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ORIGINAL RESEARCH ARTICLE

Deep water masses in the Iceland Basin during the Last Interglacial (MIS 5e): Evidence from benthic foraminiferal data☆

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Summary The Last Interglacial period, marine isotope stage (MIS) 5e, is a potential analogue for the Holocene. In this study, we investigated a marine sediment core, AMK-4442, recovered from the northern part of the Iceland Basin. The multiproxy approach used in this study, which includes foraminiferal and lithological analyses, identifies the difference in intensity of deep circulation between MIS 5e and the Holocene. Our data indicate that during early MIS 5e, the Iceland-Scotland Overflow Water (ISOW) flux into the Iceland Basin was suppressed. We suggest that the less active North Atlantic Deep Water (NADW) formation at this time was related to the obstruction of warm surface water inflow into the Nordic Seas.

1. Introduction

The Subpolar North Atlantic is a key region for the reflection of changes in the Atlantic Meridional Overturning Circulation (AMOC). AMOC is driven by deep water formation due to surface water cooling and subsidence in the Nordic Seas. The warm (roughly, 8—15°C) and saline (35—36 psu) Atlantic surface waters are delivered to that region in large volume by the North Atlantic Current (NAC) (Haine et al., 2008). Near 53°N, the NAC splits into several branches. One branch circulates along the Reykjanes Ridge to form the Irminger

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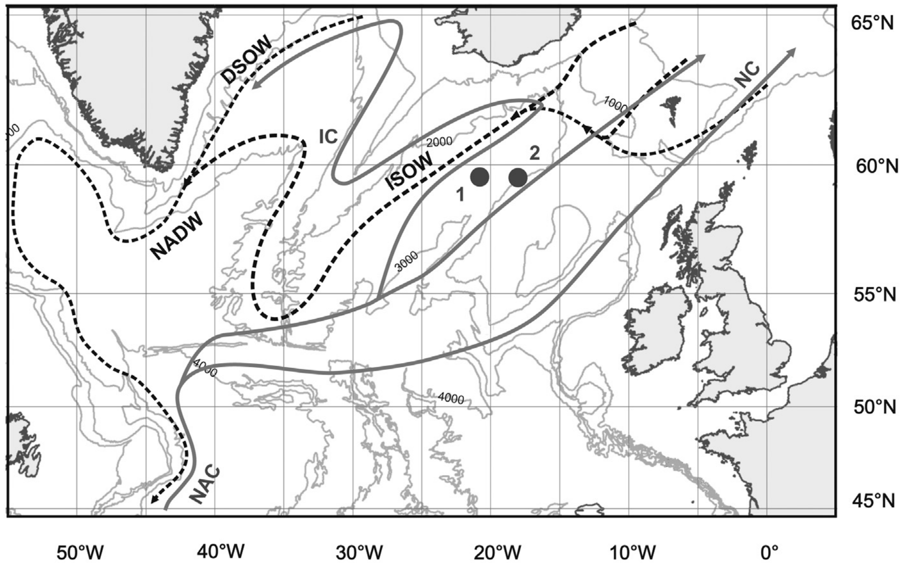

Figure 1 The position of the studied core and a general diagram of the deep (dashed black lines) and surface (solid gray lines) circulation (after Brambilla et al., 2008; Rhein et al., 2011): NAC, North Atlantic Current; NC, Norwegian Current; IC, Irminger Current; DSOW, Denmark Strait Overflow Water; ISOW, Iceland-Scotland Overflow Water; NADW, North Atlantic Deep Water. 1 — the studied AMK-4442 core; 2 — previously investigated AMK-4438 core (Lukashina, 2013a,b).

Current (IC). South of the Denmark Strait, a small branch of the IC separates to circulate along the west coast of Iceland. The remainder of the IC merges with the East Greenland Current (roughly, $T < 4°C$, $S < 34.60$ psu). Other branches of the NAC flow past Ireland, the Faroes, and into the Nordic Seas to become deep water (Brambilla et al., 2008; Haine et al., 2008; Rhein et al., 2011) (Fig. 1).

From the Nordic Seas, deep water masses enter the subpolar Atlantic region. Denmark Strait Overflow Water (DSOW) with temperature 0—2°C and salinity 34.88—34.93 psu is derived from the overflow of deep water through the Denmark Strait. Iceland-Scotland Overflow Water (ISOW) with temperature 1.8—3°C and salinity 34.98—35.03 psu is formed from the deep water masses that overflow through the deep saddle in the Faroe Bank Channel over the Iceland-Faroe Ridge and the Wyville Thomson Ridge (Dickson and Brown, 1994; Haine et al., 2008; Sarafanov et al., 2009; Wright and Miller, 1996). ISOW flows southward through the Iceland Basin and, subsequently, along the Reykjanes Ridge, after which it merges with the DSOW near Cape Farewell to form North Atlantic Deep Water (NADW) with temperature 1.6—4°C, salinity roughly, 34.9 psu — the densest of the salty northern water masses ($\sigma_\theta = 27.80$ kg/m^3) that propagates throughout the World Ocean (Dickson and Brown, 1994; Haine et al., 2008).

