Quaternary Science Reviews 30 (2011) 934–946

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Evidence for delayed poleward expansion of North Atlantic surface waters during the last interglacial (MIS 5e)

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ARTICLE INFO

Article history:
Received 24 June 2010
Received in revised form
17 January 2011
Accepted 19 January 2011
Available online 11 February 2011

Keywords:
Last Interglacial
MIS 5e
Dinoflagellate cysts
North Atlantic
Nordic seas

ABSTRACT

The Last Interglacial (Marine Isotopic Stage or MIS 5e) surface ocean heat flux from the Rockall Basin (NE Atlantic) towards the Arctic Ocean was reconstructed by analysing dinoflagellate cyst (dinocyst) assemblages in four sediment cores. Together with records of stable isotopes and ice-rafted detritus, the assemblage data reflect the northward retreat of ice(berg)-laden waters and the gradual development towards interglacial conditions at the transition from the Saalian deglaciation (Termination II) into MIS 5e. At the Rockall Basin, this onset of the Last Interglacial is soon followed by the appearance of the thermophilic dinocyst species *Spiniferites mirabilis*, with relative abundances higher than those observed at present in the area. North of the Iceland-Scotland Ridge, however, *S. mirabilis* only appears in significant numbers during late MIS 5e, between ~118 and 116.5 ka. Hence, fully marine Last Interglacial conditions with most intense Atlantic surface water influence occurred during late MIS 5e in the Nordic seas, and consequently also farther north in the Arctic Ocean, and at times when northern hemisphere summer insolation was already significantly decreased. The stratigraphic position of this Late Interglacial optimum is supported by planktic foraminifers and contrasts with the timing of the early Holocene climatic optimum in this area. We interpret the delayed northward expansion of Atlantic waters towards the polar latitudes as a result of the Saalian ice sheet deglaciation and its specific impact on the subsequent water mass evolution in this region.

1. Introduction

Transient past warm intervals constitute critical time periods with the potential to offer insight into the natural range of climate change. One of these past warm periods, the Last Interglacial or Marine Isotope Stage (MIS) 5e, had environmental constraints (e.g., temperatures) comparable to the present warm interval, i.e. the Holocene period (e.g., Kukla et al., 2002). Thus, this time interval comprises a reasonable candidate to evaluate and compare the mechanisms which steer the development of warm climate intervals and their climate transitions.

Although there are some region- and proxy-dependant discrepancies regarding the timing of the Holocene thermal optimum across the NE Atlantic and Norwegian Sea (Hald et al., 2007; Andersson et al., 2010; but also the discussion by Bauch and Erlenkeuser, 2008), several phytoplankton (-derived) records (e.g., Birks and Koç, 2002; Calvo et al., 2002; Marchal et al., 2002; Andersen et al., 2004; Leduc et al., 2010) as well as some zooplankton (-derived) records (e.g., Bauch et al., 2001; Hald et al., 2001) suggest the thermal optimum occurred during the first half of the Holocene, more or less in step with high northern hemisphere summer insolation (Laskar et al., 2004). Accordingly, an early optimum at times of elevated summer insolation was also revealed for MIS 5e in the temperate North Atlantic (e.g., Cortijo et al., 1999; Bauch and Kandiano, 2007) as well as the Norwegian Sea (Cortijo et al., 1994). However, more recent results from the eastern Nordic seas, which involved planktic foraminifers, dinoflagellate cysts and other proxies, would indicate that the upper ocean hydrography of both interglacial intervals appears to have evolved quite differently, with warm surface water advection into the (north) eastern Nordic seas intensifying only late in MIS 5e (Rasmussen et al., 2003; Van Nieuwenhove and Bauch, 2008; Van

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doi:10.1016/j.quascirev.2011.01.013

Nieuwenhove et al., 2008). This particular development of the Last Interglacial climate remained largely undetectable in previous, low-resolution studies (cf. Bauch and Erlenkeuser, 2008), perhaps partly explaining the conflicting interpretations for both a reduced northward heat transport on the one hand (Bauch et al., 1999) as well as a rather warm water mass advection reaching the Arctic margins during MIS 5e on the other hand (e.g. Matthiessen et al., 2001; Grøsfjeld et al., 2006). In addition, the general lack of, and the difficulty to obtain highly-resolved MIS 5e sediment sections from the Fram Strait and Arctic basin, complicates a refined paleoceanographic reconstruction and precise stratigraphic allocation of the events characterizing the MIS 5e climate development in the high-polar latitudes.

The present study aims at tracing variations in the intensity of the warm surface water flux from temperate to polar latitudes across the eastern Nordic seas as the Last Interglacial progressed, by using four cores spanning a transect from 55°N to 77°N along the modern pathway of the northbound Atlantic surface waters. The new data elaborate on some of the results from the previous investigations but provide a more highly-resolved overview of the MIS 5e surface water circulation development for the mid-to-high latitude eastern North Atlantic realm. By creating this over-regional view, an attempt is made to also refine the stratigraphic and paleoceanographic context of marine MIS 5e sediment sections retrieved from the polar region. This will be achieved by evaluating changes in the composition of dinoflagellate cyst (dinocyst) assemblages, supported by some “traditional” proxies (stable isotopes, ice-rafted detritus (IRD), planktic foraminifera). In particular, the association of the warm-temperate dinocyst species *Spiniferites mirabilis* with interglacial optima in the northern North Atlantic evidenced by previous studies (Sánchez-Goñi et al., 1999, 2000; Eynaud et al., 2004; Penaud et al., 2008; Van Nieuwenhove and Bauch, 2008; Van Nieuwenhove et al., 2008) will be used to reconstruct the northward-directed flow of warm water masses towards the high Arctic during MIS 5e.

2. Regional setting

Two meridionally orientated ocean currents dominate the modern surface circulation in the Nordic seas (Fig. 1). Relatively warm and saline surface waters from the northern continuation of the Gulf Stream system pass the Rockall Basin as the North Atlantic Drift (NAD) and flow across the Iceland-Scotland ridge and into the eastern Nordic seas (e.g. Mork and Blindheim, 2000). There, they continue north as the Norwegian Atlantic Current (NwAC) and define the Atlantic Domain. Eventually, these Atlantic surface waters enter the Arctic basin through Fram Strait and across the Barents Sea. The NwAC is influenced from the east by fresher waters from the Norwegian Coastal Current (NCC), a northward flowing marginal current originating from the Baltic Sea/North Sea region. In the western Nordic seas, a southward outflow along the Greenland coastline of cold and freshened Arctic surface waters constitutes the East Greenland Current (EGC), which occupies the Polar Domain. In between the EGC and NwAC lies a zone of mixed water masses, the Arctic Domain, which is bordered by the Polar Front in the west and the Arctic Front in the east.

3. Materials and methods

Sediment samples were collected from the CALYPSO piston cores MD95-2004 (east of the Rockall Plateau) and MD95-2009 (north of the Iceland-Scotland Ridge), and from the large Kastencores M23323-1 (Vøring Plateau) and M23455-3 (southeast of the Fram Strait) (Fig. 1; Table 1). Stadial and (de)glacial core sections enriched in IRD alternate with interglacial intervals characterised by brown-grey clays, silts and a sand fraction mainly made up of foraminiferal shells.

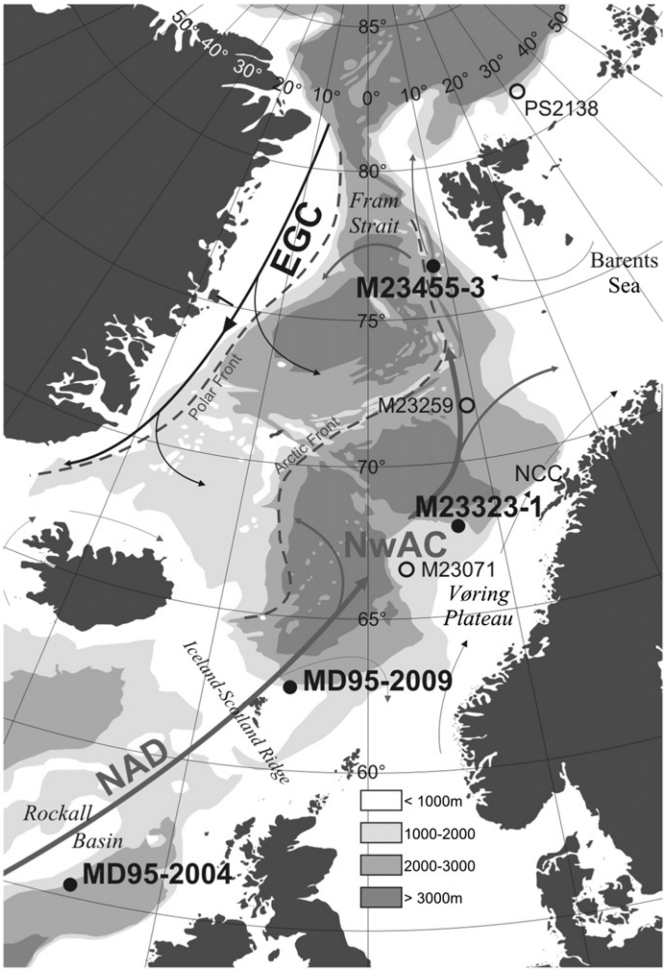


Fig. 1. Map showing the position of the studied cores (black circles) and other cores referred to in the text (M23071: Van Nieuwenhove and Bauch, 2008; Van Nieuwenhove et al., 2008; M23259: Baumann, 2007; PS2138: Matthiessen and Knies, 2001; Matthiessen et al., 2001) in relation to the generalised modern surface oceanography in the NE Atlantic and Nordic seas. Grey arrows indicate warm surface currents, black arrows indicate cold surface currents. EGC: East Greenland Current; NAD: North Atlantic Drift; NCC: Norwegian Coastal Current; NwAC: Norwegian Atlantic Current.

