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Article

Paleoenvironment Variability during Termination I at the Reykjanes Ridge, North Atlantic

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Abstract:

The micropaleontological study (radiolarians and foraminifera) of the sediment core AMK-340, Reykjanes Ridge, North Atlantic, combined with the radiocarbon dating and Oxygen/Carbon isotopic record, provided data for the reconstruction of the summer paleotemperature on the water depth of 100 m, and paleoenvironments during the Termination I in the age interval of 14.5-8 ka. The response of the main microfossil species on the paleoceanographic changes within the Bølling-Allerød (BA) warming, the Younger Dryas (YD) cold event, and final transition to the warm Holocene was different. The BA warming was well reflected in the radiolarian and benthic but not planktic foraminiferal record. The high abundances of the cold-water radiolarian species *Amphimelissa setosa* as the Greenland/Iceland Sea indicator marked a cooling at the end of the BA and within the start of the YD at 13.2-12.3 ka. The micropaleontological and isotopic data together with the paleotemperature estimates for the Reykjanes Ridge at 60°N document that, after the warm BA, the middle YD ca. 12.5-12.2 ka was the next significant step toward the Holocene warming. Start of the Holocene interglacial conditions was reflected in abundant occurrence of the microfossils being indicators of the open boreal North Atlantic environments and lower oxygen isotope values indicating increasing warmth.

Keywords: global warming and environmental change; Late Quaternary paleoenvironments; Termination I; sea-water paleotemperature; marine microfossils; North Atlantic; stable isotopes

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1. Introduction

Our study presents new results on the North Atlantic paleoceanography during the last deglaciation which was time of the abrupt climatic changes (general warming superimposed by sudden short glacial reversals). Climatic situation in the North Atlantic, through the Atlantic thermohaline circulation or North Atlantic meridional overturning circulation (NAMOC), mediates climate on the surrounding land, and climatic connections between hemispheres [1]. The sea surface conditions in the North Atlantic significantly influence the major modes of regional atmospheric circulation (meridional or zonal) [2] causing warming or cooling episodes. Rapid changes in the NAMOC and on the North Atlantic surface during the last deglaciation could be strongly related to the changes of the climatic conditions (global warming, melt-water discharge from land ice, sea-ice distribution) [3]. Overpeck et al. (1998) [4] postulated an apparent synchroneity of the rapid climate events in the circum-North Atlantic during the last deglaciation but called for new high-resolution studies to prove this.

We use the micropaleontological data from the sediment core AMK-340, combined with the radiocarbon dating of the absolute age and oxygen/carbon isotopic record, to estimate the sea subsurface summer temperature and to describe the paleoenvironmental changes within the Termination I on the Reykjanes Ridge, at ca. 60°N of the North Atlantic. Multiple publications on the Late Quaternary paleoceanography of the subpolar to polar North Atlantic revealed main characteristics of the climatic trends and variations during the last glacial cycle based on the extensive analysis of the micropaleontology and paleotemperature reconstructions [5, and references therein). Our aim is to get an additional quantitative information on the local paleoenvironments (sea subsurface temperature), and compare it with the global/regional paleoclimatic archives. Working approach is a reconstruction of the paleotemperature based on the factor analysis of the radiolarian and planktic foraminiferal data in the same samples of the sediment core. The radiolarian distribution and paleotemperature estimates on the radiolarians (old "graphical" paleotemperature method, and method of spline interpolations as a modification of the Q-mode analysis) for the core AMK-340 was presented by Matul [6], and Matul and Yushina [7]. This paper uses a deeply reworked modern radiolarian database, corrected radiolarian data in the core, newly constructed modern planktic foraminiferal database, a standard paleotemperature

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method of the Q-mode analysis and transfer functions realized as a software PanTool Box [8], and involves unpublished data on the planktic and benthic foraminifera in the core.

The study area is located on the eastern margin of the Subpolar (Irminger) Gyre. The western branch of the Irminger Current, splitted from the warm North Atlantic Current, influences a modern oceanographic situation on the Reykjanes Ridge [9]. Conversion of surface/deep warm/cold waters of the Irminger Current, East Greenland Current, and Labrador Sea Water within the Irminger Gyre is unstable exhibiting large interannual variability of the water flows on the sea surface and deeper levels thus complicating the local features of the NAMOC [10]. The average summer sea surface temperature in the location of the core AMK-340 is ca. 12°C [11]. At the end of the last glacial period, before ca. 14 thousand years ago (ka), sea surface temperatures south of Iceland dropped down to 0-2°C [12], and we expect to get a picture of the prominent temperature and environmental changes within the transition from the last glacial to the Holocene interglacial on the Reykjanes Ridge.

2. Material and Methods

The sediment gravity core AMK-340, 4th cruise of the Russian RV "Akademik Mstislav Keldysh" in 1982, was obtained from the central area of the Reykjanes Ridge, North Atlantic (58°30.6′N, 31°31.2′W; water depth of 1689 m; core length of 387 cm) (Figure 1). A general lithology of the core is (1) 0 to 241 cm pelitic calcareous muds with $CaCO_3$ content of 40-50%, (2) 241 to 307 cm pelitic weakly calcareous muds with $CaCO_3$ content of 10-25%, (3) 307 to 387 cm pelitic muds with $CaCO_3$ content of ≈10% intermittent by the thin layers of the pelitic weakly siliceous muds.

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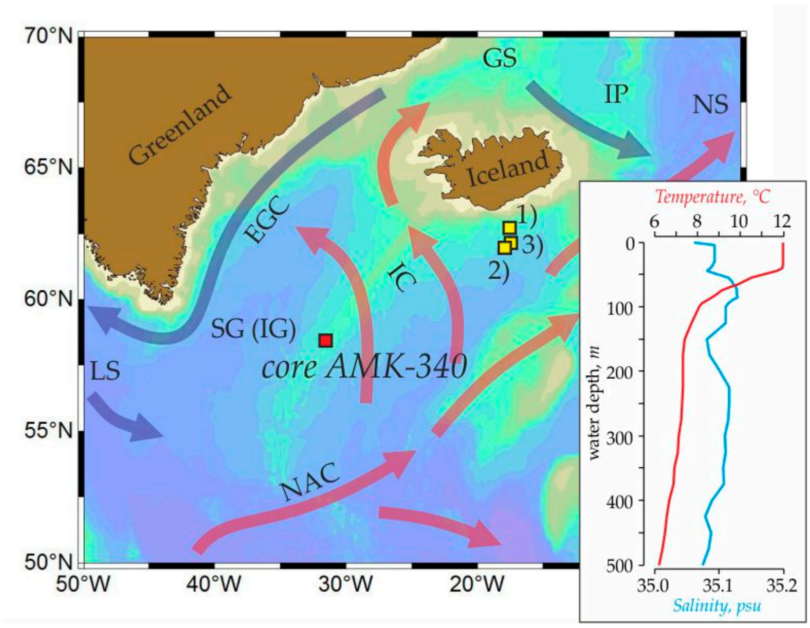

Figure 1. Core location (red square) and modern regional oceanographic conditions. Sediment cores (yellow squares) which were mentioned in the paleoceanographic interpretations: 1) RAPiD-10-1P, 62.9755°N, 17.5895°W, 1237 m water depth; 2) RAPiD-12-1K, 62.09°N, 17.82°W, 1938 m water depth; 3) RAPiD-15-4P: 62.293°N, 17.134°W, 2133 m water depth [13-14]. Vertical summer salitity/temperature profiles are extracted from the World Ocean Atlas 2013 [11, 15]. Red and blue arrows schematically show flows of the warm and cold waters, respectively. GS is Greenland Sea, IP is Iceland Plateau, NS is Norwegian Sea, EGC is East Greenland Current, IC is Irminger Current, SG (IG) is Subpolar (Irminger) Gyre, LS is Labrador Sea, NAC is North Atlantic Current.