It is well known that there were three different AMOC states prevailing during interglacials, glacials and so-called Heinrich events respectively (e.g., Rahmstorf, 2002).

During interglacials, particularly during the one of the Holocene analogues, MIS 5e (Eemian; 117—128 ka), the circulation of deep water masses was similar on a basic level to that of the modern age (Kukla et al., 2002). Intensive advection of the warm Atlantic surface waters into the high latitudes and active deep convection with NADW formation occurred in the Nordic Seas stabilizing the AMOC system.

In glacial periods, ice sheets appeared around the Nordic Seas; these sheets weakened the NAC, which partially shifted toward the Iberian Peninsula (Barash, 1988; Eynaud et al., 2009). As a result, the circulation system of the AMOC was significantly suppressed (Kleiven et al., 2003; Oppo and Lehman, 1993).

When icebergs melted (Heinrich events), the surface water layer became fresher because of influx of huge amount of melting water. This led to the appearance of a halocline (Cortijo et al., 1997; Knies et al., 2007). Deep convection processes may have occurred further south, that is, between 50° N and 60° N, in areas not affected by the salinity decrease what led to instability of AMOC system (Vidal et al., 1997, 1999).

Studies of marine sediments that include deep-water benthic foraminiferal analyses have shown that benthic foraminifera are sensitive to the Late Pleistocene glacial—interglacial shifts. This sensitivity enables their use in reconstructions of the deep paleocirculation (Gooday, 2003; Smart, 2002, 2008; Smart and Gooday, 1997; Thomas et al., 1995).

The primary goal of the present work is to trace changes in deep water circulation during the last two glacial—interglacial transitions in the northern part of the Iceland Basin with a special emphasis on MIS 5e using benthic foraminiferal variability.

2. Material and methods

2.1. Core location and stratigraphy

A marine sediment core, AMK-4442 (59°32,08 N, 21°51,13 W; water depth 2787 m; core length 286 cm), was recovered from the northern part of the Iceland Basin during the 48th voyage of the research vessel "Akademik Mstislav Keldysh"

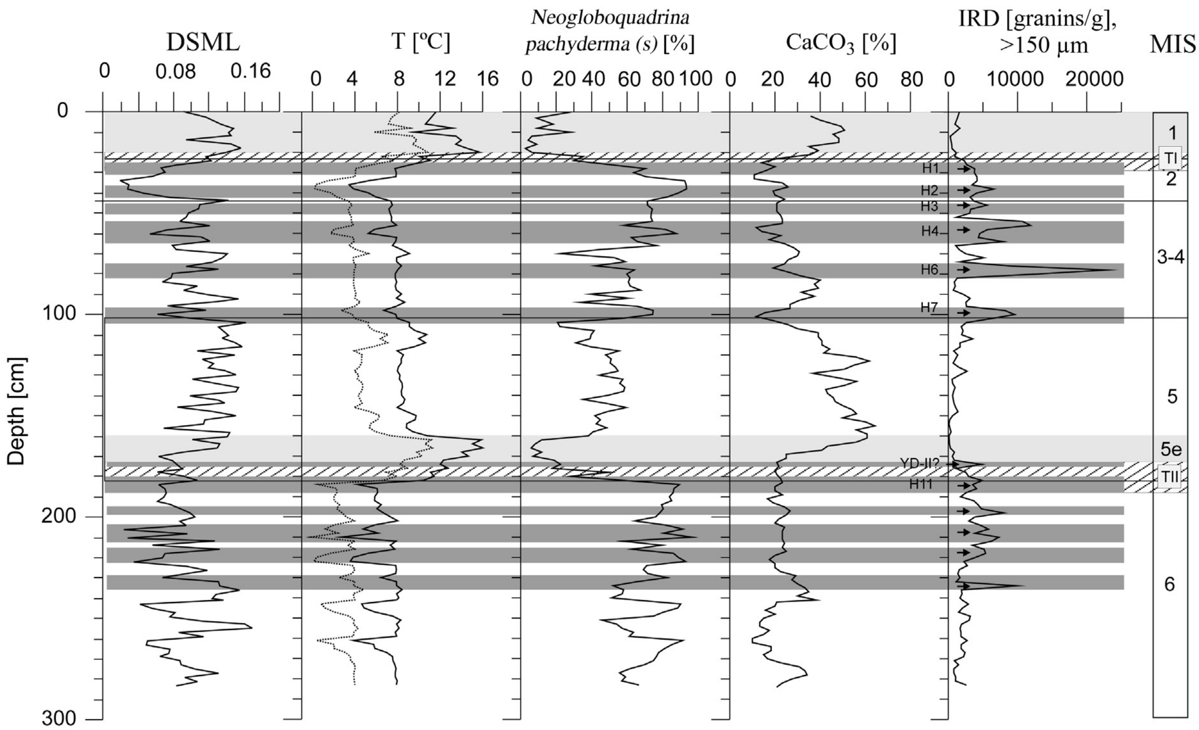

Figure 2 Stratigraphic subdivision of the AMK-4442 marine sediment core. DSML — dissimilarity coefficient. Winter SSTs are shown with gray lines; summer SSTs are indicated with black lines. SST maxima are marked with light-gray bars. Arrows and dark-gray bars indicate Heinrich events (H1—11) and Heinrich-like events. YD-II — so-called Younger Dryas II (Bauch et al., 2012). Terminations I and II are marked with diagonal hatch marks.

