weaver & Clement (1986); C. Flower (1999); D. Spiegler & Jansen (1989); F. Flower (1999); Mediterranean: Lourens et al. (1996)
[1.8]	LO *Neogloboquadrina atlantica* (dextrally-coiled) +/- LCO (consistent) *N. pachyderma* (dextrally-coiled)	PF	1st order: Above top C2n (Site 918), near top C2n (Sites 910 & 911), and above base C2n (Site 644). Equivalent to the LO of *N. atlantica* species including both coiling morphotypes, observed just above the Pleistocene GSSP at Vrica (Aguirre & Pasini, 1985). Due to difficulty in differentiating these two taxa this event probably ranges from the top of the Upper *N. atlantica* (dextral) Zone to the top of the *N. pachyderma* (dextral) Zone of Spiegler & Jansen (1989).		1.7		1.9		1.8		B. Spezzaferri (1998); D. Spiegler & Jansen (1989); F. Spiegler (1996); Mediterranean:Aguirre & Pasini (1985)
1.8	LCO *Elphidiella hannai* [At upper neritic paleo-waterdepths]	BF	1st order: Top C2n (Olduvai) magnetochron (B10-3, B13-3 and B17-5/B17-6 cored wells in the southern North Sea). It is absent or occurs much older at deeper paleodepths, probably close to the base of the Gelasian.							1.8	G. Kuhlmann (2004)

