Inverse response of $^{231}Pa/^{230}Th$ to variations of the Atlantic Meridional Overturning Circulation in the North Atlantic intermediate water

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Abstract

This study aims to provide a more detailed understanding of the behavior of $^{231}Pa/^{230}Th$ under varying ocean circulation regimes. The North Atlantic provides a unique sedimentary setting with its Ice-Rafted-Detritus (IRD) layers deposited during glacial times. These layers have been found north of 40°N (Ruddiman Belt) and are most pronounced during Heinrich Stadials. Most of these sediments have been recovered from the deep North Atlantic basin typically below 3000 m water depth. This study reports sedimentological and sediment geochemical data from one of the few sites at intermediate depth of the open North Atlantic (core SU90-I02, 45°N 39°W, 1965 m water depth) within the Ruddiman Belt. The time periods of Heinrich Stadials 1 and 2 of this core were identified with the help of the major element composition by XRF scanning and by IRD counting. Along the core profile the sedimentary $^{231}Pa/^{230}Th$ activity ratio has been measured as a kinematic proxy for the circulation strength. The $^{231}Pa/^{230}Th$ record shows highest values during the Holocene and LGM, above the natural production ratio of these isotopes. During Heinrich Stadial 1 and 2, when AMOC was most reduced, the $^{231}Pa/^{230}Th$ record shows overall lowest values below the production ratio. This behavior is contrary to classical findings of $^{231}Pa/^{230}Th$ from the northwestern Atlantic where a strong Holocene circulation is associated with low values. However, this behavior at the presented location is in agreement with results from simulations of the $^{231}Pa/^{230}Th$-enabled Bern3D Earth System Model.

1. Introduction

Changes in the paleoclimate of the North Atlantic region have been related to variations in the Atlantic Meridional Overturning Circulation (AMOC) on glacial-interglacial down to millennial scale timescales as observed from deep marine sediments (e.g. Lynch-Stieglitz, 2017). One example of the sedimentary features of the North Atlantic is the episodic occurrence of distinguished layers of terrigenous sediments ranging from detrital carbonate to cm-wide clastic rocks in sediments north of 40°N (Ruddiman Belt; Ruddiman, 1977). These prominent sediment layers are associated with discharge-events of icebergs originated from the Labrador Sea and are known as Ice Rafted Detritus (IRD) or Heinrich layers (Heinrich, 1988; Andrews and Tedesco, 1992; Bond et al., 1992; Broecker et al., 1992; Hemming, 2004). Heinrich layers have been the target of a great amount of studies aiming for understanding their origin, climatic background and consequence (Heinrich, 1988; Andrews and Tedesco, 1992; Bond et al., 1992; Broecker et al., 1992; Grousset et al., 2001; Hemming, 2004, Rashid and Boyle, 2007; Hodell et al., 2008; Bradtmiller et al., 2014; Hodell et al., 2017, Andrews and Voelker, 2018). Most paleoclimatologic studies agree that Heinrich layers are associated with Heinrich Stadials, climate periods on millennial scales with an extraordinary cold and dry climate. Large inputs of freshwater into the North Atlantic are a common feature of Heinrich Stadials (e.g. Duplessy et al., 1992; Clark et al., 2001; Roche et al., 2004). Since the North Atlantic region and its adjacent seas are key regions for the AMOC with their deep water formation zones, the AMOC is highly sensitive to abrupt changes by e.g. freshwater input into the area (McManus et al., 2004). One consequence is the reorganization of water mass distributions in the Atlantic during Heinrich Stadials (e.g. Henry et al., 2016).

The reconstruction of changes in AMOC strength is often enabled with the kinematic circulation strength proxy $^{231}Pa/^{230}Th_{(xs,0)}$. The radioisotopes ^{231}Pa and ^{230}Th are the radioactive decay products of ^{235}U and ^{234}U, respectively. Uranium is homogenously dissolved in the world ocean and decays to ^{231}Pa and ^{230}Th at a constant activity ratio of 0.093 (so called "production ratio"; Henderson and Anderson, 2003). In contrast to uranium, protactinium and thorium are highly particle-reactive elements with residence times in the range of ~150 and ~20 years, respectively (Henderson and Anderson, 2003). The higher residence time of protactinium is caused by its lower affinity to particles in the water column, compared to thorium. The resulting fractionation, due to particle reactivity, is the key process of the $^{231}Pa/^{230}Th$ proxy. While ^{230}Th is virtually scavenged completely from the water column after production, ^{231}Pa can be laterally advected by deep water currents on a basin scale. Therefore, high ratios indicate slow circulation and vice versa. Accordingly, $^{231}Pa/^{230}Th$ is anti-correlated with the basin-scale circulation strength (e.g. Yu et al., 1996; McManus et al., 2004). However, protactinium shows a high affinity to biogenic opal (Chase et al., 2003), which acts as an effective sink for protactinium (e.g. in the Southern Ocean; Rutgers van der Loeff et al., 2016) potentially obscuring its circulation signal.