(Fig. 1). The selected site is located in the NADW formation area, immediately east of the IC, at the northern boundary of the Subpolar Gyre. This site is directly influenced by both surface and deep AMOC elements. Hence, the core is ideal for a detailed reconstruction of the Late Pleistocene glacial—interglacial changes in these two AMOC elements.

The lithologic description of the investigated core was previously carried out during the 48th voyage of the research vessel "Akademik Mstislav Keldysh" (Scientific report, 2002). The stratigraphic subdivision of the AMK-4442 core is accomplished using the changes in iceberg-rafted debris (IRD) counts, the carbonate content and sea surface temperature (SST) derived from planktonic foraminiferal assemblages (Fig. 2).

For SST reconstructions, the Modern Analogue Technique (MAT; Prell, 1985) was applied to compare directly the measured planktonic foraminiferal assemblages with assemblages from a modern database (Pflaumann et al., 2003). To obtain paleoSST, a modern hydrological database was used (Antonov et al., 1998). The 10 so-called best analogues for every core sample were searched for. We used the dissimilarity coefficient (the squared chord distance) (Overpeck et al., 1985) to estimate the error of the MAT calculations. The dissimilarity coefficient usually did not exceed the critical value 0.15.

Planktonic foraminiferal analysis used for SST reconstructions was performed in 2-cm steps (>150 μm mesh-size). A total of 143 samples were considered. Each sample was examined to count planktonic foraminifera (using a minimum of 300 specimens) and to identify their species. A total of seven dominant species were determined: *Neogloboquadrina pachyderma* (s), *Turborotalita quinqueloba*, *Globigerina bulloides*, *Neogloboquadrina incompta*, *Globorotalia inflata*, *Globigerinita glutinata*, and *Globorotalia scitula* (Fig. 3). The latter two are well-known as species which are susceptible to the dissolution (Kucera, 2007).

The IRD counts and $CaCO_3$ analysis were done every 2 cm on the same samples as the foraminiferal counts. The $CaCO_3$ analysis was performed using a coulometric method with an AN-7529M express analyzer. The carbonate content was calculated from the carbon content.

Terrigenous material (IRD; >150 μm mesh-size) was examined under the microscope to count ≥300 grains per sample. The data are presented as the number of lithic grains per gram of sediment. The IRD counts provide information about iceberg discharge and melt-water propagation in the North Atlantic. The data obtained allow the identification of Heinrich events with well-known ages (Heinrich, 1988; Rasmussen et al., 2003a; Sarnthein et al., 2001).

The age model is based on interpolating between assigned Heinrich events 1—11 commonly used as the reliable reference points (Kandiano and Bauch, 2003; Van Nieuwenhove et al., 2011) and supported by carbonate content data which are suggested to be a very good proxy for identifying the glacial and interglacial periods (Barash, 1988; Helmke et al., 2002).

To support stratigraphic subdivision and define the marine isotope stage boundaries, we use the relative abundance of polar species *N. pachyderma* (s) (Ehrenberg). The change in abundance is highly correlated with SST variations and is a