3.1. Stable oxygen isotope stratigraphy

A high-resolution downcore oxygen isotope stratigraphy from MIS 5d back into early Termination II was produced for core M23323-1 at 1 cm steps from 720.5 cm downwards. For core M23455-3 we improved a formerly low-resolution stable isotope record (Kottke, 1998, 1999) with new, much denser sampling at 0.5 cm steps between 290.25 and 320.75 cm core depth. In both

Table 1
List of investigated cores.

Core	Geographical position		Water depth (m)
	Latitude	Longitude	
MD95-2004	55°28′N	14°40′W	2177
MD95-2009	62°44′N	04°00′W	1027
M23323-1	67°46′N	05°55′E	1286
M23455-3	76°51′N	08°22′E	2497

cores, light values clearly indicate the position of MIS 5e (Fig. 2). Stable isotope ratios were measured on 25–30 specimens (200 μm average size) of the polar planktic foraminifer *Neogloboquadrina pachyderma* (s) per sample, and on 9–15 specimens of the epibenthic foraminifer *Cibicidoides wuellerstorfi*. For cores M23323-1 and M23455-3, this was done at the Leibniz Laboratory for Radiometric Dating and Stable Isotope Research, Kiel University, with the fully automated Kiel Carbonate Preparation Device and a Finnigan MAT 251 mass spectrometer. The analytical accuracy of this system is ±0.07‰ for $\delta^{18}O$. All measurements were calibrated on the Pee Dee Belemnite isotope scale (PDB).

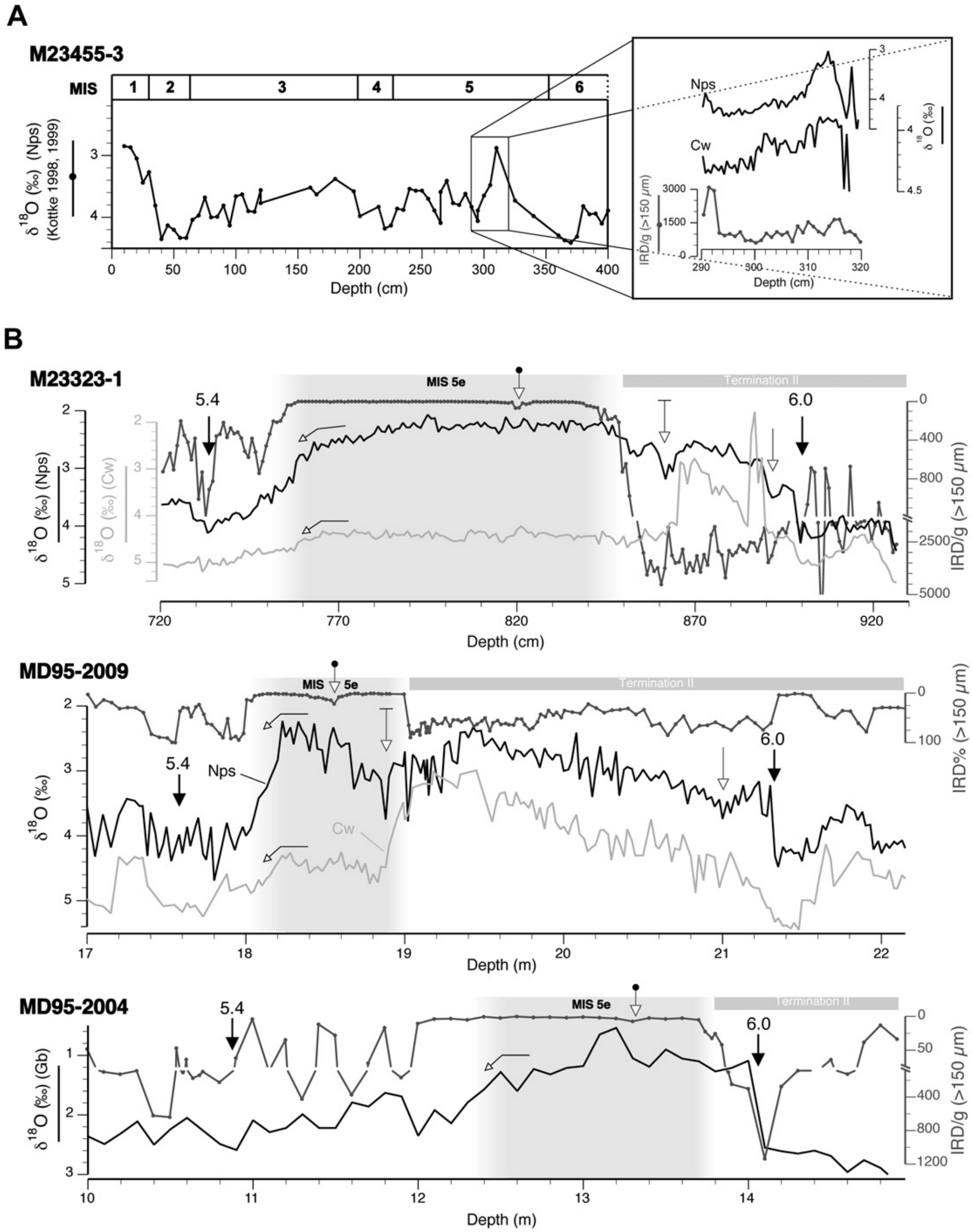


Fig. 2. (A) Low resolution planktic stable oxygen isotope stratigraphy of core M23455-3 with indication of the isotopic stages (Kottke, 1998, 1999), and refined planktic (Nps: *Neogloboquadrina pachyderma* (s)) and benthic (Cw: *Cibicidoides wuellerstorfi*) stable oxygen isotope and ice-rafted detritus (IRD) data for the densely-sampled core section studied here. (B) Downcore records of IRD, planktic and benthic stable oxygen isotopes of the sections spanning latest Termination II/MIS 5e/early MIS 5d in the studied cores, with indication of isotopic events 6.0 and 5.5 and the most significant tie points used in constructing the age model (open arrows). IRD is given as grains per gram dry sediment except for core MD95-2009 where it is given as percent. Note the vertical axis break in the IRD records of cores M23323-1 and MD95-2004. The grey shaded area indicates the interval representing "real" interglacial conditions (i.e., with little or no IRD). The IRD records of cores MD95-2009 and MD95-2004 are from Rasmussen et al. (1999) and Manthé (1998), respectively. The planktic and benthic $\delta^{18}O$ records of core MD95-2009, derived from *Neogloboquadrina pachyderma* sinistral (Nps) and *Cibicidoides wuellerstorfi* (Cw) respectively, are from Balbon (2000). The planktic $\delta^{18}O$ record of core MD95-2004, derived from *Globigerina bulloides* (Gb), is from Manthé (1998). Also shown is the position of the basaltic ash layer "5e-low/BAS-IV" in core MD95-2009 (Wastegård and Rasmussen, 2001).

The allocation of substage 5e in cores MD95-2004 and MD95-2009 is based on the comparison of the foraminiferal stable oxygen isotope record with the SPECMAP curve (Martinson et al., 1987), and is further supported by IRD, magnetic susceptibility and carbonate content data (Chassery, 1997; Manthé, 1998; Eynaud, 1999; Balbon, 2000). The benthic and planktic $\delta^{18}O$ records of core MD95-2009 (Rasmussen et al., 1999, 2003; Balbon, 2000; Risebrobakken et al., 2006) were produced at a ~2–5 cm interval from *C. wuellerstorfi* and *N. pachyderma* (s), respectively. The planktic $\delta^{18}O$ record for core MD95-2004 was established at 10 cm step intervals using *Globigerina bulloides* (Manthé, 1998).