Furthermore, the usage of the $^{231}Pa/^{230}Th$ proxy is complicated in regions of high particle fluxes and weak deep water advection such as ocean margins (Anderson et al., 1983; Hayes et al., 2015a). In contrast, the role of Ice Rafted Detritus (IRD) and lithogenic particles in general is thought to be of minor importance on the scavenging behavior of ^{231}Pa (Chase et al., 2002,2004; Roberts et al., 2014).

The expected anti-correlated response of $^{231}Pa/^{230}Th$ to AMOC strength has been demonstrated by several model approaches (Gu and Liu, 2017; Marchal et al., 2000; Siddall et al., 2007; Rempfer et al., 2017), and represents a general feature in the deep West Atlantic (McManus et al., 2004; Gherardi et al., 2005; Bradtmiller et al., 2007; Gherardi et al., 2009; Lippold et al., 2012a; Bradtmiller et al., 2014; Böhm et al., 2015; Henry et al., 2016; Lippold et al., 2016; Mulitza et al., 2017; Voigt et al., 2017; Ng et al., 2018; Waelbroeck et al., 2018; Süfke et al., 2019). However, a number of downcore profiles from the shallower North Atlantic give a different picture of high $^{231}Pa/^{230}Th$ during the Holocene despite its evident strong export of North Atlantic Deep Water (NADW) (Hall et al., 2006; Gherardi et al., 2009; Lippold et al., 2012a, 2012b, 2016) and therefore the generally accepted notion of a pronounced ^{231}Pa export (Deng et al., 2018). This contradictory behavior, however, has been already predicted for the shallower northern North Atlantic by models of simple and intermediate complexity (Luo et al., 2010; Rempfer et al., 2017). In particular, Rempfer et al. (2017) noted that the area north of ~40°N and above 2500 m water depth is supposed to show a positive correlation between $^{231}Pa/^{230}Th$ and AMOC strength based on the Bern3D model.

This study aims to provide a deeper understanding of the relation between $^{231}Pa/^{230}Th$ and AMOC strength variations by presenting a new $^{231}Pa/^{230}Th$ downcore profile from the mid-depth North Atlantic at 45°N. The $^{231}Pa/^{230}Th$ profile is complemented by foraminifera abundance data and the information of the sedimentary composition by XRF scanning, IRD counting and biogenic opal content that were analyzed to identify and investigate the impact of climate events like Heinrich Stadial 1 and 2 on the research area.

2. Methods and Material

2.1. Core location and age model

In this study sediments from interface core SU90-I02 with a total length of 43 cm on top of one of the easternmost Milne Seamounts (45°05’ N, 39°26’ W) at 1965 m water depth were analyzed (Fig. 1). The Milne Seamounts are located in the open North Atlantic east from the Grand Banks of Newfoundland. The investigated site lies within the Ruddiman Belt (Ruddiman, 1977) and sediments deposited before the Holocene are therefore characterized by high amounts of IRD. Today the core site is bathed by Labrador Sea Water which is part of southward flowing NADW (Ferreira and Kerr, 2017).

The general core chronology is based on the correlation of the $\delta^{18}O$ record to other records of the North Atlantic region (Fig. S2) and was refined by four ^{14}C Accelerator Mass Spectrometry (AMS) dates. The new radiocarbon-based age tie-point dates have been measured at the LARA laboratory at the University of Bern, Switzerland (Szidat et al., 2014; Gottschalk et al., 2018). The CALIB 7.1 online tool tied to the Marine13 calibration curve was used (Reimer et al., 2013) with a 400 year reservoir age correction (Table S1).