Chronology of the core has been established from the four AMS ^{14}C-datings of the planktic foraminifera *Neogloboquadrina (N.) pachyderma* (sin.) shells in the Leibniz Laboratory for Radiometric Dating and Stable Isotope Research at the Christian-Albrechts-University of Kiel, Germany (Table 1).

Table 1. List of the accelerator mass spectrometer ^{14}C-datings of the absolute age of the sediment core AMK-340. Conversion of ^{14}C-datings to the calendar ages was made according [16].

Depth in core	^{14}C-datings, years	Calendar age, years	Dating code
118 cm	5480±50	5767	KIA4187
181 cm	8030±60	8902	KIA4188
260 cm	9220±60	10397	KIA4189
356 cm	11830±70	13600	KIA4190

Radiocarbon ages were converted to the calendar ones by the calibration program CALIB 7.1 using MARINE13 scale (standard reservoir age correction R is 405 years with ΔR of 85±79 years) [16]. Age-depth plot is presented in Figure 2. The core AMK-340 spans from ca. 5.7 to ca. 14.5 ka, which is the mid-Holocene and the end of the last glacial period including most part of the Bølling-Allerød (BA) warming, and Younger Dryas (YD) cooling. To identify the above-mentioned paleoclimatic intervals, we have used the standard ages of the Greenland stadials and interstadials from the INTIMATE event stratigraphy [17]: start of the BA is at ca. 14.7 ka, start of the YD is at ca. 12.9 ka, and start of the Holocene is at ca. 11.7 ka. Average sedimentation rate of the core is ≈26 cm*ky^{-1}. The planktic foraminiferal species *N. pachyderma* (sin.) and *Globigerina (G.) bulloides* tests were picked out for the oxygen and carbon isotopic analysis in the Marine Stable Isotope Lab (MASTIL) of the National Centre of Antarctic and Ocean Research, Vasco-da-Gama, Goa, India. The size range of the planktic foraminiferal tests chosen is >100 μm. The external precisions of $\delta^{18}O$ and $\delta^{13}C$ analysis are ±0.15‰ and ±0.09‰, respectively (1σ standard deviation) obtained by repeatedly running NBS-19 as the Standard (n=33). The $\delta^{18}O$ and $\delta^{13}C$ values are reported with respect to V-PDB.

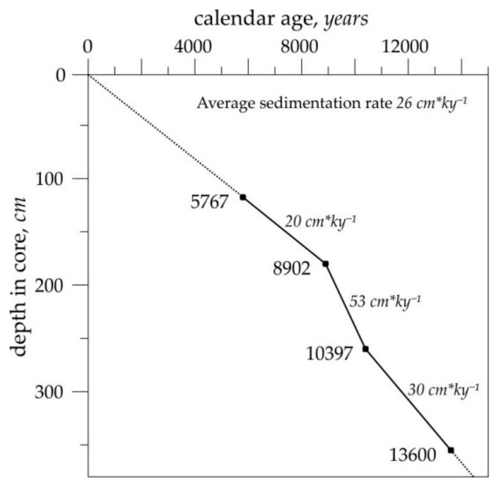

Figure 2. Age-depth plot for the core AMK-340 based on the AMS ^{14}C-datings converted to the calendar ages (black squares). Sedimentation rates are displayed.

We studied the marine microfossils (polycystine radiolarians as siliceous microorganisms, and benthic and planktic foraminifera as calcareous microorganisms) in 37 sediment samples of 2-cm thickness throughout the core with the best time resolution of 133 years. The interpretation of the microfossil data will be focused on the interval between 14.5 and 8 ka when the major paleoclimatic

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changes occurred within the transition between conditions of the last glacial time and recent Holocene interglacial state.

For the radiolarian analysis, air-dried sediment samples of 1-2 g were boiled in a solution of 30% hydrogen peroxide and sodium pyrophosphate, and the carbonates were removed by adding solution of 10% hydrochloric acid. The residue was washed through a 50 μm sieve, and then limited part of the washed fraction was settled on the cover glass and mounted on the slide in Canada balsam. As a rule, at least 250-300 radiolarians tests were counted under the transmitted light microscope at the x300-600 magnification.

For the foraminiferal analysis, air-dried sediment samples of available weight were washed through 100 μm sieve, and then numbers of the benthic and planktic species, and mineral grains were counted.

The sea paleotemperature was reconstructed by a method of Q-mode factor analysis and transfer functions. A PaleoTool Box software with its latest PC-version [8] provides complete facilities to make a statistical environmental analysis of the micropaleontological data and to estimate conditions of the marine paleohabitat.

Transfer functions which allow paleotemperature estimates are based on the treatment of the modern micropaleontological datasets. The North Atlantic reference datasets on the microfossils in our study are counts of (1) 36 polycystine radiolarian species in 91 bottom surface sediment samples from the area between 40 and 73°N [18], and (2) 23 planktic foraminiferal species in 237 bottom surface sediment samples from the area between 40 and 80°N as a compilation from the Atlantic Ocean database of the Shirshov Institute of Oceanology, Moscow, Russia (134 stations from [19]) and World Ocean database (103 stations from [20]. Stations are presented in Figure 3. Limitations to the construction of modern datasets are described in details by Matul and Mohan [18] regarding the radiolarians study but they also can be applied to the planktic foraminifera. The southern boundary of stations in our datasets is approximately 40°N because, north of this latitude, the North Atlantic was an area of the extremely pronounced environmental changes associated with movements of the Subpolar Front during the Late Quaternary glacials [e.g., 21]. We used the micropaleontological information from those stations which were sampled before 1980th, i.e., before an instability of the North Atlantic thermohaline circulation increased [22]. Thus, our dataset, containing an averaged

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environmental (climatic) signal, may not be affected by the significant short-term intra-decadal hydrological changes within the last decades. A temperature at the subsurface depth of 100 m is chosen as a basic parameter for the interpretation because this depth can be a median level of the prevailed habitat of radiolarians [23] and planktic foraminifera [24]. In the North Atlantic, the highest abundances of the marine microzooplankton were found during May-September [25-26], and we operate with summer temperature. The World Ocean Atlas 2013 [11] provides data on the modern summer temperature in the North Atlantic and Nordic Seas averaged for 1955-1964.