The general trend of our planktic isotope data shows a much better similarity to the stacked SPECMAP curve than our benthic oxygen isotope records, which display strongly depleted values during Termination II (Fig. 2). It has been argued that in the Nordic seas local hydrographical changes and suborbital climate variability during deglacial phases can have a strong regional imprint on the benthic oxygen isotopes, which therefore do not phase the global signal of ice sheet decay and sea level rise (Skinner and Shackleton, 2005, 2006; Thompson and Goldstein, 2006). In contrast, by combining the IRD data with the planktic oxygen isotope curves, it is possible to separate (at least qualitatively) the local effects of meltwater input from the temperature signal contained in the planktic $\delta^{18}O$ record.

3.2. Dinoflagellate cyst analysis

Dinocyst samples were taken at a 1- to 2-cm interval in cores M23323-1 and M23455-3, and at a 5- to 10-cm interval in cores MD95-2004 and MD95-2009. Standard palynological methods were used in preparing the samples (e.g. Matthiessen, 1995). These involved the use of cold HCl and HF to remove carbonates and silicates, respectively, and sieving over a 6–10 and 150 μm polymer mesh. No oxidation was done to avoid the loss of (proto)peridiniacean cysts (Dale, 1976). The final residue was centrifuged and mounted on microscopy slides using glycerine gelatine. A known number of *Lycopodium clavatum* spores was added to each sample prior to chemical treatment in order to calculate absolute cyst concentrations (Stockmarr, 1971). The complete protocol of the preparation methods can be found in de Vernal et al. (1996) and Van Nieuwenhove (2008).

Dinocyst analysis of cores MD95-2004 and MD95-2009 was done by F. Eynaud, cores M23323-1 and M23455-3 were analysed by N. Van Nieuwenhove. The extensive surface sediment database from the North Atlantic and Nordic seas (Rochon et al., 1999; de Vernal et al., 2001, 2005; Marret and Zonneveld, 2003; Marret et al., 2004) reveals a close relationship between the distribution of dinocyst species and sea surface parameters (salinity, temperature, sea ice cover), indicating the potential of these organic algal remains as palaeoceanographic tool (e.g., de Vernal et al., 2005). The taxonomic nomenclature follows de Vernal et al. (1992), Rochon et al. (1999), Head et al. (2001) and Fensome and Williams (2004). Following standard praxis (e.g., Rochon et al., 1999), some taxa were grouped during counting when preservation or unfavourable orientation hampered determination on species level, or afterwards, in order to “normalise” the records for comparison. We refer to Van Nieuwenhove et al. (2008) for more information about the grouping. Between ~300 and 600 cysts were counted per sample in the IRD-poor interval from the three southern cores, guaranteeing statistical robustness and inter-laboratory reproducibility of the dataset (Mertens et al., 2009). Statistical analysis (conducted with the “statcounts” EXCEL add-in developed by D. Heslop (Pers. Comm. 2010 based on the algorithmic approach of Sison and Glaz (1995) and May and Johnson (2000)) reveals that this allows to estimate changes within ±4% with 0.95 ($p = 0.05$) probability and ±2.50% at the 0.75 probability level for the total assemblages at key site M23323-1. The lower and upper limits of the 75% simultaneous confidence interval for the relative abundance of *S. mirabilis* in cores M23323-1, MD95-2009 and MD95-2004 are shown in Fig. 3. Samples with low cyst concentrations (in nearly all samples from core M23455-3 and the deglacial interval of the other cores) usually allowed only 100–250 cysts to be determined at species level. The relative abundances are based on the total sum of counted cysts excluding unidentified taxa and reworked specimens. Absolute abundances are expressed as number of cysts per gram dried sediment for cores M23323-1 and M23455-3, and as cysts per cm^3 dried sediment for cores MD95-2004 and MD95-2009. The use of different units does not hamper core-to-core comparison of dinocyst productivity changes, since sizeable discrepancies in the calculated absolute abundances can exist between laboratories (Mertens et al., 2009). Thus, only changes by an order of magnitude are considered to be significant in our study.

3.3. Planktic foraminifer and IRD analysis

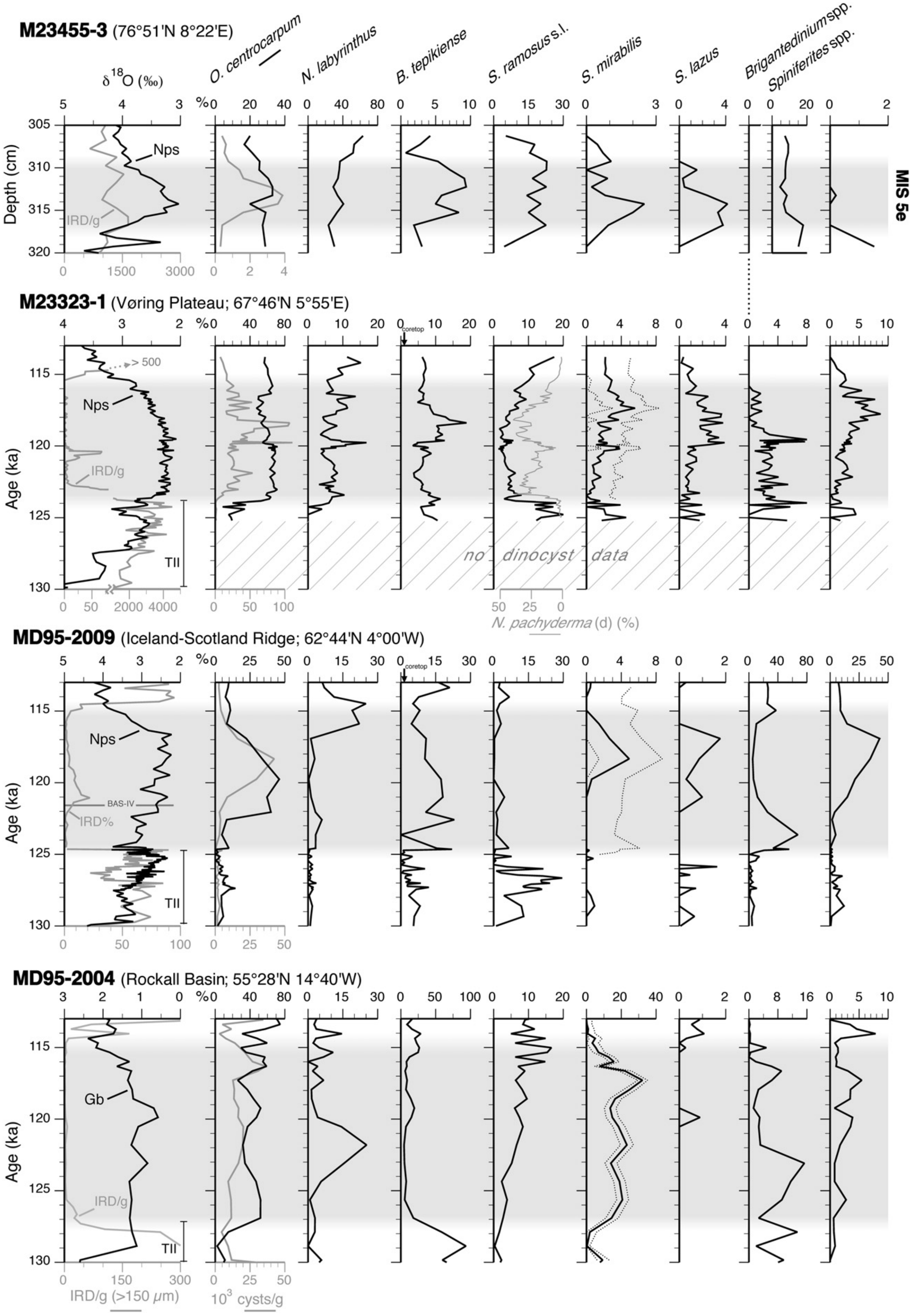
Census data of the planktic foraminifer assemblages were calculated from the >150 μm size fraction for core M23323-1 and from the 80–150 μm size fraction for core M23455-3 by H. Bauch and E. Kandiano. IRD was counted in the >150 μm size fraction for both cores. IRD and planktic foraminifer assemblage counts were done in the >150 μm size fraction in cores MD95-2009 and MD95-2004. The IRD records of the latter two cores are from Rasmussen et al. (1999) and Manthé (1998), respectively. The use of a lower mesh size limit of 150 μm for the foraminifer census counts follows general paleoceanographic practice (e.g., CLIMAP Project Members, 1976; Pflaumann et al., 1996) and provides consistent reconstructions of climate variability during interglacial periods at those “warm” core sites (Kandiano and Bauch, 2002; Smart, 2002). In areas influenced by Polar and Arctic water masses, on the other hand, planktic foraminiferal assemblages tend to be nearly monospecific in the >150 μm fraction (dominated by *N. pachyderma* (s)), and the use of a smaller mesh size better allows to trace climate variability in those cold regions (Kandiano and Bauch, 2002).