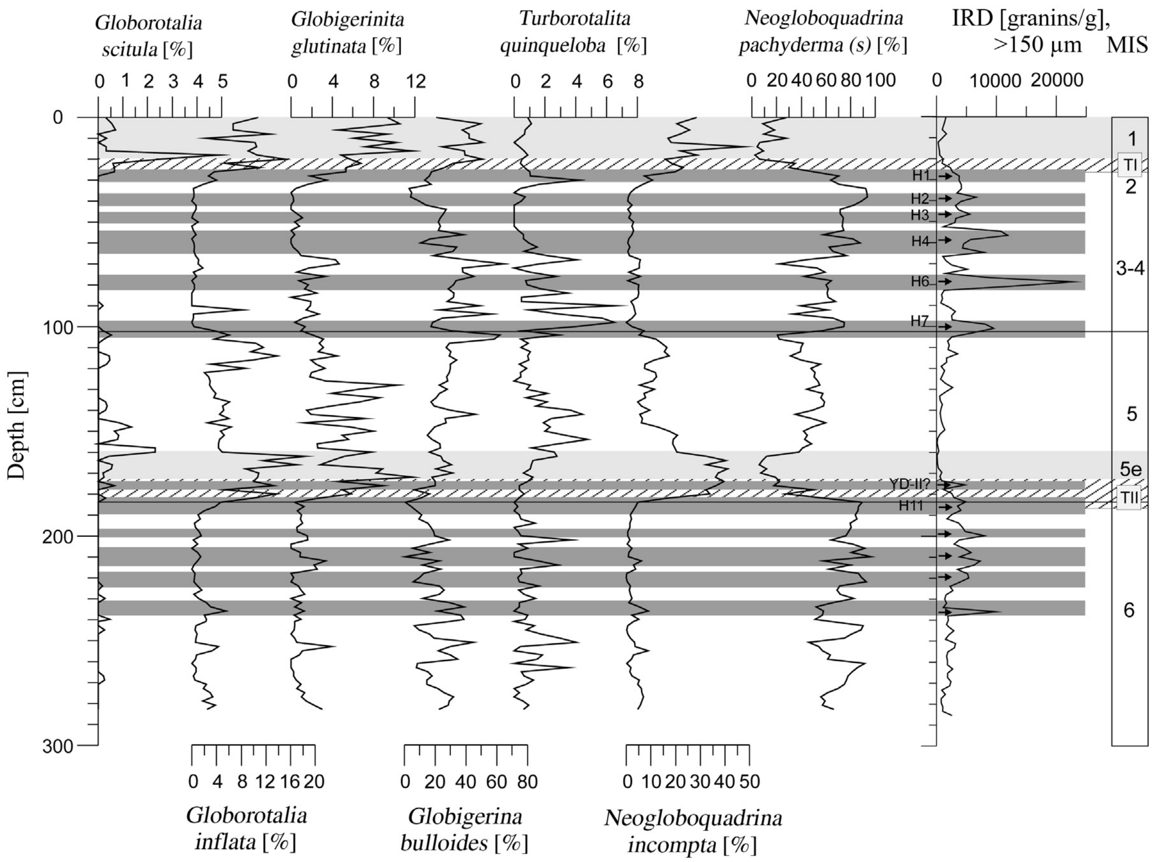

Figure 3 Planktonic foraminiferal relative abundance used for SST reconstructions and iceberg-rafted debris (IRD) counts in the AMK-4442 marine sediment core. Arrows and dark-gray bars indicate Heinrich events (H1—11) and Heinrich-like events. YD-II — so-called Younger Dryas II (Bauch et al., 2012). Terminations I and II are marked with diagonal hatch marks.

perfect indicator of cold periods (Barash, 1988; Kohfeld et al., 1996).

2.2. Benthic foraminifera and their habitat preferences

From the AMK-442 core, 143 samples with benthic foraminiferal assemblages were studied (>150 μm mesh-size). All samples were collected from 2-cm thick sediment slices. The species composition and quantitative distribution were measured. The specimens' concentration was calculated using the number of tests per gram of sediment.

From these data, 60 secreting and 15 agglutinating species were positively identified. A total of six dominant species (>20%) were determined: *Planulina wuellerstorfi*, *Hoeglundina elegans*, *Melonis pompilioides*, *Melonis barleeanum*, *Pullenia bulloides*, and *Uvigerina peregrina*. Two groups of benthic foraminifera were also distinguished: the order *Miliolida* and the genus *Cibicides*. The investigated assemblages also contained several dominant agglutinating species.

It was believed that the main factor controlling species composition and benthic foraminiferal abundance was the propagation of bottom water masses in the deep World ocean. These water masses have specific temperature and salinity characteristics (Caralp, 1984; Gadyukov and Lukashina, 1988; Schnitker, 1979; Streeter, 1976). However, new evidence during recent decades showed that there are two main parameters determining the specimens' concentration in the sediment and the species abundances and composition: the subsidence of organic matter on the seafloor and the oxygen concentration in the bottom water layer or in the interstitial water (Fariduddin and Loubere, 1997; Smart, 2008; Thomas et al., 1995). The chemical composition of bottom water, as well as the bathymetry, type of sediment, bottom current rates and hydrostatic pressure are less significant factors (Jorissen et al., 2007).

All benthic bottom-dwelling organisms are divided into epifauna (living on the surface of the sediment) and infauna (burrowing into the sea floor). The ratio of benthic foraminiferal epifauna to infauna is an indicator of the bottom environment; in particular, it is an indicator of the availability of food and dissolved oxygen (Fariduddin and Loubere, 1997; Gooday, 2003; Loubere, 1996; Lutze and Coulbourn, 1984). The pore sizes of the organisms are related to oxygen levels in the porewater (Corliss and Rathburn, 2008).

Infaunal species, such as *M. pompilioides*, *M. barleeanum* and *U. peregrina*, have pores that are widely distributed over most of the test surface, which reflect low oxygen level in the porewater (Corliss and Rathburn, 2008).

However, there is evidence that *M. pompilioides* inhabits oxygen-rich saline deep waters. It is also suggested that *M. pompilioides* is a good NADW indicator (Schmiedl et al., 1997). Today, *M. pompilioides* lives in the Iceland Basin at depths between 1800 m and 2600 m. In a community, its abundance does not exceed 10%. The species *M. barleeanum* inhabits high saline waters (Kostygov et al., 2010; Tarasov and Pogodina, 2001) and is regarded as "highly productive" and is tolerant to some organic matter reduction (Gooday, 2003). It is assumed that the species feeds on bacteria (Caralp, 1989; Smart, 2008). *M. barleeanum* dominates communities found on the northern slope of Iceland, near the Iceland-Faroe Ridge and in the Faroe-Shetland Channel at depths between 300 m and 700 m, where it reaches up to 40% abundance (Lukashina, 1987).