3. Results and Discussion

3.1. Modern distribution of the radiolarian and planktic foraminiferal factors (= assemblages) as a base for the paleotemperature estimates

Factor analysis revealed 5 Factors in the modern distribution of both planktic foraminifera and radiolarians (Figure 3). They describe main oceanographic provinces within the studied area.

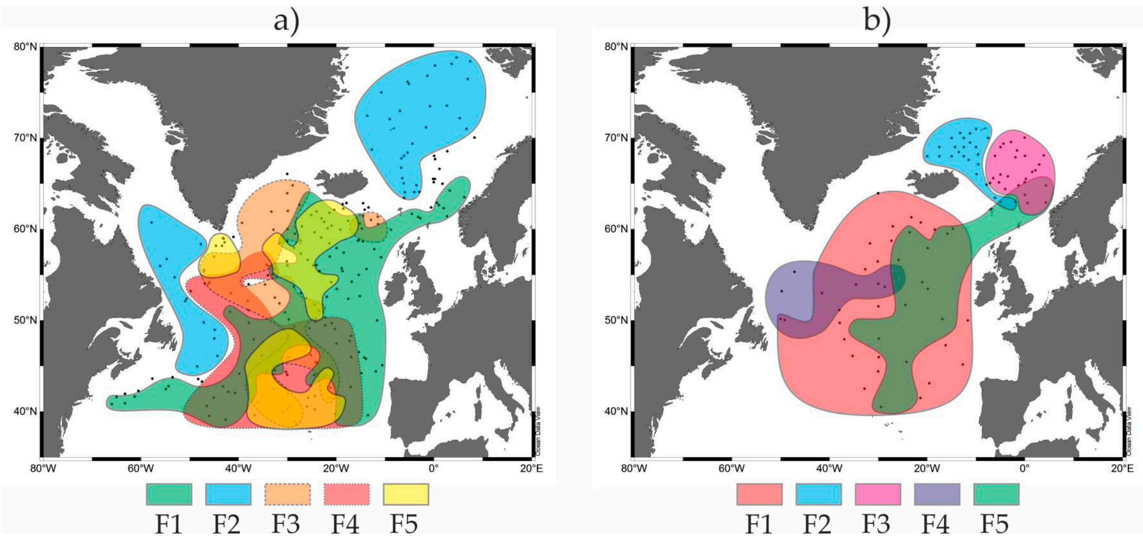

Figure 3. Generalized areas of Factors (≈ assemblages): a) planktic foraminiferas (PF) (this study), b) radiolarians (R) (modified from [18] with simplification) in the bottom surface sediments of the North Atlantic. F1 is Factor 1 with loadings >0.6 and >0.8 for PF and R, respectively, F2 is Factor 2 with loadings <-0.9 and >0.9 for both PF and R, respectively, F3 is Factor 3 with loadings >0.5 for both PF and R, F4 is Factor 4 with loadings >0.4 for both PF and R, F5 is Factor 5 with loadings >0.1 for both PF and R.

Cold-water end-member is Factor 2, with a leading foraminiferal species *N. pachyderma* (sin.) and radiolarian species *Amphimelissa (A.) setosa*. Foraminiferal assemblages, belonging to Factor 2,

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are typical for Greenland, Iceland, western and northern Norwegian, and Labrador Sea. Similarly, radiolarian assemblages of Factor 2 occur in the southern Greenland and Iceland Seas but not in the Labrador Sea. The Polar/Arctic waters occupy these areas contacting with branches of the warmer Atlantic waters. Temperate-water Factor 1 lies within the boreal open North Atlantic, where the dominant species are foraminiferal *N. pachyderma* (dex.) and radiolarian *Lithelius (L.) spiralis/minor* group. Other factors give an additional view on the regional patterns of the microfauna in the open North Atlantic. Foraminiferal Factors 3, 4, and 5 are distributed in the western, southern to southwestern, and central parts of the North Atlantic between latitudes of 40 and 65°N with leading species *Turborotalia quinqueloba*, *G. bulloides*, and *Globigerinita glutinata*, respectively. Radiolarian Factors 4 (dominated by *Artostrobium tumidulum* and *Phorticium clevei*) and 5 (dominated by *Lithomelissa setosa* and *Stylodictya validispina*) indicate the mixing waters of the Labrador Sea and western North Atlantic, and eastern North Atlantic, respectively. Radiolarian Factor 3 (dominated by *Pseudodictyophimus gracilipes* and *Actinomma boreale/A. leptoderma* group) is typical for the southern Norwegian Sea, an area of the active interaction of the warmer Atlantic and colder Arctic waters; it has no counter partner in the foraminiferal distribution.

Patterns in the distribution of Factors (= microfaunal assemblages) clearly reflect the biogeographic realms of the open North Atlantic and Nordic Seas inferred from different groups of the marine animals and plants [27], radiolarians [28], and planktic foraminifera [29, and references therein]. We present here only generalized areas of the factors as details both on factors and typical species distribution were described in [e.g., 30] for planktic foraminifera, and in [18, 31] for radiolarians. For our purposes it is important to fix that the microfaunal assemblages are closely related to the different environments associated with the cold Polar/Arctic (the Nordic and Labrador Seas with temperatures of 0-5°C on 100-m depth level) and warm temperate (the open North Atlantic with temperatures of 8-15°C on 100-m depth level) water masses. This conclusion gives us a possibility to estimate, based on the transfer functions, the paleotemperature shifts at the principal climatic transitions like the sharp global warming (Termination I) between the last glacial maximum 21 ka and the Holocene as recent interglacial time (start at 11.7 ka) when the temperatures on sea-surface in the high latitudes and air temperatures in Greenland could increase at least on 3-6°C and 15°C, respectively [32].

3.2. Main indications of the warm and cold-water events in the down-core records covering Termination I 14.5-11.7 ka.

The most prominent warming event within the Termination I (BA), and the following cold YD event as a return to the quasi-glacial state had a weak reflection in the records of the total microfaunal abundances (Figure 4). Associated changes in the accumulation of radiolarians and planktic/benthic foraminifera were subtle with small peaks during the BA and stable low values during the YD.