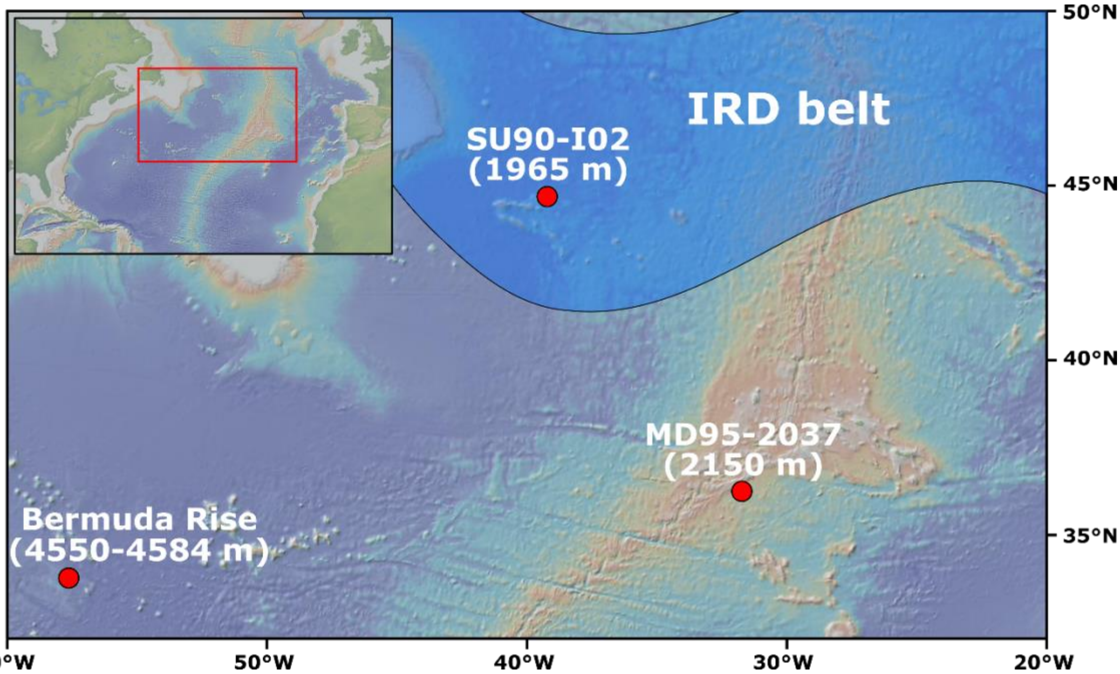

Fig. 1 Overview map of the northern North Atlantic region with the position of core SU90-I02 (45°05'N 39°26'W) on the Milne Seamounts, MD95-2037 (37°05'N 32°01'W; Gherardi et al., 2009) and the Bermuda Rise site (OCE329-GGC5: 33°42'N 57°35'W, McManus et al., 2004; ODP 1063: 33°41'N 57°37'W, Lippold et al., 2009). Number in brackets indicate the water depth of the sites. The blue shaded area depicts the main area of IRD depositions during Heinrich Events 1 and 2 (after Hemming, 2004).

2.2. Analytical methods

The light-colored sandy sediments of interface core SU90-I02 were first sampled continuously in July 1990 on board of the research vessel Le Suroit at 2 cm intervals down to 42.5 cm core depth. These samples were used for investigation of the foraminifera assemblage, stable isotope analyses, radiocarbon dating and IRD counting on the washed sand fraction. Later in 2018, the last available series of bulk sediment samples was collected from Bordeaux University (EPOC) for sedimentary $^{231}Pa/^{230}Th$, XRF and opal analysis (Table S1). This sample series covers continuously the whole core but with discontinuous sample widths up to 2.5 cm (Table S1). Sample splits from the first sample series for planktic foraminifera analyses were freeze-dried, wet-sieved over a 63 µm screen, and oven-dried at 40°C. Counts were conducted on the whole residue or on splits of the size fraction >150 µm and examined under a stereo-dissecting microscope in order to obtain the sand fraction of >150 µm and to quantify the inorganic (IRD counts) and microfossil (foraminifera) components. Planktic foraminifera were identified to the species level (Banner and Blow, 1960; Bandy, 1972; Kucera, 2007; Storz et al., 2009; Schiebel and Hemleben, 2017). Foraminifera samples of *Neogloboquadrina pachyderma sinistral* were cracked and cleaned with methanol in an ultra-sonic bath before $\delta^{18}O$ analysis. The $\delta^{18}O$ analysis (Schulz, 1995b) were carried out in the former Institute for Pure and Applied Nuclear Physics at the University of Kiel, Germany.

Separation and purification of protactinium, uranium and thorium isotopes from sediment samples of SU90-I02 followed the protocol described by Süfke et al. (2018). Samples were spiked with ^{229}Th, ^{236}U and ^{233}Pa before total dissolution in a mixture of concentrated HCl, HNO_3 and HF, which was then followed by further chemical purification by column chromatography. Since ^{233}Pa is a short lived isotope ($t_{1/2}$= 27 d) it had been milked from a ^{237}Np solution (Regelous et al., 2004) directly before the chemical treatment and purification of the samples. The ^{233}Pa spike was calibrated against the reference materials UREM-11 (Süfke et al., 2018), IAEA-385 (Pham et al., 2008) and an internal pitchblende standard (Fietzke et al., 1999). Finally, concentrations of the radioisotopes ^{230}Th, ^{231}Pa, ^{232}Th, ^{234}U, and ^{238}U were measured with a Neptune Plus MC-ICP-MS at the Geozentrum Nordbayern in Erlangen, Germany.