Small numbers of *U. peregrina* inhabit ridges and continental slopes at depths between 1000 m and 3000 m (Gadyukov and Lukashina, 1988; Streeter and Laveri, 1982). Its abundance correlates with a high organic matter influx (Gooday, 2003). This species is also a good indicator of deep slow currents (Lutze and Coulbourn, 1984; Smart, 2008). *P. bulloides* lives within the upper centimeter of the sediment and feeds on detritus (Corliss and Chen, 1988). It occurs in areas with a prolonged high influx of organic matter and often in areas of upwelling (Mackensen et al., 1993; Smart, 2008).

H. elegans is an epifaunal species which inhabits the upper centimeter of the sediment. It has abundant small pores over most of the test, indicating low oxygen within the sediments. Epifaunal *P. wuellerstorfi* is associated with young, well-oxygenated bottom waters (Gooday, 2003) and has large pores only on the spiral surface. These pores are useful for streaming protoplasm to attach the organism to hard substrates (Corliss and Rathburn, 2008). At the present time, *P. wuellerstorfi* is abundant in the Nordic Seas at depths between 1700 m and 3200 m (Lukashina, 1988; Struck, 1997).

Both *P. wuellerstorfi* and *H. elegans* are found in the northern part of the Iceland Basin, on the southern terminal part of the Reykjanes Ridge, on the southern continental slope of Greenland and on the Mid-Atlantic Ridge, at depths between 2000 m and 3800 m; these regions are where the ISOW — one of the NADW components — circulates (Lukashina, 1988; Struck, 1997). The *H. elegans*/*P. wuellerstorfi* community is a good indicator that NADW formation is occurring on the northern slope of the Iceland Basin. This community was abundant during Terminations and warm periods (Hermelin and Scott, 1985; Lukashina, 2008; Streeter, 1976; Streeter and Laveri, 1982).

The distribution of agglutinating species is also influenced by the organic matter content of the benthos. The species' communities were widely distributed in the Arctic and North Atlantic during the Eocene and were replaced by secreting fauna when the cold and oxygen-rich North Atlantic Bottom Water appeared there (Kaminski et al., 1989). At the present time, agglutinating foraminifera are abundant in low carbonate sediments with a high organic carbon content (Lukashina, 2008). Large quantities of organic carbon are delivered to these two regions by geostrophic and vertical flows (Gooday et al., 1997; Jones, 1986; Murray et al., 2011). The genera *Rhabdammina* and *Hyperammina* are abundant on the slopes of the North American Basin, on the continental slope of Bay of Biscay and on the Rockall Plateau slopes (Miller and Lohman, 1982; Murray et al., 2011; Pujos-Lamy, 1984). In the Iceland Basin region, agglutinating foraminifera occur occasionally.

Miliolida gen. sp. and *Cibicides* ssp. taxa are quite common in Atlantic. However, their relative abundance usually does not exceed 10%.

3. Results

3.1. Down-core stratigraphy and SST

The AMK-4442 core shows a continuous record which is confirmed by the lithologic description (Scientific report, 2002) and by the accordance between all applied methods (Fig. 2).

The measured section covers a time period extending back to the early MIS 6 (Fig. 2). Intervals corresponding to marine isotope stages were allocated as follows: 0—23 cm — MIS 1 (Holocene), 23—43 cm — MIS 2, 43—102 cm — MIS 3—4, 102—182 cm — MIS 5, and 182—286 cm — MIS 6. Also, the Last Interglacial period (MIS 5e) was identified as the interval 160—173 cm.

There is a negative correlation between IRD and SST variations. The distribution of the $CaCO_3$, the IRD content and the relative abundance of the polar species *N. pachyderma* (s) clearly reflect glacial—interglacial shifts.

Species with thin shells *G. glutinata* and *G. scitula* are relatively abundant in the assemblage (up to 5 and 12%).

Interglacial periods (MIS 1 and MIS 5e) are marked by a dramatic decrease in *N. pachyderma* (s) abundance (0—20%), minimal IRD (up to 1000 grains/g) and high SST records. The late MIS 5e was marked by a high $CaCO_3$ content (60%), while during MIS 1 (Holocene), $CaCO_3$ did not exceed 50%.

Glacial periods (MIS 2, 3—4, 6) are identified by a high relative abundance of *N. pachyderma* (s) (80—100%), a high IRD content (5000—10,000 grains/g), low $CaCO_3$ levels (20—30%) and low SSTs (1—4°C and 4—8°C in winter and summer, respectively).

Intervals with high IRD contents (>5000 grains/g) correspond to Heinrich events (H1—11) (Fig. 2). All Heinrich events are marked by a decrease in SST and $CaCO_3$ content, and also by an increase in the relative abundance of *N. pachyderma* (s). Event H11 begins at 188 cm (an abrupt *N. pachyderma* (s) increase and SST decrease) and ends at 175 cm. The last IRD peak (173—175 cm) could obviously be classified as the so-called Younger Dryas-II (YD-II) (Bauch et al., 2012).

We suggest that the intervals 173—188 cm and 20—30 cm correspond to Termination II and Termination I, respectively (a continued high relative abundance of *N. pachyderma* (s) and IRD content). The end of the penultimate glacial period (Termination II) is indicated by dramatic decrease in IRD grains and in the relative abundance of *N. pachyderma* (s). An increase in $CaCO_3$ content and in SSTs is also evidence of the early MIS 5e onset.