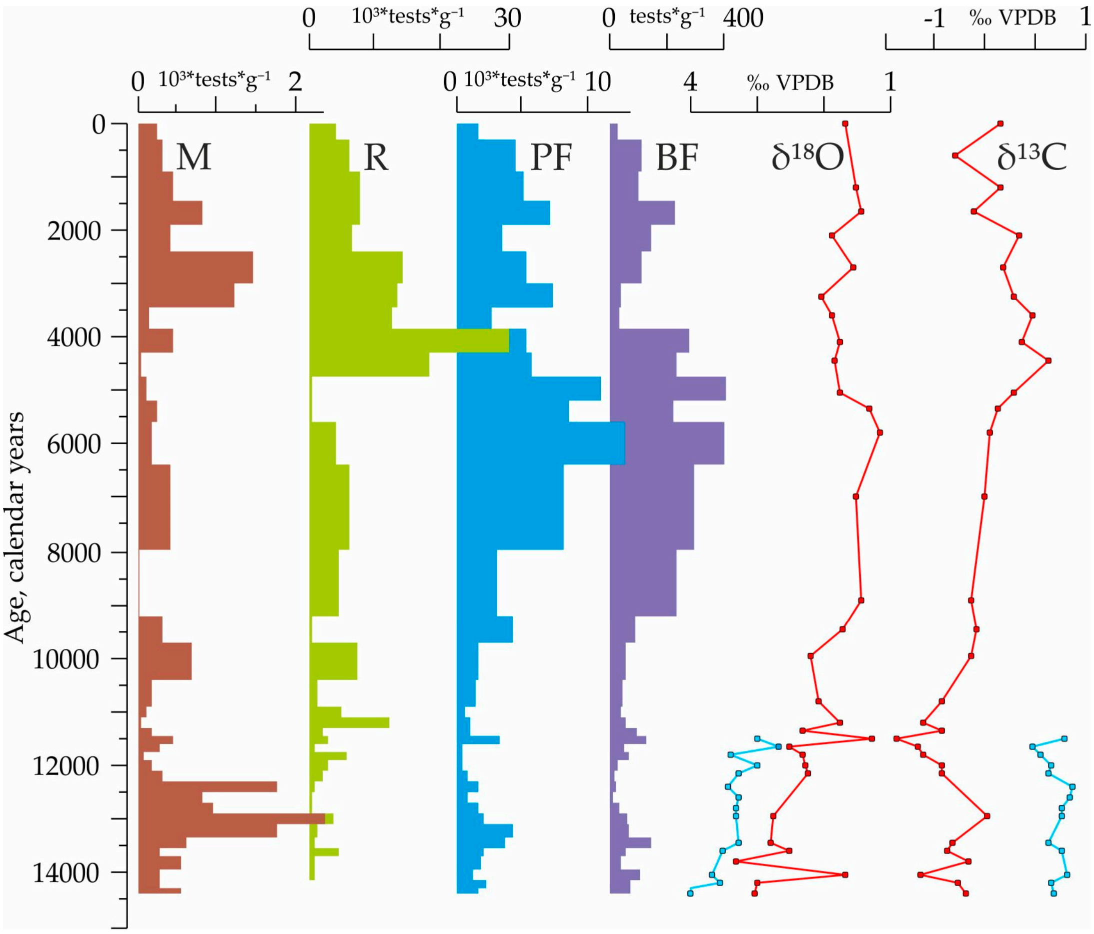

Figure 4. Main initial micropaleontological and isotopic data on the core AMK-340. M is a number of the mineral grains in the sediment fraction >100 μm calculated per 1 g of dry bulk sediment. R, PF and BF are total abundances of radiolarians, planktic and benthic foraminiferas, respectively, calculated per 1 g of dry bulk sediment. $\delta^{18}O$ and $\delta^{13}C$ were measured in the shells of the planktic foraminiferas *G. bulloides* (red line) and *N. pachyderma* sin. (blue line).

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The response of the main species characterizing the microfossil factors on the paleoclimatic changes within the BA and YD was different (Figure 5). The boreal radiolarian indicator *L. spiralis/minor* group had high abundances comparable to the modern ones during the BA warming, then decreased in numbers during the cold YD before reaching its typical percentages at the beginning of the Holocene (Figure 5a). Similar changes can be recognized in the distribution of the benthic foraminifera *Cassidulina (C.) teretis* which feed on the bacterias from the soft, enriched by the organic matter sediments [33]. In contrast, the polar species *N. pachyderma* (sin.) permanently dominated (40 to 100%) the planktic foraminiferal assemblages both during the warm BA and cold YD indicating the persistent cold-water conditions on the subsurface depths. But the radiolarian species *A. setosa*, which is typical for cold-water Greenland and Iceland Seas [31], had a very prominent peak just at the final part of the BA and earlier part of the YD ca. 13.2-12.3 ka up to 40% being rare or absent before and after.

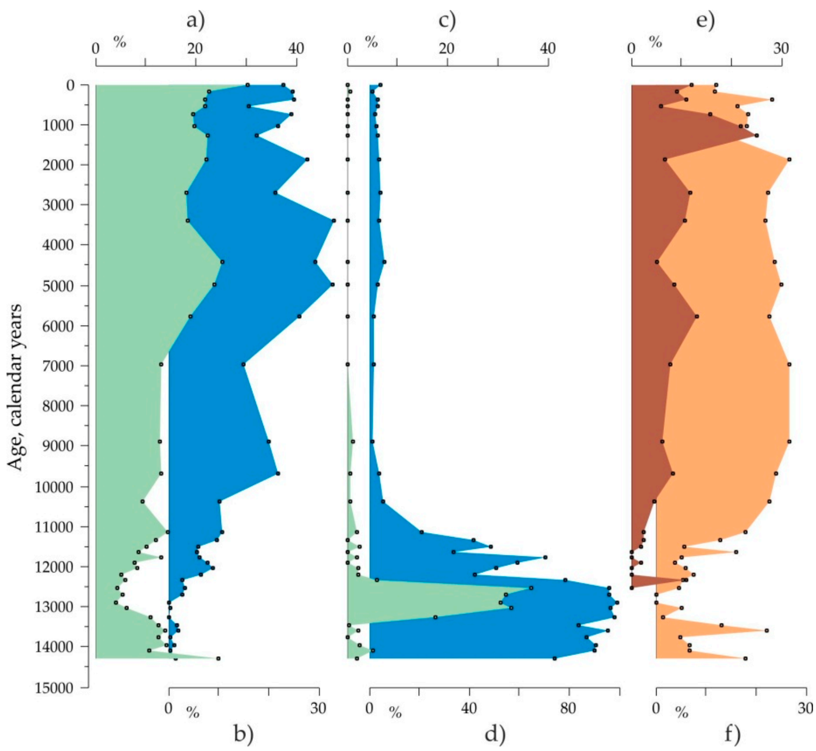

Figure 5. Down-core distribution of the main radiolarian, planktic and benthic foraminiferal species. Temperate North Atlantic species: a) radiolarian *L. spiralis/minor* group, and b) planktic foraminifera *N. pachyderma* dex. Subpolar/Polar species: c) radiolarian *A. setosa*, and d) planktic foraminifera *N. pachyderma* sin. Benthic foraminiferas: e) *G. subglobosa* as marker of spring phytodetrital fluxes [34], and f) *C. teretis* as dweller in soft surface sediment, rich on bacterias, being abundant during the summer [33].