4. Results

4.1. Stratigraphy and age model

The position of MIS 5e in core M23455-3 is clearly conceivable from the low values in the oxygen isotope record (Fig. 2) alongside increased absolute dinocyst occurrences (Fig. 3). However, we refrained from developing an age model for core M23455-3 since (1) the low resolution of the core makes it difficult to allocate specific tie points unequivocally; (2) almost no foraminifers could be recovered for isotope measurements from the interval (presumably) belonging to the MIS 6-5e transition; (3) the lower part of MIS 5e appears to be less well represented (see discussion).

For the other three cores, the supporting framework for constructing the age model is based on the identification of SPECMAP events 6.0 and 5.4 (Martinson et al., 1987) in the planktic $\delta^{18}O$ records. The changeover from glacial to interglacial conditions, marked by an ~1.8‰ decrease in the planktic $\delta^{18}O$ values, occurs in two main steps separated by a clear reversal towards heavier values in cores MD95-2009 (between ~19.30 and 18.75 m core depth) and M23323-1 (between 870 and 860 cm core depth) (Fig. 2). The high amounts of IRD in the interval of light planktic oxygen isotopes from the first step, with isotopic ratios as low as 2.4‰, reveal a strong meltwater overprint. Hence, those core sections were deposited during the Saalian deglaciation and belong


M23455-3 (76°51'N 8°22'E)
δ18O (‰)
O. centrocarpum
N. labyrinthus
B. tepikiense
S. ramosus s.l.
S. mirabilis
S. lazus
Brigantedinium spp.
Spiniferites spp.
Depth (cm)
Nps
IRD/g
MIS 5e
M23323-1 (Vøring Plateau; 67°46'N 5°55'E)
coretop
Age (ka)
> 500
TII
no dinocyst data
N. pachyderma (d) (%)
MD95-2009 (Iceland-Scotland Ridge; 62°44'N 4°00'W)
BAS-IV
IRD%
MD95-2004 (Rockall Basin; 55°28'N 14°40'W)
Gb
IRD/g (>150 μm)
10^3 cysts/g
%

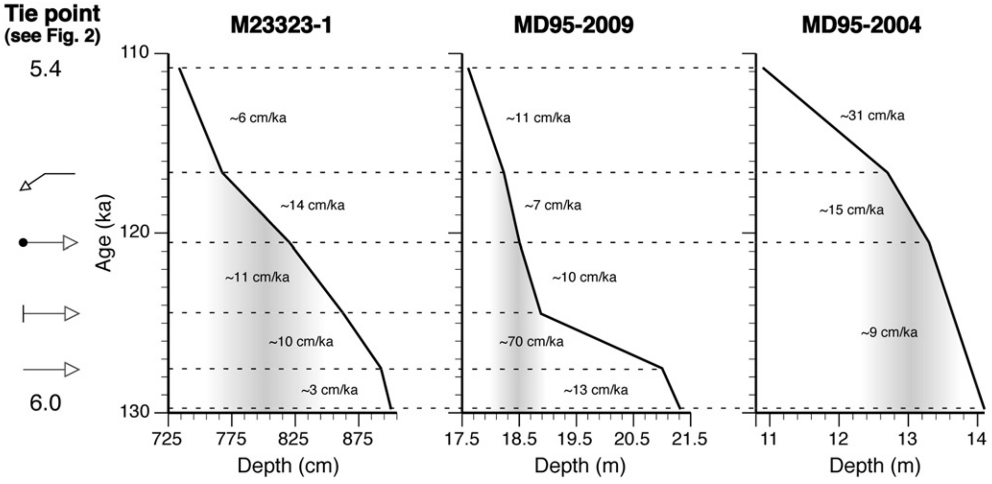


Fig. 4. Depth vs. age plot for core MD95-2004, MD95-2009 and M23323-1, with indication of the sedimentation rates and the tie points used in constructing the age model. The shaded grey area delineates the "real" interglacial interval (see also Figs. 2 and 3).

stratigraphically to Termination II (Fig. 2). The drastic drop in IRD input marks the end of Termination II and the onset of the "full" interglacial (Bauch et al., 1996), further characterised by a sharp increase of subpolar foraminifers (dominantly *N. pachyderma* (d) and *Turborotalita quinqueloba*) and absolute dinocyst concentrations in core M23323-1 (Figs. 3 and 5). Increasing δ^{18}O values followed by renewed IRD input around 115 ka indicate the end of MIS 5e and the return to stadial conditions.

The age model was further refined through correlation of conspicuous features in the planktic and benthic δ^{18}O, planktic δ^{13}C (not shown; Manthé, 1998; Eynaud, 1999; Balbon, 2000) and IRD records between the cores, in which the age model of core M23323-1 was used as reference base (Fig. 2). Additional fine-tuning and crosschecking with the age models of nearby cores located at sites west and south of site M23323-1 allowed circumventing, at least to some extent, the issue of uneven sedimentation rates between isotopic events 6.0 and 5.4, as well as maintaining consistency with the published age model of core M23071-3 also discussed here (Fig. 5) (Bauch and Erlenkeuser, 2008; Van Nieuwenhove and Bauch, 2008). Note that the age model constructed in this way for core MD95-2009 differs from previously published age models for this core (Rasmussen et al., 1999, 2003; Risebrobakken et al., 2006). The "5e-low/BAS-IV" ash layer at 1860.5 cm core depth (Wastegård and Rasmussen, 2001) is shown in Figs. 2 and 3 as stratigraphic reference to the age model of Rasmussen et al. (1999, 2003).

Some features that were used as tie points in the cores from the Nordic seas could not be identified in the lower MIS 5e section of core MD95-2004, presumably due to the lower temporal sampling resolution in the latter core, as well as differences in the (post-) deglacial oceanographic development between both regions. This specific interval of core MD95-2004 was therefore "fine-tuned" through correlation with core MD95-2042 at the Iberian continental margin (Shackleton et al., 2002). The recognition of a stepwise retreat of IRD from south to north, between $\sim$127.5 and 124 ka, would support our revised age model across the transition from Termination II to MIS 5e (Fig. 3). The sedimentation rates that result from our age model range consistently between $\sim$7 and 15 cm/ka for the interglacial interval of all 3 cores (Fig. 4). High sedimentation rates characterise the deglacial phase of core MD95-2009 and the MIS 5e/5d transition - early MIS 5d of core MD95-2004 (respectively $\sim$70 cm/ka and $\sim$31 cm/ka).

We are aware that there still exists a lot of controversy about the onset and duration of MIS 5e (e.g. Shackleton et al., 2002), and the validity and accuracy of the orbitally tuned SPECMAP stack with respect to radiometric datings from raised coral terraces – the latter topic in return also being a subject of debate (e.g. Stirling and Andersen, 2009). For instance, Waelbroeck et al. (2008) recently challenged the SPECMAP age for the midpoint of sea level rise (isotopic event 6.0) and suggested a much older age for the beginning of the benthic δ^{18}O plateau. In contrast, Thompson and Goldstein (2006) found the original SPECMAP chronology to be "extremely accurate", with significant inconsistencies only occurring at the MIS7/6 transition (ibid.) and before 625 ka (Lisiecki and Raymo, 2005). However, we would like to emphasize that our age model is not intended to assess the SPECMAP chronology for the time interval from Termination II to MIS 5d, but to be used as a tool that allows us to cross-correlate between identified events over a relatively large area. Thus, in spite of the chronological issues mentioned above, as well as region-specific differences in ocean-climate development in particular, we are confident that our age model offers an internally coherent framework that is robust enough for an over-regional core-to-core comparison of the relative timing of major episodes in the Last Interglacial climate cycle.