For the calculation of $^{231}Pa_{excess}$ and $^{230}Th_{excess}$ from measured bulk ^{231}Pa and ^{230}Th a detrital correction of $^{238}U/^{232}Th$ = 0.55 has been applied (Henderson and Anderson, 2003). This correction is in agreement with the overall minimum of bulk $^{238}U/^{232}Th$ in the samples of SU90-I02 and within typical lithogenic activity ratios (0.5 to 0.6) found in the western Atlantic sector (Henderson and Anderson, 2003). Variations in the detrital correction do not show a significant effect on the age corrected sedimentary $^{231}Pa/^{230}Th_{excess}$ record (Lippold et al., 2016; Missiaen et al., 2018; Fig. S1) even for time periods of distinctly different sedimentation regimes (e.g. Heinrich Events). This argues in favor of a negligible impact of the lithogenic particle flux on the resulting $^{231}Pa/^{230}Th_{excess}$ record. ^{231}Pa and ^{230}Th excess concentrations were decay corrected to the time of deposition. All individual isotope concentrations are provided in the supplement (Table S1).

To investigate the potential influence of biogenic opal on ^{231}Pa (Chase et al., 2002, 2003; Rutgers van der Loeff et al., 2016) the sedimentary opal concentration was analyzed by automated leaching following the procedure described by Müller and Schneider (1993). Furthermore, the major element composition (Al, Si, K, Ca, Ti and Sr) of discrete bulk sediment samples were analyzed with a fourth generation Avaatech XRF core scanner at the Institute of Earth Sciences at Heidelberg University, Germany. Elemental ratios (e.g. Ca/Sr) are a useful tool to identify Heinrich-Layers in the North Atlantic (Hodell et al., 2008).

<u>3. Results</u>

3.1. Age model refinement by ^{14}C and $\delta^{18}O$

The core chronology was established for SU90-I02 based on stable oxygen isotope data (Schulz, 1995b), as well as on four ^{14}C dates. The radiocarbon dates at sediment depths of 21 and 33 cm were obtained from *N. pachyderma s.* and give absolute ages of 9 and 22.5 ka BP, respectively. Radiocarbon dates from sediment depths 9 and 19 cm were obtained from *Globigerina bulloides* and give absolute ages of 6.3 and 7.3 ka BP, respectively (Fig. 2; Table S1). A potential negative influence of analyzing different species for radiocarbon dating on the accuracy of the age model is possible but has been found not to be significant for the here investigated species and time periods (Manighetti et al., 1995). For a further refinement of the age model the planktonic $\delta^{18}O$ record of *N. pachyderma s*. (Schulz, 1995b) was correlated to established $\delta^{18}O$ records from the North Atlantic IRD belt (Bond et al., 1992; Labeyrie et al., 1995; Grousset et al., 2001; Jullien et al., 2006; Rashid and Boyle, 2007; Hodell et al., 2017; Fig. S2). All records from the before mentioned studies show a consistent picture of a shift in planktic $\delta^{18}O$ (from *N. pachyderma s.*) to lighter values between 17 and 17.5 ka right before the major IRD depositions of Heinrich Stadial 1, as seen at 24 cm core depth in SU90-I02 (Fig. 2). Further, the slight shift from lighter to heavier $\delta^{18}O$ at 35 cm in SU90-I02 can be correlated to a similar shift in $\delta^{18}O$ observed in the North Atlantic during Heinrich Stadial 2 between 24 and 25 ka (Broecker et al., 1990/1992; Jullien et al., 2006; Rashid and Boyle, 2007). The increase in $\delta^{18}O$ in the deeper part of the presented record can be related to a warm phase between Heinrich Stadial 2 and 3 (Heinrich 1988; Broecker et al., 1990; Bond et al., 1992).

With these age constraints a hiatus in SU90-I02 is apparent in the depth below 21 cm (Fig. S3). While the onset of Heinrich Layer 1 is present at 24 cm (see section 4.1.) the late Heinrich Stadial 1, the Younger Dryas, the Bølling/Allerød and the very early Holocene parts are missing (Fig. S3). Additionally, it has to be kept in mind that the exact timing and duration of SU90-I02 variations in $^{231}Pa/^{230}Th$ and XRF samples are less well defined since these samples integrate up to 2.5 cm of sediment (Table S1). Sample widths of 2.5 cm can integrate up to 1000 years in SU90-I02 and therefore limit the time resolution.