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We may suppose that a specific oceanographic situation existed on the Reykjanes Ridge during this 1-ky long time as high percentages of *A. setosa* in the Nordic Seas mark environments of the active mixing of cold (down to ca. -2°C), relatively refreshed Arctic/Polar waters and warmer saline North Atlantic water [35]. Together with *A. setosa*, a significant increase in the abundances of the mineral grains in the sediment fraction of >100 μm marks interval of the YD (Figure 4). Probably, this can be an indication of the Heinrich-like event H-0 as a massive accumulation of the ice-rafted sediment material on the bottom of the northwestern Atlantic Ocean occurred during the YD [36]. Andrews [37] proposed the Hudson Bay as a source area for the ice-rafted sediments. However, high abundances of the Greenland cold-water radiolarian species *A. setosa*, which is rare now in the Labrador Sea, could point on the southern Nordic Seas to be main origin place of the ice-rafting within the YD on the Reykjanes Ridge.

The final transition toward the recent interglacial state occurred coincidently in all micropaleontological records of the core AMK-340 at the end of the YD. But the first changes indicating the warming started in the middle YD chronozone just after time level of 12.5 ka (Figure 5). For example, the indicator of the open North Atlantic waters, planktic foraminiferal species *N. pachyderma* (dex.), and benthic foraminiferal species *G. subglobosa* as a marker of high phytodetrital fluxes [34] significantly increased percentages or even appeared (in the latter case) from this level. Thus, according to our data on the distribution of the microfossils, the final half of the YD might be an interval of the progressed warming on the Reykjanes Ridge at the latitude of ca. 60°N.

The oxygen isotopic signal $\delta^{18}O$ in the planktic foraminiferal shells of both *N. pachyderma* (sin.) and *G. bulloides* exhibits rather monotonous shift (with short deviations) to the "lighter" values from 14.5 to ca. 11 ka (Figure 6). Time interval of 8 to 5.5 ka with lower $\delta^{18}O$ values of 1.5-1 ‰ (Figure 4) can represent a thermal optimum of the middle Holocene within the Atlantic chronozone [38]. This is supported by the prominent peak of the elevated total abundances of the planktic and benthic foraminifera. We are aware that the $\delta^{18}O$ changes can't act as a conclusive paleotemperature index because $\delta^{18}O$ of the foraminiferal shells reflect the $\delta^{18}O$ of sea water as well governed predominantly by ice volume change on land [39]. Nevertheless, both the temperature increase and hence lesser ice-volume will lower the $\delta^{18}O$ values, which we observe during 8-5.5 ka. Interpretation of the $\delta^{13}C$ signal in the planktic foraminiferal shells is more complicated. It is under the influence of the

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photosynthesis vs respiration ratio in the surface to subsurface waters, $\delta^{13}C$ of the dissolved inorganic carbon, carbonate system parameters, and also temperature [39-40]. Temperature though has a very small effect on the $\delta^{13}C$ values with a slope of 0.1‰ increase per degree Celsius decrease in temperature [39]. Though, it is advisable to use $\delta^{13}C$ variability in combination with other proxies. In our study, $\delta^{13}C$ of *G. bulloides* increases from early Holocene to mid-Holocene and declines slightly thereafter (Figure 4). The total abundances of radiolarians, planktic and benthic foraminifera also show a similar variability (Figure 4). The abundance of benthic foraminiferal species *G. subglobosa* – marker of spring phytodetrital fluxes, and *C. teretis* – inhabits surface sediments rich on bacterias, also increase during the Holocene (Figure 5). During BA warming, the $\delta^{13}C$ values as well as the abundances of planktic and benthic foraminifera, and percentages of benthic foraminifera *C. teretis* increase slightly. Thus, we infer that the $\delta^{13}C$ values of planktic foraminifera *G. bulloides* reflect the increased photosynthetic activity during the warm periods.

3.3. Paleotemperature estimates for the core AMK-340 and correlation with other paleoclimatic archives.

As discussed in the previous subsection, a reaction of the radiolarian and foraminiferal assemblages from the core AMK-340 on the paleoceanographic oscillations during the Termination I was not concurrent. Our micropaleontological records do not coincide in details with the conventional warmings and coolings, the Greenland Stadials and Interstadials [17], at the transition to the Holocene. Reconstructions of the paleotemperature for 100-m water depth (Figure 6) are also not fully coherent with standard oxygen isotopic archives of the Greenland ice cores [41].

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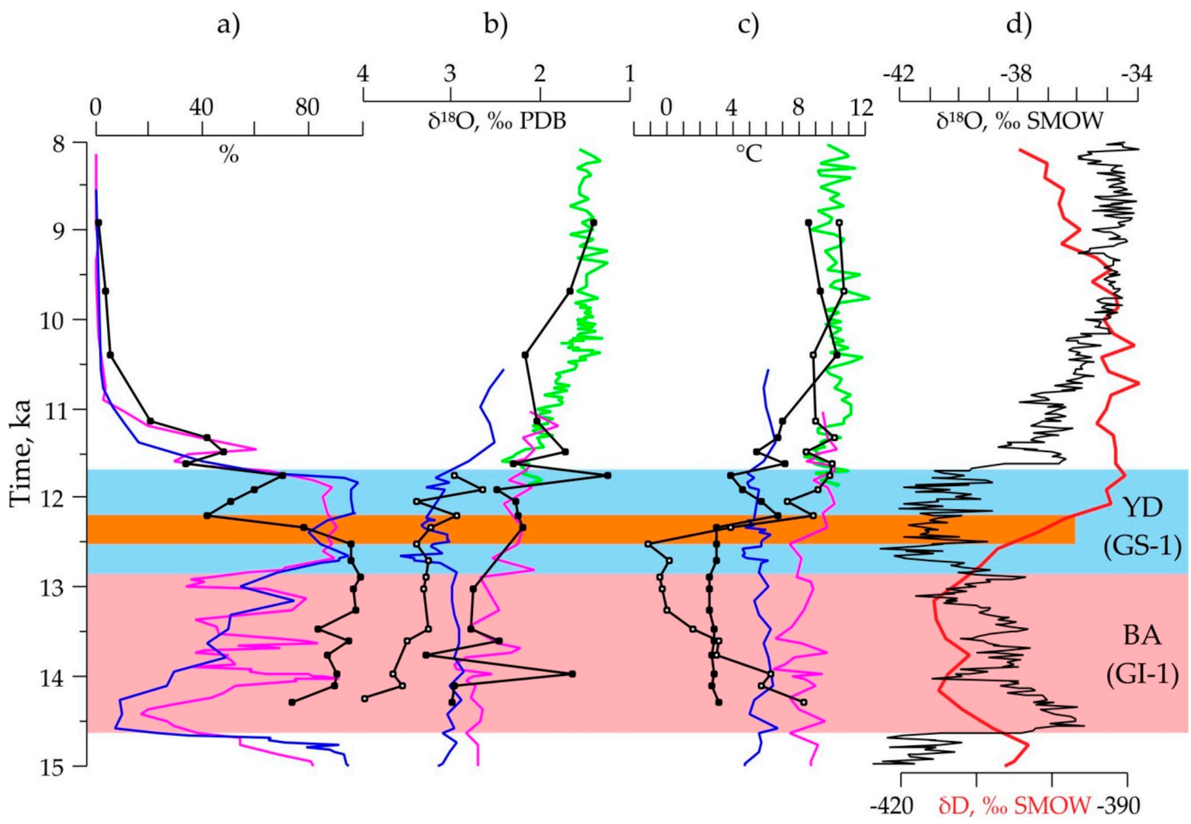