4.2. Dinoflagellate cyst assemblages

The Last Interglacial dinocyst assemblages proved to be fairly diverse in all investigated cores, with 10 to over 25 different taxa

Fig. 3. Total absolute dinocyst abundances and relative abundance fluctuations of selected dinocyst species along planktic stable oxygen isotopes and IRD records (see Fig. 2 for data sources and abbreviations) in the MIS 5e interval of the studied cores, plotted against depth for core M23455-3 and versus age for the other cores. The dotted curves indicate the upper and lower limits of the 75% simultaneous confidence interval on the relative abundance of *Spiniferites mirabilis*. The relative abundances of *Spiniferites* spp. are only plotted for core M23455-3, as this taxon is only rarely present in the MIS 5e sections of the other cores. Note the antiphase behaviour of *S. ramosus* and the subpolar planktic foraminifer *Neogloboquadrina pachyderma* (d) during early and the second half of MIS 5e in core M23323-1. The arrows indicate the relative abundance of *Bitectatodinium tepikiense* in the core top assemblages of core M23323-1 and MD95-2009, as a present-day comparison. The figure illustrates how the time interval representative of "real" interglacial conditions (i.e. with little or no IRD; grey area) becomes shorter from the Rockall Basin to the Vøring Plateau as the deglaciation (Termination II) persists northwards. BAS-IV: ash layer "5e-low/BAS-IV" (Wastegård and Rasmussen, 2001).

per sample. *Operculodinium centrocarpum*, *Nematosphaeropsis labyrinthus*, *Bitectatodinium tepikiense*, *Spiniferites* spp., *S. mirabilis*, *S. lazus*, *S. ramosus*, *Brigantedinium* spp. and cysts of *Pentapharsodinium dalei* are among the most abundant taxa in the Last Interglacial samples and usually constitute over 85% of the total assemblage. Total cyst concentrations and the relative abundance fluctuations of these taxa in the studied core sections are shown in Fig. 3. The raw dinocyst counts are available as supplementary data from the Pangaea database (www.pangaea.de).

Most interglacial assemblages, except those from core M23455-3 and from earliest MIS 5e in core MD95-2009, are dominated by *O. centrocarpum*, with highest relative abundances (>60%) at the Vøring Plateau. The dominant species in those early MIS 5e assemblages from core MD95-2009 is *Brigantedinium* spp., whose occurrence in the other cores is only moderate and essentially restricted to the lower part of the MIS 5e section (see also Van Nieuwenhove et al., 2008). The relative abundances of the cold-temperate species *B. tepikiense* in the Last Interglacial samples fluctuate between ~5 and 20%. The species dominates the assemblages from the late deglacial phase in core MD95-2004, but its abundance gradually decreases with the onset of MIS 5e at the core site around 127.5 ka to be replaced by *O. centrocarpum* as the dominant species. Another important component from early MIS 5e on in core MD95-2004 is *S. mirabilis*, generally making up 15% and more of the assemblages. Only one conspicuous abundance maximum of *S. mirabilis*, occurring towards the end of MIS 5e, is recognised in cores MD95-2009 and M23323-1. In the latter core, and also in the northernmost core M23455-3, the *S. mirabilis* maximum is associated with high relative abundances of the subpolar planktic foraminifer *Turborotalita quinqueloba* (Fig. 5), a species which is regarded as an indicator species for Atlantic water input in the Nordic seas (e.g., Carstens et al., 1997; Kandiano and Bauch, 2002). The palaeoceanographic significance of the abundance variations shown by *O. centrocarpum*, *Brigantedinium* spp., *B. tepikiense* and *S. mirabilis* will be discussed in more detail in Section 5.

Nematosphaeropsis labyrinthus is the dominant species in most of the samples from core M23455-3. This subpolar to temperate species is at present most abundant in areas where Atlantic water mixes with cold Arctic water masses (Rochon et al., 1999; Marret et al., 2004), and its relative abundance accordingly decreases from north to south in our samples. The increase of *N. labyrinthus* in parallel with oxygen isotope values towards the end of MIS 5e in cores M23455-3, M23323-1 and MD95-2009 appears to confirm the correlation of this species with the MIS 5e–5d transition in (sub-)Arctic areas influenced by the NAD/NwAC (Matthiessen and Knies, 2001; Eynaud et al., 2004; Van Nieuwenhove et al., 2008).

Although the modern distribution of *S. ramosus* ranges from the tropics to the polar regions (de Vernal et al., 1998; Rochon et al., 1999; Marret and Zonneveld, 2003), the species appears to be linked to colder water masses in our samples. It is the third-most abundant taxon in core M23455-1, and one of the dominant taxa during latest Termination II in cores M23323-1 and MD95-2009. The relative abundance increase of *S. ramosus* and its antiphase behaviour with the subpolar planktic foraminifer *N. pachyderma* dextral (d) towards MIS 5d (Fig. 3) confirms previous observations from the Vøring Plateau (Van Nieuwenhove et al., 2008).

Cysts of *P. dalei* constitute an important part of the assemblages only in core MD95-2009, especially towards the second half of MIS 5e. The species is at present a strong component of dinocyst assemblages from the North Atlantic Ocean where summer sea surface temperature exceeds 4 °C (Matthiessen, 1995; Rochon et al., 1999; Marret et al., 2004). However, it occurs under a wide range of surface ocean conditions (de Vernal et al., 2001; Marret and Zonneveld, 2003) and it is thus difficult to obtain more specific palaeoceanographic information from the trend shown by *P. dalei* in core MD95-2009.

5. Discussion

Our high-resolution data from core M23323-1 offer a refined insight into the climatic development of MIS 5e in the eastern

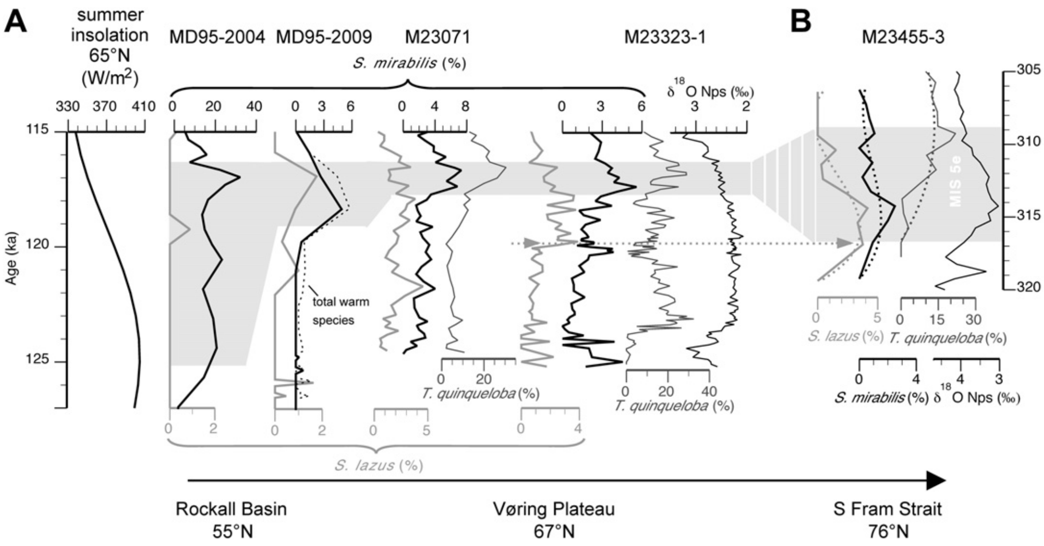


Fig. 5. (A) Mean summer insolation at 65°N (computed with ANALYSERIES 2.0 (Paillard et al., 1996) using the Laskar et al. (2004) data), and relative abundances of *Spiniferites lazus* (grey) and *S. mirabilis* (black) in the Last Interglacial sections of the studied cores and core M23071, also from the Vøring Plateau (Van Nieuwenhove and Bauch, 2008). Also shown is the planktic $\delta^{18}O$ record derived from *N. pachyderma* (s) (Nps) for core M23323-1. The grey area depicts the stepwise expansion of Atlantic water masses and optimal, marine interglacial conditions towards the north as derived from raised relative abundances of *S. mirabilis*. The relative abundance record of the subpolar foraminifer *Turborotalita quinqueloba* in cores M23323-1 and M23071 supports the late stratigraphic position of the MIS 5e marine optimum. (B) Relative abundances (dotted lines indicate smoothed trends) of *S. lazus*, *S. mirabilis* and *T. quinqueloba*, and the planktic $\delta^{18}O$ record derived from *N. pachyderma* (s) (Nps) in core M23455-3. The (raised) appearance of *S. lazus* before the *S. mirabilis* peak seems to be a constant feature in our cores. Simple stratigraphic correlation between the Vøring Plateau and core M23455-3 of this feature as well as the characteristic slightly shifted maximum abundance of *S. mirabilis* and *T. quinqueloba* suggests that a typical interglacial environment developed at site M23455-3 only during the late MIS 5e optimum.