During Terminations II and I, the relative abundance of *N. pachyderma* (s) reaches 60% and the $CaCO_3$ content does not exceed 30%. SST calculations indicate temperatures of 8°C and 12°C in winter and summer, respectively.

During the late MIS 5e, SST reached 12°C and 16°C in the winter and summer, respectively. The modern SST in the study area is approximately 10°C and 12°C in winter and summer, respectively (Antonov et al., 1998). Therefore, SSTs were warmer than modern surface conditions.

3.2. Benthic foraminiferal abundances

The uppermost section (0—27 cm) of the AMK-4442 core is dominated by *M. barleeanum* (~20%) and *M. pompilioides* (~20%) (Fig. 4c and d). A high relative abundance of

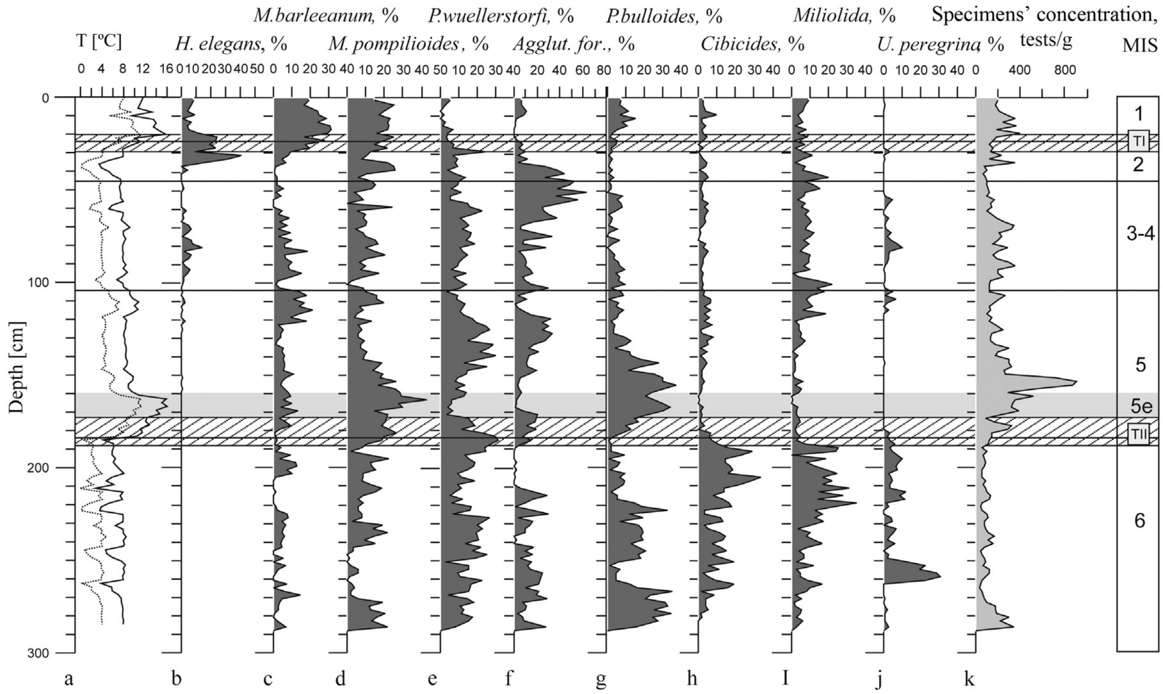

Figure 4 Sea surface temperature (a), benthic foraminiferal relative abundance (b—j) and specimens' concentration (k) in the AMK-4442 marine sediment core. Terminations I and II are marked with diagonal hatch marks.

M. pompilioides (up to 45%) is also recorded for the late MIS 5e. The specimens' concentration varies from 200 to 400 tests/g (Fig. 4k).

The presence of the *H. elegans* community (Fig. 4b) is notable on the boundary between MIS 2 and MIS 1 (Termination I). The relative abundance of the dominant species *H. elegans* with respect to its community reaches 40%. In lower section layers, the abundance of *H. elegans* is dramatically reduced. *P. wuellerstorfi* dominates (>20%) during Terminations I and II (MIS 2/MIS 1 and MIS 6/MIS 5), MIS 3 and MIS 6 (Fig. 4e). Specimens' concentration during the terminations was relatively low, ranging from 100 to 300 tests/g.

A numerous and speciose community of agglutinating foraminifera (up to 60%) is distinguished during the interval between the early MIS 2 and late MIS 3 (35—67 cm) in dun silts with a high IRD content and low specimens' concentration (<200 tests/g). They also dominate in the interval between 115 cm and 130 cm. This community includes the orders *Astrorhizida* (genus *Rhabdammina*), *Ammodiscida* (genus *Hyperammina*), *Lituolida* (genera *Haplophragmoides* and *Cyclammina*), *Textulariida* (genus *Siphotextularia*) and *Ataxophragmiida* (genera *Trochammina* and *Martinotiella*) (Fig. 4f). The genera *Rhabdammina* and *Hyperammina*, which have elongated cylindrical "tubular" shells, are most abundant in the community.

The interval 140—175 cm and some intervals of MIS 6 (220 cm and 265—285 cm) are dominated by *P. bulloides* (up to 35%) (Fig. 4g). Specimens' concentration reaches 800 tests/g at the depths between 150 cm and 160 cm (Fig. 4k).