Fig. 6. Summer paleotemperature for the water depth of 100 m in the core AMK-340 vs other paleoclimatic data: a) down-core distribution of the polar planktic foraminifera *N. pachyderma* sin. in the cores AMK-340, black line with black dots [this study], RAPiD10-1P, blue line, RAPiD-12-1K, green line, and RAPiD15-1P, purple line [13-14]; b) oxygen isotopic curves for the cores AMK-340, black line with solid black dots based on *G. bulloides* shells and black line with open dots based on *N. pachyderma* sin. shells [this study], RAPiD10-1P, blue line based on *N. pachyderma* sin. shells, RAPiD-12-1K, green line based on *G. bulloides* shells, and RAPiD15-1P, purple line based on *G. bulloides* shells [13-14]; c) paleotemperature for the cores AMK-340, black line with solid black dots based on the planktic foraminifera and black line with open dots based on the radiolarians (this study), RAPiD10-1P, blue line based on Mg/Ca in *N. pachyderma* sin. shells, RAPiD-12-1K, green line based on Mg/Ca in *G. bulloides* shells, and RAPiD15-1P, purple line based on Mg/Ca in *G. bulloides* shells [13-14]; d) oxygen isotopic curve for the Greenland NGRIP ice core, black line [41], and deuterium curve for the Antarctic EPICA ice core [42]. Light-blue stripe is an interval of the cold YD (Greenland Stadial GS-1), rose stripe is an interval of the warm BA (Greenland Interstadial GI-1), and light-brown stripe is a transition to the warmer conditions [this study] within the conventional cold YD.

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The foraminiferal temperature had monotonous, low values of 2-3°C from 14.5 to ca. 12.2 ka, and then it started to increase, with some fluctuations, up to 8-10°C at the beginning of Holocene. Low but weakly variable foraminiferal temperature could arise from the stable dominance of the polar species *N. pachyderma* (sin.). The monospecific (*N. pachyderma* (sin.)) planktic foraminiferal assemblages now are distributed in the cold-water Labrador and Seas within the wide range of summer sea-surface temperatures of 6 to -2°C [43] or, in our database, summer temperature at 100 m depth of 3 to -1°C. It could be that the statistical program of the paleotemperature calculations, operating with *N. pachyderma* (sin.) dominance, may not provide the proper values from this temperature range.

The radiolarian paleotemperature at the BA start, in contrast to the foraminiferal one, exhibits high values of about 8°C being comparable with modern and Holocene numbers in the area. It dropped steadily toward the BA end, and was very low of 0 to -2°C from ca. 13.5 to 12.5 ka, i.e., just until the middle YD cold interval.

The next warming step after the BA, as documented both by the radiolarian and foraminiferal temperatures, occurred in the area of core AMK-340 12.5-12.2 ka (Figure 6) or considerably earlier than the Holocene started. Neither oxygen isotopic records nor sea-surface paleotemperature estimates on Mg/Ca in the planktic foraminifera, and percentages of the polar *N. pachyderma* (sin.) from the North Atlantic cores south of Iceland [13-14] fixed such event. But some other studies can support our results. Pearce et al. [44] found the start of the pre-Holocene warming at the time level of 12.2 ka based on the diatom study of the sediment core south of Newfoundland. They concluded the evident difference of the early to late YD local paleoceanography. Ebbesen and Hald [45] reported similar results on the cold YD before 12.5 ka and warmer conditions after this level in the Norwegian Sea. We may see a good visual correlation of this warming step with a sharp change from lower to higher δD values in the Antarctic EPICA ice-core records [42]. This can allow us to suspect in our records of the subsurface paleotemperature a teleconnection to the paleoclimatic changes in the Southern Hemisphere which was proposed, e.g., by Rickaby and Elderfield [46] for the coolings during the pre-BA Heinrich-1 event and YD, and by Barker et al. [47] for some abrupt paleoclimatic events during the last deglaciation.

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4. Conclusions.

The North Atlantic areas of the radiolarian and planktic foraminiferal assemblages or main Factors, as defined by the Q-mode analysis of the PanTool Box software, match together in their general outlines and reflect a regional biogeography, distribution and interaction of the major cold- and warm-water masses. However, there is a dissimilarity possibly arising from the specific habitat of different radiolarian and foraminiferal species.

The response of the main microfossil species on the paleoceanographic changes within the transition from the BA warming BA through the cold YD to the warm Holocene was different. The BA warming was well reflected in the radiolarian and benthic but not planktic foraminiferal record. The cold-water radiolarian species *A. setosa* as the Greenland Sea indicator is, probably, alone to mark cooling at the end of the BA and within the start of the YD event 13.2-12.3 ka. Our micropaleontological and isotopic data along with the paleotemperature estimates for the Reykjanes Ridge at ca. 60°N document that, after the warm BA, the middle YD ca. 12.5-12.2 ka is the next significant step toward the Holocene warming. Probably, the paleoceanographic changes in the area of study during the global warming within the Termination I occurred on the subsurface depths earlier than on the sea surface.

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References

1. Delworth, T.L.; Zeng, F. The Impact of the North Atlantic Oscillation on Climate through Its Influence on the Atlantic Meridional Overturning Circulation. *J Climate* **2016**, *29*, 9412-962. DOI: 10.1175/JCLI-D-15-0396.1.
2. Löfverström, M.; Lora, J.M. Abrupt regime shifts in the North Atlantic atmospheric circulation over the last deglaciation. *Geophys. Res. Lett.* **2017**, *44*, 8047-8055. DOI:10.1002/2017GL074274.
3. Knorr, G.; Lohmann, G. Rapid transitions in the Atlantic thermohaline circulation triggered by global warming and meltwater during the last deglaciation. *Geochem. Geophys. Geosyst.* **2007**, *8*, Q12006: 22. DOI:10.1029/2007GC001604.
4. Overpeck, J.T.; Peterson, L.C.; Kipp, N.; Rind, D. Climate change in the circum-North Atlantic region during the last deglaciation. *Nature* **1989**, *338*, 553-557. DOI:10.1038/338553a0.
5. Bauch, H.A.; Kandiano, E.S.; Helmke, J.P. Contrasting ocean changes between the subpolar and polar North Atlantic during the past 135 ka. *Geophys. Res. Lett.* **2012**, *39*, L11604: 7. DOI:10.1029/2012GL051800.
6. Matul, A.G. On the problem of paleoceanological evolution of the Reykjanes ridge region (North Atlantic) during the last deglaciation based on a study of radiolaria. *Oceanology* **1995**, *34*, 806-814.
7. Matul, A.G.; Yushina, I.G. Radiolarians in North Atlantic sediments. *Ber. Polarforsch.* **1999**, *306*, 35-45.
8. Sieger, R.; Grobe, H. PanTool – a Swiss Army Knife for data conversion and recalculation. *PANGAEA:* Alfred Wegener Institute, Helmholz Center for Polar and Marine Research (AWI), Bremerhaven,

Peer-reviewed version available at *Geosciences* **2018**, *8*, 375; doi:10.3390/geosciences8100375

Center for Marine Environmental Sciences, University Bremen (MARUM), Bremen, Germany, 2012. Available online: https://doi.org/10.1594/PANGAEA.787549 (accessed on 31 July 2018).