Nordic seas, revealing a twofold division of MIS 5e. A first interval of interglacial conditions at the Vøring Plateau started with the drastic drop of IRD input at ~124 ka (Fig. 3). These interglacial conditions appear to have been interrupted by a major cooling event as suggested by a conspicuous IRD increase centred around 120.5 ka, in agreement with several terrestrial and marine records from NW Europe and the high North Atlantic that illustrated the existence of some significant intra-MIS 5e climate variability (e.g., Guiot et al., 1993; Field et al., 1994; Seidenkrantz et al., 1995; Fronval and Jansen, 1996; Lehman et al., 2002). The lack of any obvious cooling signal in the planktic isotope records is likely explained by the counterbalancing effect of isotopically light meltwater input at that time.

The warm conditions that returned after the cooling lasted for ~4000 years before significant amounts of IRD reappeared in our records around 115 ka (Fig. 3), altogether implying that climate change had reinitiated enhanced iceberg drift by this time (Chapman and Shackleton, 1999). The differences in the composition of the planktic fossil records between the early and late warm phase corroborate previous findings from combined foraminiferal and dinocyst studies from the Vøring Plateau which suggested the existence of two main interglacial intervals with a differently structured upper ocean during MIS 5e (Van Nieuwenhove and Bauch, 2008).

The general outline of the MIS 5e climate development, with two warm phases separated by a cooling event around ~120.5 ka, is also recognisable in the isotope and IRD records from the two southern cores MD95-2009 and MD95-2004 (Fig. 3). Below we will evaluate the over-regional significance of specific local features in the fossil records from the studied core sites in light of the MIS 5e scenario provided by the high-resolution data from the Vøring Plateau.

5.1. Latest Termination II and early MIS 5e

5.1.1. The stable oxygen isotope record

The reversal in the deglacial warming trend around 125 ka as expressed by a return towards heavier values in the planktic $\delta^{18}O$ records from cores M23323-1 and MD95-2009 during Termination II (Figs. 3 and 5) is a known feature in marine and terrestrial records across the northern hemisphere (e.g. Seidenkrantz et al., 1996). This reversal has been interpreted as a Younger Dryas-like climate oscillation (e.g., Sarnthein and Tiedemann, 1990; Seidenkrantz et al., 1996; Sánchez-Goñi et al., 2005), although it has been questioned to what extent the magnitude of the cooling event during Termination II was actually comparable to the Younger Dryas (e.g., Brauer et al., 2007; Carlson, 2008). The significant increase by about 0.50–0.70‰ in the planktic $\delta^{18}O$ records of cores M23323-1 and MD95-2009 cannot be attributed to reduced meltwater input, since no drastic change in IRD content is noticeable at the onset of the reversal (Fig. 3). Thus, our records would indeed suggest a brief cooling that interrupted the general deglacial trend from MIS 6 into MIS 5e (Risebrobakken et al., 2006; Bauch and Erlenkeuser, 2008). Interestingly, the entire isotopic reversal event falls within the deglacial core section (i.e. with high amounts of IRD) in core M23323-1, stratigraphically defining the cooling as a feature of Termination II at high latitudes. In contrast, the event appears to span the Termination II/MIS 5e transition in the more southerly core MD95-2009 (Fig. 3), while it postdates the main IRD input off the Iberian coast (Sánchez-Goñi et al., 2005). All this once more illustrates the south-to-north change in the duration of deglacial processes, such as water mass evolution, related to Termination II.

The strongly depleted benthic oxygen isotopes characterising Termination II in cores M23323-1 and MD95-2009, with lowest values on average up to 1.2‰ lower than those of the ensuing interglacial interval (Fig. 2), are a marked feature that has often been observed before for the deglacial phase in the Nordic seas (e.g., Risebrobakken et al., 2006). As mentioned above, benthic isotope records in the region can be subject to local hydrographic features and climatic fluctuations on a suborbital scale (Skinner and Shackleton, 2006; Thompson and Goldstein, 2006). The significant meltwater input during deglaciation would have freshened the surface waters and might have lead to increased seasonal sea ice growth and brine formation. Hence, transport of the light oxygen isotope surface water masses to the deep sea via brines has been put forward as the explanation for such low benthic $\delta^{18}O$ values (Dokken and Jansen, 1999). However, more recent studies argued that this mechanism is unlikely to work for a deep and open-ocean environment like the Nordic seas, because the brines would become either too strongly diluted and loose their low-isotope signal (Bauch and Bauch, 2001), or are not dense enough to penetrate an underlying, more saline Atlantic water mass (Rasmussen and Thomsen, 2009). Alternative explanations, such as an increased influence of depleted Antarctic Bottom Water (Skinner and Shackleton, 2006) masses and/or a contribution from a temperature increase of the deep water (Bauch and Bauch, 2001) have been suggested partly responsible. In this respect, an unambiguous explanation of the light benthic isotope values during deglaciation in cores M23323-1 and MD95-2009 seems to require the introduction of other, perhaps quite different, proxies.

5.1.2. The dinocyst record

The cyst abundance increase at the transition from Termination II to MIS 5e in the two northern cores M23323-1 and M23455-3 (Fig. 3) agrees with previous observations from the Vøring Plateau (Van Nieuwenhove et al., 2008) and the northern Barents Sea margin (Matthiessen and Knies, 2001). In the two southern cores, however, the onset is not accompanied by a drastic change in absolute cyst concentrations. Differences in sedimentation rate changes between the core sites likely might have played a role. But it can additionally be argued that the larger sediment load and meltwater input from drifting ice(bergs) during Termination II had been a much stronger impeding factor for seasonal autotrophic algal growth in the (sub)Arctic relative to the sites of cores MD95-2009 and MD95-2004 in the northern North Atlantic.

Although *O. centrocarpum* is a cosmopolitan taxon (e.g. Marret and Zonneveld, 2003), its distribution in North Atlantic surface sediments reveals that high relative abundances of this species are linked to the NAD/NwAC (e.g. Harland, 1983; Rochon et al., 1999). In fossil records from the Arctic and sub-Arctic, *O. centrocarpum* is therefore often regarded as an indicator for interglacial intervals with Atlantic water advection (e.g. Matthiessen et al., 2001; Eynaud et al., 2002; Grøsfjeld et al., 2006). Indeed, *O. centrocarpum* becomes dominant in our records as IRD-input drops and more marine oceanic conditions prevail. In core MD95-2009, this feature is obscured by the high relative abundances of *Brigantedinium* spp. between ~124.5 and 122.5 ka. The *Brigantedinium* spp. taxon groups cysts produced by heterotrophic dinoflagellates and therefore also relates to the trophic state of the surface waters in addition to temperature and salinity (cf. Devillers and de Vernal, 2000). The fact that absolute cyst abundances do not increase in this specific interval of core MD95-2009 would point towards a phenomenon that only favoured the growth of heterotrophic species relative to autotrophic ones, rather than an overall dinoflagellate productivity increase. The specific core section dominated by *Brigantedinium* spp. was found to be very rich in diatoms (Rasmussen et al., 1999), one of the main food sources for heterotrophic dinoflagellates (Gaines and Elbrächter, 1987). The high diatom content might evidence intensive surface water mixing related to the presence of the polar front close to core site MD95-2009 (Rasmussen et al., 2003). Indeed, cysts derived from heterotrophic dinoflagellates commonly outnumber other dinocysts at frontal zones and sea ice margins (Mudie and Short, 1985; Harland and Pudsey, 1999). Alternatively, free-drifting icebergs in the vicinity of core site MD95-2009 occasionally might have created favourable surface water conditions for enhanced phytoplankton biomass production (mainly diatoms; Smith et al., 2007), which then caused proliferation of heterotrophic dinoflagellate species. The low absolute cyst concentrations and IRD content in the specific core section could point at the sporadic character of these events. It is in this respect interesting to see that *Brigantedinium* spp. increases again as IRD input returns to site MD95-2009 at the transition to MIS 5d, similar to what is seen in the South Icelandic Basin (Eynaud et al., 2004) and the Bay of Biscay (Penaud et al., 2008). The argument of iceberg-induced enhanced primary productivity at site MD95-2009 might seem contradictive with the iceberg-related low productivity suggested above for Termination II in the northern cores. However, and in addition to the difference in trophic behaviour between autotrophic and heterotrophic dinoflagellates, it has been shown that icebergs can influence phytoplankton productivity both positively and negatively, depending on distribution, numbers and initial conditions (Schwarz and Schodlok, 2009). The fact that only core MD95-2009 shows this dominance of *Brigantedinium* spp. in the early stage of MIS 5e could be due to some skewing by selective preservation (Zonneveld et al., 2001; Hopkins and McCarthy, 2002). But it can also be argued that the site of core MD95-2004 was cut off early from major nutrient input, while at the Vøring Plateau the signal might have been subdued by the productivity increase of autotrophic dinoflagellate species at the onset of MIS 5e.