MIS 6 (interval 185—220 cm) is dominated by a *Cibicides* ssp./*Miliolida* community (>20%). The interval 250—260 cm is dominated by *U. peregrina* (up to 30%). The specimens' concentration during MIS 6 does not exceed 200 tests/g.

4. Discussion

During MIS 1—6, deep water conditions in the Iceland Basin were changing considerably. These changes are reflected in the benthic foraminiferal assemblages from the AMK-4442 sediment core.

Our data indicate that during glacial periods, nutrient-rich and oxygen-poor water of southern origin propagated into the northern part of the Iceland Basin. During MIS 6, the benthic foraminiferal community was dominated by the infaunal species *U. peregrina*, which prefers a fine-grained substrate (Qvale, 1986) and is a good indicator of deep currents with low speeds (Lutze and Coulbourn, 1984). This species is considered to be a possible indicator for high seasonality with seasonal pulsed organic matter fluxes. However, *U. peregrina* has also been interpreted by some authors (e.g. Garcia et al., 2013) as an opportunistic species.

U. peregrina was dominant in the eastern North Atlantic during the Last Glacial Period at depths between 1200 m and 3500 m (Lukashina, 2008; Schnitker, 1979). In the AMK-4442 core, this species also appears in the assemblage during the Last Glacial Period (MIS 4—2).

At that time, the benthic foraminiferal community in our core was also dominated by agglutinating foraminifera, which prefer high levels of organic carbon in sediments. They are genera distinguished by their elongated cylindrical shells, and never occur in shallow water conditions (Murray et al., 2011). Hence, their presence and abundance in sediments are not related to iceberg transport from shelves, but instead reflect the stagnant conditions in the bathyal and deep regions. The existence of nutrient-rich and oxygen-poor water in the Subpolar Atlantic below 2000 m during the Last Glacial Maximum is also supported by others (Oppo and Lehman, 1993).

The modern ISOW has appeared in the Iceland Basin in the latter half of the Last Glacial Maximum. At that time, the Polar Front began to withdraw to the north and warm North Atlantic surface water flowed into the Nordic Seas. Deep water overflow through the Iceland-Faroe Ridge promoted the exchange of "old" deep water with "young" oxygen-rich water, which correlates with the dramatic increase in the abundance of *H. elegans* in assemblages.

Although there is evidence (Garcia et al., 2013) that *H. elegans* is dominant in the living stock and, in contrast, *U. peregrina* is abundant in the fossil assemblages, our data show a dominance of the latter only during MIS 6 (Fig. 4j). It is well known that carbonate dissolution has a deleterious effect on calcareous foraminifera (Gooday, 2003; Vénec-Peyré et al., 1992). Thus, the presence of the species *H. elegans* and planktonic *G. glutinata* and *G. scitula* with thin shells indicate that there was no significant dissolution in the study area.

Deep ventilation in the Iceland Basin was intensified during Termination II, Termination I, the late MIS 5e, the Holocene and periodically during glacial intervals (MIS 6, 4—2). This was indicated by the increase in the *P. wuellerstorfi* abundance during these intervals. Thornalley et al. (2013) also registered an increase in ISOW intensity through the early Holocene.

During Termination II, deep water conditions probably differed from those during the Termination I. A difference was measured in the composition of benthic foraminiferal community. Termination II is dominated by the species *P. wuellerstorfi* and *M. pompilioides*. Termination I is dominated by *H. elegans*, *M. pompilioides* and *M. barleeanum*. Our findings about rapid increase of *P. wuellerstorfi* at the beginning of the Terminations II and I agree with Rasmussen et al. (2007) data. The relatively small abundance of *P. wuellerstorfi* during Termination I in the AMK-4442 core most likely indicates that deep ventilation in the Iceland Basin was not very strong. Our results agree with previous data showing a weakened deep circulation in the North East Atlantic during Termination I (Skinner and Shackleton, 2004).

During most of MIS 6 and MIS 5 intervals, the study site was occupied primarily by *P. bulloides* (Fig. 4). Our previous studies have shown that *P. bulloides* dominated in the West European Basin at depths between 3500 m and 4500 m during the Last Glacial and Last Interglacial periods. In Holocene sediments, this species was occasionally present (Lukashina, 2008). There is evidence (Schnitker, 1979) that during the Late Pleistocene, the presence of *P. bulloides* was typical for a nutrient-rich and oxygen-poor water mass isolated from the surface for a long time. The high relative abundance of this species in the AMK-4442 core during early MIS 5e could be evidence of the existence of a glacial-like type of deep circulation in the Iceland Basin. In the Fram Strait, *P. bulloides* was also observed in relatively high quantities during MIS 5e (Bylinskaya and Golovina, 2012).

As species *M. pompilioides* and *M. barleeanum* are commonly inhabiting high saline waters the dominance of the *M. pompilioides*/*M. barleeanum* community during the Holocene possibly indicates a NADW presence south of Iceland (Kostygov et al., 2010; Schmiedl et al., 1997; Tarasov and Pogodina, 2001).