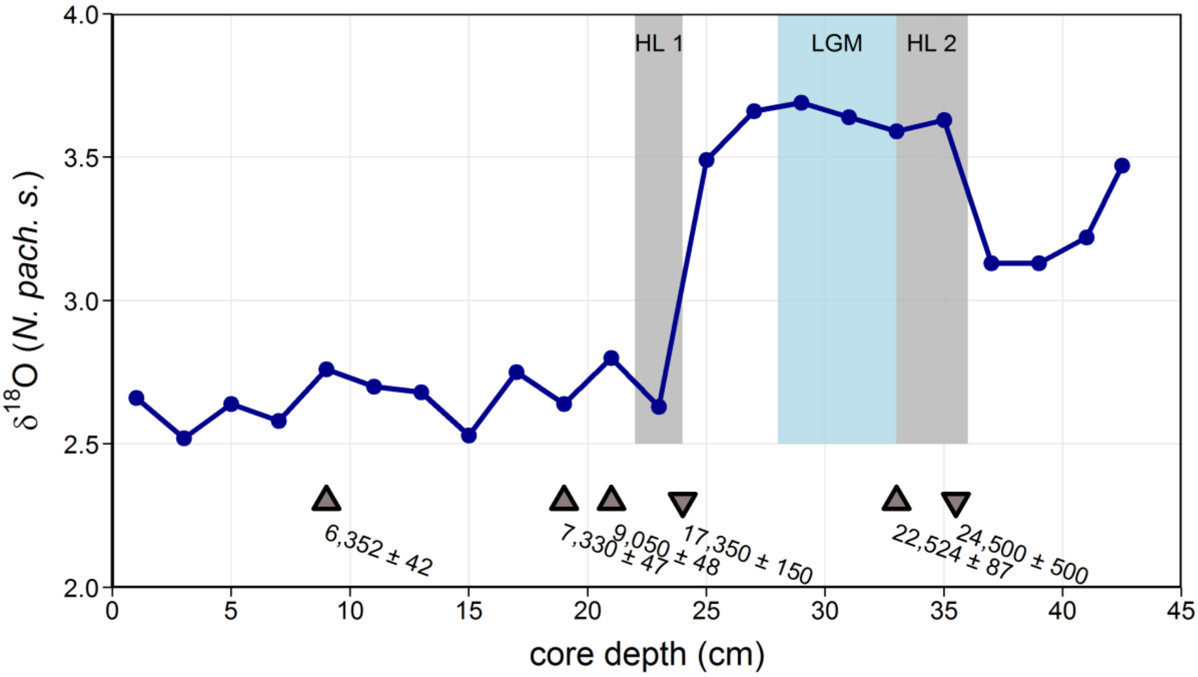

Fig. 2 The $\delta^{18}O$ record of the planktic foraminifera *N. pachyderma s* (Schulz, 1995b). Upward triangles indicate ^{14}C dates and downward triangle age tie points derived from $\delta^{18}O$ (cf. section 3.1.). Gray bars show the position of Heinrich Layers 1 (HL 1) and 2 (HL 2) (based on IRD and foraminifera data; see Fig. 3, 4) and the blue bar indicate the Last Glacial Maximum (LGM) section of SU90-I02.

3.2. Radioisotope analysis

The $^{231}Pa/^{230}Th$ profile for SU90-I02 displays high values between 0.083 and 0.116 in the upper 15 cm of the core corresponding to the Holocene period (Fig. 3a). Further, at 29 cm core depth a sharp peak in $^{231}Pa/^{230}Th$ reaches 0.130, which is the highest value of the entire record, and is related to the LGM. Between 17 and 24 cm and below 33 cm $^{231}Pa/^{230}Th$ values are quite stable between 0.06 and 0.07. These intervals are related to the early Holocene as well as Heinrich Stadials 1 and 2, respectively.