The cold-temperate species *B. tepikiense* has been depicted as an indicator for the transitional zone between the temperate and polar domain in the North Atlantic (Dale, 1996). The gradual decrease of the species between 128 and 126 ka along with IRD decline in core MD95-2004 followed by (intermittent) peaks around 125 ka in core MD95-2009 might thus reflect the northward retreat of this iceberg-laden frontal zone during Termination II and early MIS 5e (Fig. 3). This signal was also found off the southwestern European coast by Eynaud et al. (2000) and Penaud et al. (2008), and its significance is discussed in detail there. The relative abundances of *B. tepikiense* in our Last Interglacial samples from the Nordic seas fluctuate between ~5 and ~20%, i.e. much higher than in surface sediments from the area, where this species is as good as absent (arrows in Fig. 3; Baumann and Matthiessen, 1992). Based on this, and supported by transfer function reconstructions, it was therefore suggested that a higher degree of stratification and seasonality in the surface waters of the eastern Nordic seas existed during MIS 5e compared to the Holocene (Van Nieuwenhove and Bauch, 2008).

5.2. *Spiniferites mirabilis and the late MIS 5e optimum north of the Iceland-Scotland Ridge*

Highest relative abundances (>30%) of *S. mirabilis* are found today off Portugal and in the Bay of Biscay (see Fig. 4 in Penaud et al., 2008, based on the 'Dinocyst $n = 940$" modern data base of de Vernal et al., 2005). Its occurrence decreases rapidly north of this area and does not exceed 5% in surface sediments from the Rockall Basin (ibid.). The abundances of >15% in the Last Interglacial samples of core MD95-2004 thus seem to confirm the northward shift of the biogeographical distribution of *S. mirabilis* during MIS 5e as similarly inferred from high abundances in the South Icelandic Basin by Eynaud et al. (2004). This latter observation also agrees with the common view of a warmer-than-Holocene Last Interglacial for the mid-latitude NE Atlantic and western European regions (e.g., Guiot et al., 1993; Klotz et al., 2003; Kandiano et al., 2004).

In cores MD95-2009 and M23323-1, however, *S. mirabilis* becomes prominently present only late in the Last Interglacial interval, peaking between ~118 and 116.5 ka. The thermophilic character of *S. mirabilis* and the fact that the species (almost) exclusively occurs in fully marine environments (de Vernal et al., 1998; Marret and Zonneveld, 2003), therefore suggest most intense advection of Atlantic surface water into the Nordic seas at that time. Other dinocyst- and foraminiferal-based studies from the Vøring Plateau (core M23071, see Fig. 1) and core MD95-2009 would support the notion of this late stratigraphic position of the peak marine interval during MIS 5e (Fig. 5; Rasmussen et al., 1999; Van Nieuwenhove et al., 2008; Bauch and Erlenkeuser, 2008; Bauch, unpublished), thereby opposing the previous view of an early Last Interglacial optimum in the Nordic seas (e.g., Cortijo et al., 1994, 1999). That fully marine conditions occurred during late MIS 5e, with Atlantic water masses occupying the entire uppermost water column, is further substantiated in our records by *S. lazus*, a rare species in modern assemblages which is restricted to temperate areas with sea surface salinity above 34 throughout the year (Marret and Zonneveld, 2003).

The high abundances of *S. mirabilis* in areas south of the Iceland-Scotland ridge from early MIS 5e on (Fig. 3; Eynaud et al., 2004; Penaud et al., 2008) contrast with its low abundances during the first ~6000 years of MIS 5e in the Nordic seas (Fig. 5; Van Nieuwenhove and Bauch, 2008), thus pointing to a steepened south-to-north heat flux gradient in the surface waters between the Nordic seas and the NE Atlantic. The existence of such a significant gradient during MIS 5e has already been suggested by Bauch et al. (1999), who designated prolonged deglacial meltwater input from and beyond Termination II as a possible impeding factor for the northward expansion of Atlantic water masses. Indeed, Termination II is known to have continued well into the low $\delta^{18}O$ interval of MIS 5e in many cores from the Norwegian Sea (e.g., Baumann et al., 1995; Bauch et al., 1996). Furthermore, low but consistent concentrations of IRD at the Vøring Plateau after Termination II (Fig. 3; Van Nieuwenhove and Bauch, 2008) may provide evidence for ongoing meltwater input beyond the main deglacial phase (Fig. 3). For the first ~6000 years of MIS 5e, dinocyst-based quantitative reconstructions also suggest lowered SSTs at the Vøring Plateau with respect to the late optimum as well as modern-day values (Van Nieuwenhove and Bauch, 2008). Several modelling studies have shown that freshwater perturbations in the Arctic Ocean/Nordic seas can disturb the intensity of deepwater formation, which is related to the general overturning circulation and Atlantic water advection (e.g. Rahmstorf and Ganopolski, 1999; Otterå et al., 2003). The scenario of reduced Atlantic water advection into the eastern Nordic seas during early MIS 5e seems to be corroborated by stable isotope and sedimentological data from the subpolar North Atlantic, which show that the rate of deepwater overflow from the Nordic seas into the North Atlantic, and thus overturning intensity, remained at low levels for ~3.5 ka into MIS 5e (Hodell et al., 2009). Although Rasmussen et al. (2003) do suggest a change in the intensity of deepwater outflow from the Norwegian Sea already with the transition from MIS 6 to MIS 5e, these authors also recognise a delay by several thousands of years until enhanced surface warming is recognised north of the Iceland–Scotland ridge with respect to the south of the ridge. Several records thus seem to support the view of a delayed interglacial development in the Nordic seas, enforced by the particular boundary conditions created by the Saalian deglaciation. As a consequence, the MIS 5e marine optimum in the Nordic seas only developed when northern summer insolation had already decreased drastically (Fig. 5). This conclusion is in opposition to the Holocene climate development when the thermal optimum occurred during times of relatively high solar irradiance (e.g., Birks and Koç, 2002; Calvo et al., 2002).

One may assume from the absence of *S. mirabilis* and low relative abundances of subpolar planktic foraminifers in core MD95-2009 before 121 ka (i.e., below the “5e-low/BAS-IV” ash layer; Manthé, 1998; Rasmussen et al., 2003) that the main thermal gradient between the NE Atlantic and the Nordic seas was located near the Iceland-Scotland ridge during the first warm phase of MIS 5e (cf. Rasmussen et al., 2003). However, this seems to conflict with the low but consistent presence of *S. mirabilis* as well as subpolar foraminifers at that time farther north (Figs. 3 and 5). In fact, *S. mirabilis* by itself already represents a larger part of the assemblages at the Vøring Plateau than all warm dinoflagellate species together (i.e. *S. lazus*, *S. mirabilis*, and all *Impagidinium* species excluding *I. pallidum*) at core site MD95-2009 (Fig. 5). Also, data from multiple cores across the Nordic seas suggest the strongest gradient to be aligned in a zonal, i.e. east–west direction at about 70°N (Bauch et al., 1999). A comparable situation, i.e. with warmer dinocyst assemblages at the Vøring Plateau relative to core site MD95-2009, has also been observed for MIS 3, and was related to the specific position of the core sites with respect to the surface circulation pattern in the southern Nordic seas (Eynaud et al., 2002). Thus, a more distant location from the main flow path of the Atlantic water might explain the comparatively low amount of warm elements in core MD95-2009. A far easterly position of the NAD over the Faeroe-Shetland channel, with the Arctic front running along the Iceland–Scotland ridge and across core site MD95-2009, has been proposed by Rasmussen et al. (2003) based on foraminiferal data from core MD95-2009 and another core from just south of the Iceland-Scotland Ridge. The high abundances of *Brigantedinium* spp. and occasional peaks of *B. tepikiense* in the lower MIS 5e section of core MD95-2009 are possible indicators for the proximity of the Arctic front to the core site (see above). An alternative explanation for the absence of *S. mirabilis* in core MD95-2009 is a larger offshore expansion of (water masses similar to) the NCC, forcing the Atlantic surface water to circulate northwest of the core site (Bauch et al., 1999).