Similar relative abundance of *M. pompilioides* during the early MIS 5e and throughout the Holocene indicates that intensity of NADW formation was the same during these periods. These findings are in accordance with conclusions of Rasmussen et al. (2003a) that bottom water conditions in the North Atlantic during MIS 5e were comparable to the modern conditions.

It was suggested that during the early MIS 5e, the main stream of the warm North Atlantic surface water was shifted to the west, which resulted in an intensified Subpolar Gyre (Bauch et al., 2000, 2011, 2012; Van Nieuwenhove et al., 2011) and IC (Irvali et al., 2012). Other studies agree: one showing that during the early MIS 5e, the Greenland ice sheet was smaller (Cuffey and Marshall, 2000) and another that there were slightly warmer conditions in the west Iceland Sea than there were during the Holocene (Bauch and Erlenkeuser, 2008). There is evidence that during MIS 5e in the vicinity of the Labrador Basin, the surface conditions were about 4—5°C warmer and 0.5—1.0‰ saltier than during the present interglacial MIS 1 (Matul et al., 2002). Hence, warm surface water has circulated along the west side of Iceland and flowed into the Nordic Seas mainly through the Greenland-Iceland Ridge (Bauch and Erlenkeuser, 2008; Fronval et al., 1998).

Our data indicate that there were stagnant deep water conditions in the Iceland Basin during the early MIS 5e. Most likely, the NADW formation in the North East Atlantic was weakened. Rasmussen et al. (2003b) have shown that the maximum SSTs south of the Iceland-Scotland Ridge occurred during early MIS 5e, while temperatures in the Nordic Seas were still low; the outflow of deep water from the Norwegian Sea began at the MIS 6/5 transition simultaneously with when the sea surface warmed south of the ridge. This is also in agreement with our previous conclusions about the presence of a much greater volume of Antarctic Bottom Water in the west part of the Canary Basin during the Last Interglacial than during the Holocene. Obviously, this water has occupied not only the bottom water layer but also a deep layer, and met no counteraction from the NADW (Lukashina, 2008).

A small decrease of *P. bulloides* during the late MIS 5e (from 30% to 20%) and a coinciding increase of *M. pompilioides* (from 20% to 45%) indicate more active NADW formation than during the Holocene in the study area. This maximum in *M. pompilioides* (a possible NADW indicator; Schmiedl et al., 1997) is also coeval with our SST peak during the late MIS 5e (Fig. 4a and d). The NADW active formation during the late MIS 5e was also recorded in the AMK-4438 sediment core, which was collected south of Iceland near the investigated site (Fig. 1) (Lukashina, 2013a,b).

Paleocurrent reconstructions in Hodell et al. (2009) of flow speeds at the Gardar Drift suggest a weakened ISOW circulation during the early MIS 5e but a resumption of a strong, well-ventilated ISOW during the late MIS 5e. The dynamics of the relative abundances of our benthic foraminiferal assemblages also demonstrates a trend from weak (early MIS 5e) to more active (late MIS 5e) ISOW formation.

Previous studies have shown that during the late MIS 5e, SSTs in the North Atlantic were about 2°C higher than today

(Barash et al., 2002; Bauch and Kandiano, 2007; Kopp et al., 2009; Otto-Bliesner et al., 2006). This suggests that there was a more intensive surface warm water inflow into the Nordic Seas and that more active deep water formation occurred there during the late MIS 5e. Hence, more deep water has flowed back into the North Atlantic. However, deep-water ventilation in the Labrador Sea was weaker during MIS 5e than in the Holocene (Hillaire-Marcel et al., 2001).

Evidence for weakened deep circulation in the northern part of the Iceland Basin during the most of the Late Pleistocene and Holocene intervals, including the early MIS 5e, confirms the assumption about suppressed overflowing of deep water from the Nordic Seas during the Late Pleistocene (Raymo et al., 2004).

5. Conclusions

The multiproxy analysis of the AMK-4442 marine sediment core using planktonic foraminiferal census data and subsequently deriving estimates of sea surface temperature (SST), as supported by IRD data, enables the tracing of the dynamics of deep circulation in the North Atlantic during MIS 1—6. Changes in deep conditions during the investigated period are reflected in the variability of the benthic foraminiferal community structure in the AMK-4442 core. A difference was detected between the deep circulation of the MIS 5e period and the Holocene.

During most intervals from the Late Pleistocene-Holocene period in the Iceland Basin, nutrient-rich and oxygen-poor water circulated at low speed.

Formation of the "young" oxygen-rich and nutrient-poor deep water in the Iceland Basin occurred mainly during Terminations II and I.

For early MIS 5e, a glacial-like type of deep circulation was registered, marked by the dominance of *P. bulloides*. During the early MIS 5e, deep circulation in the eastern North Atlantic was suppressed. It could be related to a weakened overflow of the newly formed deep water from the Nordic Seas. The activity of the NADW formation was the same as during the Holocene.

Intensive surface warm water inflow into the Nordic Seas through the Iceland-Scotland Ridge occurred only during the late MIS 5e as marked by the dominance of *P. wuellerstorfi* and *M. pompilioides*.

The data in this study suggest that active formation of modern NADW is related to the intensification of warm North Atlantic surface water flux into the Nordic Seas during the late MIS 5e.

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