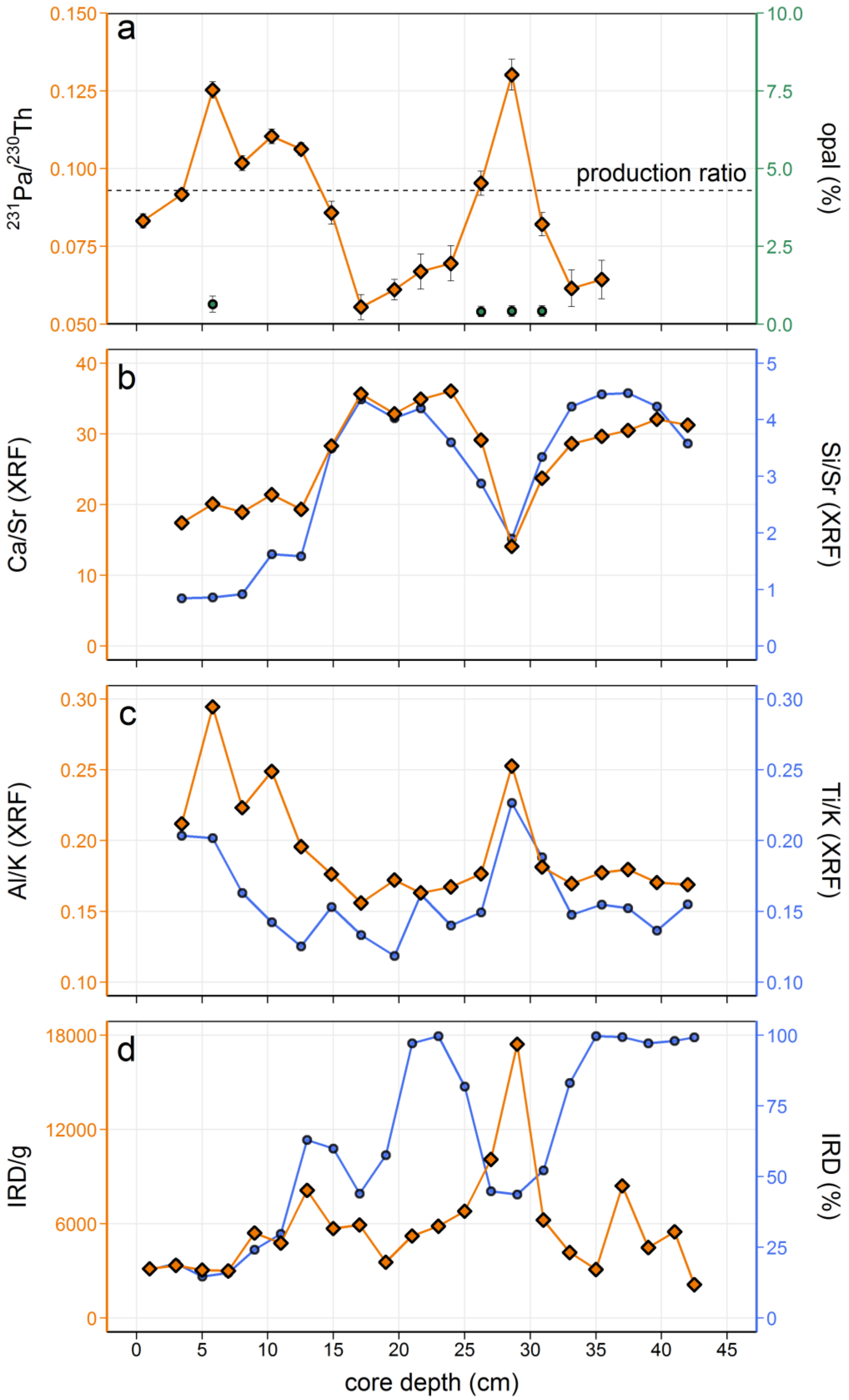

Fig. 3 Geochemical and sedimentary parameters of SU90-I02. (a) $^{231}Pa/^{230}Th$ activity ratios and opal concentration (%). The dashed line indicates the production ratio of $^{231}Pa/^{230}Th$. (b, c) Bulk element ratios of Ca/Sr, Si/Sr, Al/K and Ti/K measured on discrete sediment samples by XRF. (d) Absolute IRD counts of the bulk sediment and relative IRD percentages in the >150 µm fraction.

3.3. Sedimentary analysis of foraminifera, opal and major elements

Planktic foraminifera of the species *Neogloboquadrina pachyderma sinistral, Neogloboquadrina pachyderma dextral (also called Neogloboquadrina incompta; Schiebel and Hemleben, 2017)* and *Globigerina bulloides* were investigated for this study (Fig. 4a/b/c) as representatives for a colder/glacial (*N. pachyderma s.)* and more moderate (*N. pachyderma d*. and *G. bulloides*) environment (e.g. Manighetti et al., 1995). Species *N. pachyderma d*. and *G. bulloides* show their highest abundances in the top 10 cm of the core. Below 10 cm, *N. pachyderma s.* is the dominant species throughout the record. In the interval between 19 and 25 cm core depth (including Heinrich Stadial 1) all species show an abundance minimum (e.g. *Heinrich, 1988*). The following interval between 25 and 33 cm (LGM) is characterized by the reappearance of all species. While *N. pachyderma d*. and *G. bulloides* reached Holocene levels at 29 cm, *N. pachyderma s.* is the most dominant species with a relative abundance of 75 % of all foraminifera (Fig. 4a). Below 33 cm all species vanish again to extremely low abundance rates (Heinrich Stadial 2).