9. Krauss, W. Currents and mixing in the Irminger Sea and in the Iceland Basin. *J. Geophys. Res.* **1995**, *100(C6)*, 10,851-10,871.
10. Våge, K.; Pickart, R.S.; Sarafanov, A.; Knutsen, Ø.; Mercier, H.; Lherminier, P.; van Aken, H.M.; Meincke, J.; Quadfasel, D.; Bacon, S. The Irminger Gyre: Circulation, convection, and interannual variability. *Deep-Sea Research I* **2011**, *58*, 590-614. DOI:10.1016/j.dsr.2011.03.001.
11. Locarnini, R.A.; Mishonov, A.V.; Antonov, J.I.; Boyer, T.P.; Garcia, H.E.; Baranova, O.K.; Zweng, M.M.; Paver, C.R.; Reagan, J.R.; Johnson, D.R.; et al. World Ocean Atlas 2013. NOAA, U.S. Department of Commerce: Washington, DC, USA, 2013; NOAA Atlas NESDIS 73, Volume 1: Temperature. Available online: https://www.nodc.noaa.gov/OC5/woa13 (accessed on 31 July 2018).
12. Weinelt, M.; Vogelsang, E.; Kucera, M.; Pflaumann, U.; Sarnthein, M.; Voelker, A.; Erlenkeuser, H.; Malmgren, B.A. Variability of North Atlantic heat transfer during MIS 2. *Paleoceanography* **2003**, *18*, 1071: 18. DOI:10.1029/2002PA000772.
13. Thornalley, D.J.R.; McCave, I.N.; Elderfield ,H. Freshwater input and abrupt deglacial climate change in the North Atlantic. *Paleoceanography* **2010**, *25*, PA1201. DOI:10.1029/2009PA001772.
14. Thornalley, D.J.R.; Elderfield, H.; McCave, I.N. Reconstructing North Atlantic deglacial surface hydrography and its link to the Atlantic overturning circulation. *Global Planet. Change* **2011**, *79*, 163-175. DOI: 10.1016/j.gloplacha.2010.06.003.
15. Zweng, M.M.; Reagan, J.R.; Antonov, J.I.; Locarnini, R.A.; Mishonov, A.V.; Boyer, T.P.; Garcia, H.E.; Baranova, O.K.; Johnson, D.R.; Seidov, D.; Biddle, M.M. World Ocean Atlas 2013.NOAA, U.S. Department of Commerce: Washington, DC, USA, 2013; NOAA Atlas NESDIS 74, Volume 2: Salinity. Available online: https://www.nodc.noaa.gov/OC5/woa13 (accessed on 31 July 2018).
16. Stuiver, M.; Reimer, P.J.; Reimer, R.W., CALIB 7.1 [WWW program], 2018. Available online: http://calib.org (accessed on 31 July 2018).
17. Rasmussen, S.O.; Bigler, M.; Blockley, S.P.; Blunier, T.; Buchardt, S.L.; Clausen, H.B.; Cvijanovic, I.; Dahl-Jensen, D.; Johnsen, S.J.; Fischer, H.; et al. A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and

Peer-reviewed version available at *Geosciences* **2018**, *8*, 375; doi:10.3390/geosciences8100375

extending the INTIMATE event stratigraphy. *Quaternary Sci. Rev.* **2014**, *106*, 14-28. http://dx.doi.org/10.1016/j.quascirev.2014.09.007.

18. Matul, A.; Mohan, R. Distribution of Polycystine Radiolarians in Bottom Surface Sediments and Its Relation to Summer Sea Temperature in the High-Latitude North Atlantic. *Front. Mar. Sci.* **2017**, *4*, 330: 1-330: 12. DOI:10.3389/fmars.2017.00330.
19. Barash, M.S. Fossil Plankton Stratigraphies. NOAA/NGDC Paleoclimatology Program: Boulder, CO, USA, 1993; IGBP PAGES/World Data Center-A for Paleoclimatology Data Contribution Series # 93-037. Available online: https://www1.ncdc.noaa.gov/pub/data/paleo/paleocean/fossil_plankton/russian_fossil_plankton (accessed on 31 July 2018).
20. Pflaumann, U.; Duprat, J.M.; Pujol, C.; Labeyrie, L.D. Distribution of planktic foraminifera in surface sediments of the Atlantic Ocean. 1996. *PANGAEA:* Alfred Wegener Institute, Helmholz Center for Polar and Marine Research (AWI), Bremerhaven, Center for Marine Environmental Sciences, University Bremen (MARUM), Bremen, Germany, 1996. Available online: https://doi.org/10.1594/PANGAEA.51621 (accessed on 31 July 2018).
21. Labeyrie, L.; Vidal, L.; Cortijo, E.; Paterne, M.; Arnold, M.; Duplessy, J.C.; Vautravers, M.; Labracherie, M.; Duprat, J.; Turon, J.L.; et al. Surface and Deep Hydrology of the Northern Atlantic Ocean during the past 150 000 Years. *Phil. Trans. R. Soc. Lond. B* **1995**, *348*, 255-264. DOI:10.1098/rstb.1995.0067.
22. Stocker, T.F.; Knutti, R.; Plattner, G.-K. The Future of the Thermohaline Circulation – a Perspective. In *The Oceans and Rapid Climate Change: Past, Present, and Future, Geophysical Monograph Series 126*, 1st ed.; Seidov, D., Haupt, B.J., Maslin, M., Eds.; American Geophysical Union: Washington, DC, USA, 2013; pp. 277-293, ISBN 0-87590-985-X.
23. Zas'ko, D.N. Quantitative distribution of radiolarians in the North Atlantic plankton. *Oceanology* **2001**, *41(12)*, 86-93.
24. Rebotim, A.; Voelker, A.H.L.; Jonkers, L.; Waniek, J.J.; Meggers, H.; Schiebel, R.; Fraile, I.; Schulz, M.; Kucera, M. Factors controlling the depth habitat of planktonic foraminifera in the subtropical eastern North Atlantic. *Biogeosciences* **2017**, *14*, 827-859. DOI:10.5194/bg-14-827-2017.
25. Colebrook, J.M. Continuous plankton records: seasonal variations in the distribution and abundance of plankton in the North Atlantic Ocean and the North Sea. *J. Plankton Res.* **1982**, *4*, 435-462.