5.3. The expansion of the MIS 5e heat flux towards the Fram Strait

A constant feature in all our cores is the relative abundance increase of the warm-temperate species *Spiniferites lazus* (shortly) before the maximum of *S. mirabilis* (Fig. 5). Interestingly, this feature is observed in core M23455-3 as soon as high cyst concentrations and low $\delta^{18}O$ values indicate the existence of interglacial conditions at the core site (Fig. 3). Considering the sizeable occurrence of *S. mirabilis* in the MIS 5e section of core M23455-3, far north of the species’ modern distribution area, and its timing with respect to the *S. lazus* abundance maximum, a simple stratigraphic correlation with the cores to the south would thus suggest that only the late, peak interglacial interval is represented in the sediments from site M23455-3. This assumption agrees well with planktic foraminiferal data from the core, which also show a sole major increase of the Atlantic water indicative subpolar species *Turborotalita quinqueloba* starting within and peaking shortly after the *S. mirabilis* peak and the plateau of light oxygen isotopes (Fig. 5). Previous investigations (Risebrobakken et al., 2007; Van Nieuwenhove et al., 2008) support a late MIS 5e maximum of *T. quinqueloba* in the Fram Strait area, and the slightly shifted acme of *S. mirabilis* and *T. quinqueloba* is a distinct feature of the late MIS 5e optimum at the Vøring Plateau (Fig. 5). In accordance with the data from the Vøring Plateau, it thus seems as if the extensive deglacial processes during Termination II and post-deglacial ice rafting continuing into early MIS 5e (e.g., Baumann et al., 1995; Bauch et al., 1996) allowed interglacial conditions not to become eminent in the northern Nordic seas until the late MIS 5e optimum, the only time when a modern type of surface circulation with enhanced northward heat transport towards the Arctic became widespread in the Nordic seas. The early phase of MIS 5e at core site M23259 off the southwestern Barents Sea margin (Fig. 1) has significant abundances of the cold-indicative dinocyst species *N. labyrinthus*, *S. ramosus* and *I. pallidum* (Baumann, 2007), supporting our interpretation of a stepwise expansion of hypsithermal full-marine interglacial conditions northward along the pathway of the NwAC as MIS 5e progressed.

The offset between the peak abundances of *S. mirabilis* and *T. quinqueloba* seems a consistent feature for the late MIS 5e optimum (see above), but it is more conspicuous at the northern core site M23455-3. Although *T. quinqueloba* increases within the *S. mirabilis* high, *T. quinqueloba* peaks along with increased oxygen isotope values and seemingly after the interval for which dinocysts would reveal optimal interglacial conditions (Fig. 5). The position of the *T. quinqueloba* maximum with respect to both benthic and planktic $\delta^{18}O$ in core M23455-3 nevertheless does not disagree with the data from the Vøring Plateau, which show that the *T. quinqueloba* peak occurs at already higher $\delta^{18}O$ values just before the steep increase towards MIS 5d (Fig. 5; Bauch and Erlenkeuser, 2008). It can further be argued that the phytoplankton reacted more sensitively than the deeper-living foraminiferal zooplankton to the prolonged persistence of the winter sea-ice cover and thus shortening of the growing season caused by the decreasing insolation. In addition, we cannot completely disregard some bioturbational influence which becomes more effective in combination with low sedimentation rates.

Last Interglacial dinocyst assemblages at the northern Barents Sea margin (i.e. further north along the flowpath of Atlantic waters; Fig. 1) have a species composition similar to those from the interglacial optimum in core M23455-3, albeit that there are some distinct differences in the actual relative abundances (Matthiessen and Knies, 2001). The more frequent occurrence of typical warm-temperate dinocysts (mainly *S. mirabilis* and *S. lazus*) in core M23455-3 with respect to the northern Barents Sea margin implies that a considerable surface water temperature gradient still existed across the Fram Strait. It has been suggested that, compared to the Holocene, the EGC reached further to the east during MIS 5e, with the northward flow of Atlantic waters being partly subsurfaced and confined to a small corridor in the eastern Fram Strait (Hebbeln and Wefer, 1997; Risebrobakken et al., 2007). This situation restricted the northward heat flux across the Fram Strait, but nevertheless also brought some favourable interglacial-like conditions into the Atlantic sector of the Arctic Ocean as evidenced by fossil records (e.g., Matthiessen et al., 2001). Our over-regional comparison would imply that the records revealing the existence of interglacial conditions in the high Arctic only represent the younger and terminal parts of MIS 5e.

In contrast to MIS 5e at the northern Barents Sea margin and core-top samples from the Fram Strait area, no cysts from heterotrophic dinoflagellates such as the typical polar taxa *Brigantedinium simplex* and *Islandinium minutum* were found in the Last Interglacial samples of core M23455-3 (Fig. 3). However, cysts produced by heterotrophic dinoflagellates are known to degrade easily under oxygenised conditions (e.g., Zonneveld et al., 2001). Thus, rather than a temperature signal, the absence of those polar taxa is more likely due to the low sedimentation rates at site M23455-3, which prevented the cysts from becoming rapidly buried below the oxygenised upper centimetres of the bottom sediments, leaving them exposed to aerobic degradation long enough to be selectively removed from the assemblages (Kodrans-Nsiah et al., 2008).

6. Conclusions

Analysis of dinocyst assemblages in core sections covering a transect from the Rockall Basin along the modern pathway of the North Atlantic Drift/Norwegian Atlantic Current towards the Fram Strait reveals that the Last Interglacial developed in a different way north and south of the Iceland-Scotland Ridge. A drastic drop in IRD input marks the end of the main phase of the Saalian ice sheet melting (Termination II) and thus the beginning of the post-deglacial MIS 5e. The dinocyst assemblages reflect this stepwise northward retreat of ice(berg)-laden water masses, which happened between ~127.5 and 124 ka according to our age model. Soon after the onset of the Last Interglacial, the warm-temperate species *Spiniferites mirabilis* appeared in higher-than-present relative abundances at the Rockall Basin, indicating that favourable interglacial conditions existed in the NE Atlantic from early MIS 5e on.

Just north of the Iceland-Scotland Ridge and farther north at the Vøring Plateau, however, *S. mirabilis* is only significantly present from ~118 to 116.5 ka. In view of the modern ecology of this species, this implies most intensive advection of Atlantic water masses with the establishment of optimal, fully marine interglacial conditions (i.e., combined high surface temperatures and salinities) in the Nordic seas during late MIS 5e. Peak abundances of the warm-temperate, fully marine dinocyst *S. lazus* and subpolar planktic foraminifers confirm this late stratigraphic position of the MIS 5e marine optimum.

The late MIS 5e optimum at times of rather low summer insolation contrasts with the timing of optimal oceanic conditions during the present interglacial, which occurred early in the Holocene and when northern hemisphere summer insolation was relatively high.

Southeast of the Fram Strait at ~77°N, the existence of interglacial conditions is indicated by an interval of light oxygen isotopes with elevated dinocyst concentrations. The assemblages of this interval are characterised by the noticeable presence of *S. mirabilis*, similar to what is seen for the late MIS 5e optimum in the southern Nordic seas. This analogy suggests that only with the intensification of the meridional heat transport during MIS 5e, could fully marine interglacial conditions also develop in the Subarctic, and consequently, high Arctic region as well.

Thus, fully marine, hypsithermal interglacial conditions expanded from the Rockall Basin across the eastern Nordic seas towards the Fram Strait in a stepwise way throughout MIS 5e, steered by the late development of a modern type of surface circulation with enhanced northward flow of Atlantic surface waters which had been hindered by prolonged deglacial processes continuing beyond Termination II. The late arrival of peak interglacial conditions in the high Arctic has significant implications for the interpretation of Last Interglacial environmental records from that region, as they are probably representative of only the younger, warmest phase of MIS 5e. Our findings therefore also underline the importance of a correct stratigraphic context placement of Last Interglacial archives that might be incomplete (e.g., in coastal regions) or suffer from generally low temporal resolution (e.g., Arctic Ocean sediments).

Acknowledgements

We acknowledge the IMAGES programme, Mr. Y. Balut, the captain, and crew of the RV Marion Dufresne (IPEV) and the RV Meteor for their assistance at sea. We are grateful to Jens Matthiessen for his assistance with the palynomorph taxonomy, T. Rasmussen for providing the IRD data and S. Wastegård for the ash layer data from core MD95-2009. We thank N. Andersen and the team from the Leibniz Laboratory for Radiometric Dating and Stable Isotope Research (Kiel University) for their support in the isotope analyses, as well as O. Ther and M.-H. Castera (EPOC laboratory) for preparing palynological samples from cores MD95-2004 and MD95-2009. The manuscript benefited from the appreciated comments and suggestions made by 3 anonymous reviewers. NVN was financed by the Deutsche Forschungsgemeinschaft” (projects BA1367/6, NI1248/1).

Appendix. Supplementary data

Supplementary data related to this article can be found online at doi:10.1016/j.quascirev.2011.01.013.

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