The sedimentary composition is monitored by major element analysis as well as opal concentration measurements and IRD counts (Fig 3; Table S1). Opal concentrations are constantly very low (< 1 %) throughout the presented record (Fig. 3a). In contrast, major element ratios show a distinct pattern. Ca/Sr and Si/Sr ratios are low in the top 17 cm of the core. Between 17 and 26 cm (including Heinrich Stadial 1) highest values of these ratios are found. At 29 cm (LGM) both ratios return to low values as seen during the Holocene. Below 29 cm ratios for Ca/Sr and Si/Sr return again to higher values like seen during Heinrich Stadial 1. The lithogenic element ratios Al/K and Ti/K show high values in the top 7 cm, which then decrease to the overall lowest ratios in the interval downcore to 26 cm. At 29 cm both lithogenic element ratios return to Holocene-like values but sharply decrease back to low ratios below. The course of the XRF measurements is mirrored by the IRD counts (Fig. 3d). During intervals of high Ca/Sr ratios (21 to 25 and 35 to 42 cm) the percentage of IRD in the >150 µm fraction is nearly 100 %. Lowest IRD percentages are visible in the top 10 cm of the core (Holocene) and around 29 cm (LGM). The timing of these periods matches the most pronounced changes in the XRF data, abundances of investigated foraminifera species and $^{231}Pa/^{230}Th$.