Age or [average] in Ma	Bioevent[a]	Fossil group[b]	Calibration[c]	Calibrated Ages by Region/Basin (Ma): A. Northern Atlantic	B. Irminger Basin	C. Iceland Platea	D. Vøring Plateau	E. Greenland Sea	F. Yermak Plateau	G. North Sea	References
1.8	LO *Cibicides grossa* [At middle neritic paleo-waterdepths]	BF	2nd order: Occurs at a level between two reverse polarity intervals, where the overlying strata produced a Sr-isotope age of 1.0 Ma and the underlying strata an age of 1.4 - 2.0 Ma (central North Sea well 2/4-C-11), thus close to top Olduvai age. 3rd order: King (1989) correlated the LO *Cibicides grossa* at shallow paleodepths in the North Sea to the FO *N. pachyderma* (s) 'encrusted' (or the downhole change from dominant sinistrally-coiled to dominant dextrally-coiled *N. pachyderma*), calibrated to near top Olduvai (DSDP Sites 609, 610, 611) in the northern North Atlantic. The LO *Cibicides grossa* is absent from upper neritic deposits and is younger in lower neritic to bathyal assemblages.							~1.8	G. Eidvin et al. (1993); Eidvin & Riis (1995); King (1989); Weaver & Clement (1986)
[1.9]	Top of upper/first downhole acme of *Filisphaera filifera* +/- *Habibacysta tectata*	DC	1st order: Top C2n (Olduvai) magnetochron (Site 642). 1st order: Within C2n (B10-3, B13-3 and B17-5/B17-6 cored wells in the southern North Sea). 1st order: Within C2r.1r (Site 987), coincident with observed LO *F. filifera* here. 1st order: Within C2n (Site 911). 2nd order: As young as 1.8 Ma in the North Sea occurring at the top of the "Upper *N. atlantica* (dextral) Zone" (North Sea cored well 15/9-A-11)				1.8	2	1.9	1.8 - 1.9	D. Mudie (1989); E. Channell et al.,1999; F. Matthiessen & Brenner (1996); G. Kuhlmann (2004); Head et al. (2004)
2.09	FO *Globorotalia (Globoconella) inflata*	PF	1st order: Top (C2r.1n) Reunion (Sites 981 & 982). 1st order: from C2r.1r to C2r.2r (Sites 606, 607, 608, 609, 610, 646). The anomalous age within C2An.1n (Site 644) is probably due to contamination since all other findings approximate the astronomically calibrated age in the Mediterranean	2.0 - 2.2			"2.6"				A. Flower (1999), Weaver & Clement (1986); Aksu & Kaminski (1985). Mediterranean: Lourens *et al.* (2004)
2.3 or 3.1	LCO (consistent) *Cibicides grossa* +/- LCO *Melonis ex. gr. barleeanus* +/- LCO *Bulimina aculeata* [At lower neritic to upper bathyal paleo-waterdepths]	BF	1st order: LCO (consistent) *C. grossa* at Pl4/Pl5 zonal boundary (Site 910). 2nd order: LCO (consistent) *C. grossa, M. ex. gr. barleeanus* at LO *N. atlantica* (s) event (34/8-1 well) in the northern, deeper parts of the North Sea						3.1	2.3	F. Osterman (1996), Spiegler (1996); G. Eidvin & Riis (1995)
1.9 or 2.3 or 3.1	LO *Neogloboquadrina atlantica* (sinistrally-coiled) +/- LCO (consistent) *Globigerina bulloides*	PF	1st order: Occurs below LO *G. limbata* (Site 910). 1st order: Within C2r.2r (Sites 609, 610, 611, 981, 982, 644, 986). Within C2n (918, 907, 911). 2nd order: Occurs at a level with a Sr-isotope dating of 2.5 - 4.5 Ma (well 2/4-C-11). Anomalously young ages occur where the cold paleo- East Greenland Current may have delayed the migration of the dextral morphotype of *N. atlantica*.	2.3	1.9	1.9	2.3		1.9 & 3.1	2.5?	A. Weaver & Clement (1986), Flower (1999); B. Spezzaferri (1998); C. Flower (1999); D. Spiegler & Jansen (1989); F. Flower (1999); G. Eidvin et al. (1993)
2.0 or [2.5]	LO *Globorotalia (Globoconella) puncticulata*	PF	1st order: Base C2n (Olduvai) magnetochron (Site 644). From within C2r.2r (Site 981) to below the top of C2An.1n (Site 982)	2.4-2.6			2				A. Flower (1999); D. Spiegler & Jansen (1989)
2.5	LO *Discoaster surculus*	CN	1st order: Approximates top C2An.1n (Sites 981 & 982) ; global event with astronomically calibrated age	2.5							A. Wei (1998); Global: Lourens et al. (2004)
2.5	LO *Monspeliensina pseudotepida* +/- LO *Sigmoilopsis schlumbergeri* [At upper to middle neritic paleo-waterdepths]	BF	1st order: Above top C2An.1n (Gauss) magnetochron (B10-3, B13-3 and B17-5/B17-6 cored wells in the southern North Sea); 2nd order: Occurs at a level with a Sr-isotope dating of 2.5 - 4.5 Ma (central North Sea well 2/4-C-11)							2.5-2.55	G. Kuhlmann (2004), Eidvin et al. (1993)
2.5	Base of lower/last downhole acme of *Filisphaera filifera*	DC	1st order: Top C2An.1n (Gauss) magnetochron (B10-3, B13-3 and B17-5/B17-6 cored wells in th southern North Sea); Top C2An.1n (Site 642); Within C2r.2r (Site 911)				2.6		2.4	2.6	G. Kuhlmann (2004)
2.6	LCO (consistent) *Neogloboquadrina atlantica* (sinistrally-coiled)	PF	1st order: Top C2An.1n (Gauss) magnetochron (B10-3, B13-3 and B17-5/B17-6 cored wells in th southern North Sea); Two metres below top C2An.1n (Labrador Sea Site 646)	2.6						2.6	A. Aksu & Kaminski (1985); G. Kuhlmann (2004)

[a]Bioevents: FO = First Occurrence: LO = Last Occurrence: FCO = First Common Occurrence: LCO = Last Common Occurrenc

[b]Fossil group: DT = Diatom: CN = Calcareous Nannofossil: DC = Dinoflagellate Cyst: PF = Planktonic Foraminifer: BF = Benthic Foramini

[c]Magnetostratigraphic ages according to the astronomical calibrations (orbitally tuned) of Lourens et al. (2004)

Appendix 1. Calibrations of key microfossil bioevents in the Nordic Atlantic region. Each calibrated age is organised according to the region/basin where the calibration was made. Where nessecary, the average of these calibrated ages has been ascribed to a diachronous bioevent.