26. Parsons, T. R., Takahashi, M., Hargrave, B. *Biological oceanographic processes*, 3rd Edition. Pergamon Press: Oxford, UK, 1984, **ISBN** 9781483286174.
27. Costello, M.J.; Tsai, P.; Wong, P.S.; Cheung, A.K.L.; Basher, Z.; Chaudhary, C. Marine biogeographic realms and species endemicity. *Nat. Commun.* **2017**, *8*, 1057: 1-1057: 10. http://doi.org/10.1038/s41467-017-01121-2.
28. Boltovskoy, D.; Correa, N. Biogeography of Radiolaria Polycystina (Protista) in the World Ocean. *Prog. Oceanogr.* **2016**, *149*, 82-105. DOI:10.1016/j.pocean.2016.09.006.
29. Boltovskoy, D. Foraminifers (Planktonic). In *Encyclopedia of Marine Geosciences*; Harff, J., Mesched, M., Petersen, S., Thiede, J., Eds.; Springer Science+Business Media: Dordrecht, Netherlands, 2014; pp. 1-9, ISBN 978-94-007-6238-1.
30. Kipp, N.G. New Transfer Function for Estimating Past Sea-Surface Conditions from Sea-Bed Distribution of Planktonic Foraminiferal Assemblages in the North Atlantic. *Mem. Geol. Soc. Am.* **1976**, *145*, 9-42. DOI:10.1130/MEM145-p3.
31. Bjørklund, K.R.; Cortese, G.; Swanberg, N.R.; Schrader, H.J. Radiolarian faunal provinces in surface sediments of the Greenland, Iceland and Norwegian (GIN) Seas. *Mar. Micropaleontol.* **1998**, *35*, 105-140.
32. Clark, P.U.; Shakun, J.D.; Baker, P.A.; Bartlein, P.J.; Brewer, S.; Brook, E.; Carlson, A.E.; Cheng, H.; Kaufman, D.S.; Liu, Z.; et al. Global climate evolution during the last deglaciation. *P. Natl. A. Sci. USA* **2012**, *109 (19)*, E1134-E1142. DOI:10.1073/pnas.1116619109.
33. Gooday, A.J.; Lambshead, P.J.D. Influence of seasonally deposited phytodetritus on benthic foraminiferal populations in the bathyal northeast Atlantic: the species response. *Mar. Ecol. Prog. Ser.* **1989**, *58*, 53-67.
34. Suhr, S.B.; Pond, D.; Gooday, A.J.; Smith, C.R. Selective feeding by benthic foraminifera on phytodetritus on the western Antarctic Peninsula shelf: evidence from fatty acid biomarker analysis. *Mar. Ecol. Prog. Ser.* **2003**, 262, 153-162.
35. Bjørklund, K.R.; Hatakeda, K.; Kruglikova, S.B.; Matul, A.G. *Amphimelissa setosa* (Cleve) (Polycystina, Nassellaria) – a stratigraphic and paleoecological marker of migrating polar environments in the northern hemisphere during the Quaternary. *Stratigraphy* **2015**, *12*, 23-37.
36. Hillaire-Marcel, C.; de Vernal, A. 2008. Stable isotope clue to episodic sea ice formation in the glacial North Atlantic. *Earth Planet. Sc. Let.* **2008**, *268*, 143-150. https://doi.org/10.1016/j.epsl.2008.01.012.

Peer-reviewed version available at Geosciences 2018, 8, 375; doi:10.3390/geosciences8100375

37. Andrews, J.; Jennings, A.E.; Kerwin, M.; Kirby, M.; Manley, W.; Miller, G.H.; Bond, G.; MacLean, B. A Heinrich-like event, H-0 (DC-0): Source(s) for detrital carbonate in the North Atlantic during the Younger Dryas Chronozone. *Paleoceanography* **1995**, *10*, 943-952. https://doi.org/10.1029/95PA01426.
38. Jansen, E.; Andersson, C.; Moros, M.; Nisancioglu, K.H.; Nyland, B.F.; Telford, R.J. The Early to Mid-Holocene Thermal Optimum in the North Atlantic. In *Natural Climate Variability and Global Warming: A Holocene Perspective*; Battarbee, R.W., Binney, H.A., Eds. Wiley-Blackwell: Chichester, UK, 2008; pp. 123-137, ISBN 9781405159050.
39. Ravelo, A.C.; Hillaire-Marcel, C. The Use of Oxygen and Carbon Isotopes of Foraminifera in Paleoceanography. In *Developments in Marine Geology*; Hillaire-Marcel, C., de Vernal, A., Eds.; Elsevier: AE Amsterdam, Netherlands, 2007. Volume 1, Proxies in Late Cenozoic Paleoceanography, pp. 735-764. ISBN 978-0-444-52755-4.
40. Jonkers, L.; van Heuven, S.; Zahn, R.; Peeters, F.J.C. Seasonal patterns of shell flux, $\delta^{18}O$ and $\delta^{13}C$ of small and large *N. pachyderma* (s) and *G. bulloides* in the subpolar North Atlantic. *Paleoceanography* **2013**, *28*, 164-174. DOI: 10.1002/palo.20018.
41. NGRIP members. High-resolution record of Northern Hemisphere climate extending into the last interglacial period. *Nature* **2004**, *431*, 147-151. DOI:10.1038/nature02805.
42. EPICA community members. Eight glacial cycles from an Antarctic ice core. *Nature* **2004**, *429*, 623-628. DOI:10.1038/nature02599.
43. Eynaud, F. Planktonic foraminifera in the Arctic: Potentials and issues regarding modern and Quaternary populations. *IOP C. Ser. Earth Env.* **2011**, *14*, 1-12. DOI:10.1088/1755-1315/14/1/012005.
44. Pearce, C.; Seidenkrantz, M.-S.; Kuijpers, A.; Masser, Reynisson, N.F.; Kristiansen, S.M. Ocean lead at the termination of the Younger Dryas cold spell. *Nat. Commun.* **2013**, *4*, 1664: 1-1664: 6. DOI:10.1038/ncomms2686.
45. Ebbesen, H.; Hald, M. Unstable Younger Dryas climate in the northeast North Atlantic. *Geology* **2004**, *32*, 673-676. https://doi.org/10.1130/G20653.1.
46. Rickaby, R.E.M.; Elderfield, H. Evidence from the high-latitude North Atlantic for variations in Antarctic Intermediate water flow during the last deglaciation. *Geochem. Geophys. Geosyst.* **2005**, *6*, Q05001: 12. DOI:10.1029/2004GC000858.

47. Barker, S.; Diz, P.; Vautravers, M.J.; Pike, J.; Knorr, G.; Hall, I.R.; Broecker, W.S. Interhemispheric Atlantic seesaw response during the last deglaciation. *Nature* 2009**, *457*, 1097-1102.** DOI:10.1038/nature07770.

48. Matul, A. Distribution of the polycystine radiolarian species in the Quaternary sediment cores of the subarctic North Atlantic and Sea of Okhotsk. *Data in Brief* **2018**, *17*, 438-441. https://doi.org/10.1016/j.dib.2018.01.041.