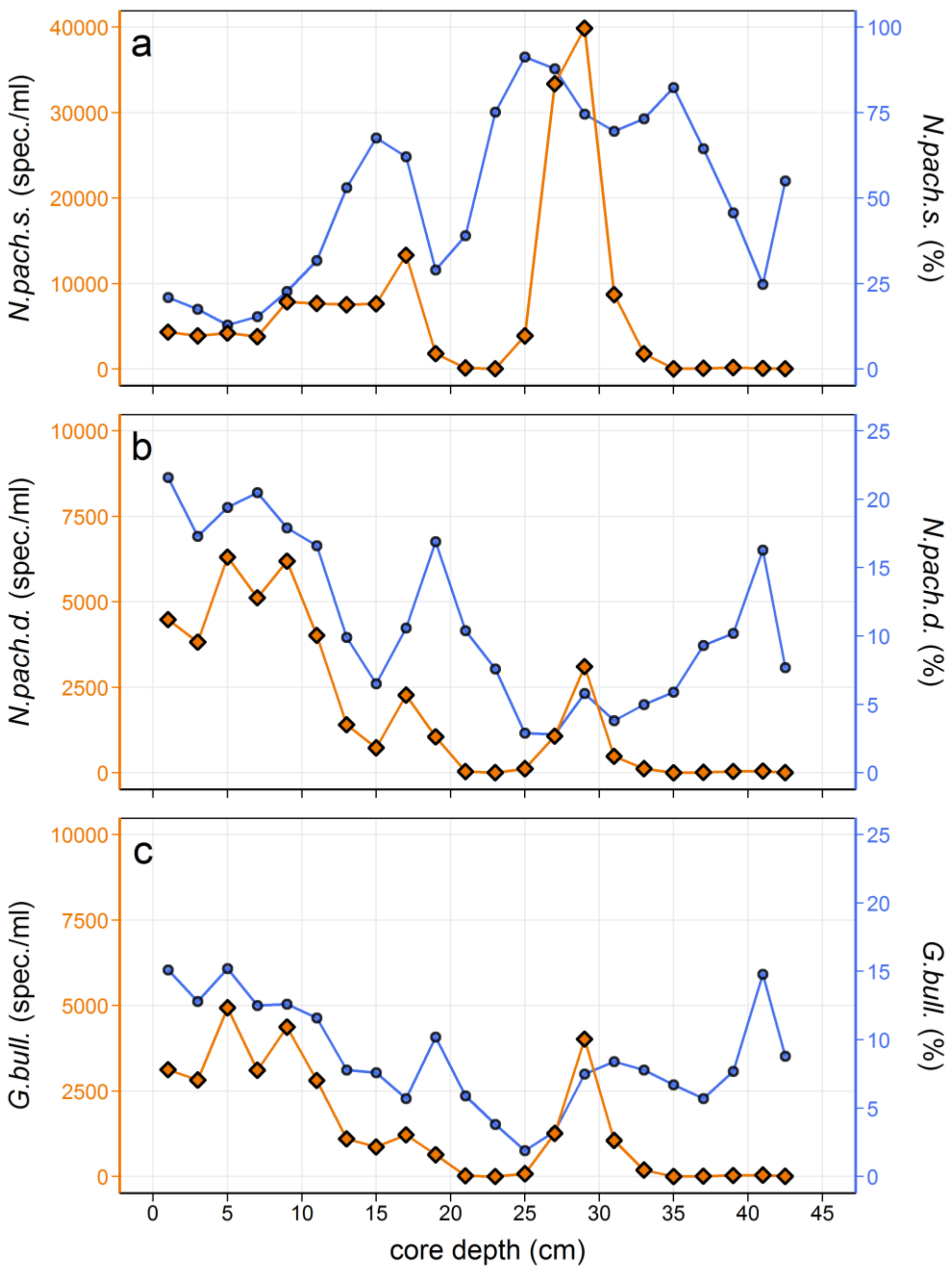

Fig. 4 Absolute (orange; in specimens per ml) and relative (blue; in % of all foraminifera; Schulz, 1995b) abundances of the foraminifera species *N. pachyderma s.* (a), *N. pachyderma d.* (b), and *G. bulloides* (c). Please note the different y-scale for panel a compared to panels b and c.

4. Discussion

4.1. Characterization of Heinrich layers

The core chronology is extended by the identification of Heinrich layers in SU90-I02. Heinrich layers are characterized by detrital carbonate which can easily be identified in North Atlantic sediments by its high Ca/Sr signature compared to regular marine sediments (Hodell et al., 2008). In SU90-I02 highest Ca/Sr ratios were identified in the depth interval between 15 and 25 cm as well as below 30 cm down to 42 cm (Fig. 3b). The course of Ca/Sr is also reflected in Si/Sr, which indicates the presence of silicate-rich IRDs (Hodell et al., 2008; Fig. 3b). Accompanied by the relative amount of IRD in the >150 µm fraction (IRD %; Fig. 3d), with highest values of nearly 100 % of IRD between 21 and 25 cm as well as below 33 cm, both these intervals can be assigned to Heinrich Layers 1 and 2, respectively. Both Heinrich layers are interrupted by a sharp decrease in Ca/Sr and Si/Sr at 29 cm (LGM) which occurs at the same interval as absolute foraminifera abundance as well as the $^{231}Pa/^{230}Th$ record are increased. The low Ca/Sr can be interpreted as absent detrital carbonate and a sediment source different from Heinrich-IRDs inferred from low Si/Sr (Hodell et al., 2008; Hodell et al., 2017). Further, the ratios of the terrigenous elements (Ti/K and Al/K) show an anomaly at the same core depth (Fig. 3c). IRD deposits during Heinrich Events can be linked to a North Canadian source (e.g. Andrews and Tedesco, 1992), while IRDs during the LGM most likely originated from Greenland (Watkins et al., 2007). Additionally, absolute IRD counts are highest at the core depth of 29 cm, while the relative amount of IRD in the >150 µm fraction is much lower (~44 %) than in Heinrich layers. The lower concentrations of IRD during the LGM is the effect of the high abundances of preserved foraminifera diluting the IRD in the >150 µm fraction. In contrast, during Heinrich Stadial 1 and 2 foraminifera are nearly absent in the >150 µm fraction (Fig. 4) caused either by an environment not favorable for foraminifera growth or a massive dilution of foraminifera shells in the sediment by IRDs.

4.2. The role of particle flux on $^{231}Pa/^{230}Th$ at SU90-I02

The new $^{231}Pa/^{230}Th$ downcore profile of SU90-I02 displays high Holocene values, above production ratio, preceded by lower values during the intervals of the Heinrich Stadial 1 and 2 interrupted by a distinctive peak of high $^{231}Pa/^{230}Th$ during the LGM (Fig. 3a). The high sedimentary $^{231}Pa/^{230}Th$ above the production ratio from a North Atlantic sediment core during the Holocene calls at first glance for a strong influence of particle flux and/or particle composition on protactinium-scavenging (Anderson et al., 1983; Christl et al., 2010). However, preserved opal concentrations, known as an effective scavenger of protactinium (Chase et al., 2003; Rutgers van der Loeff et al., 2016), are low during the Holocene and LGM (Fig. 3a) and thus clearly below the range (>5-10 %) for which any empirical correlation between opal and increased $^{231}Pa/^{230}Th$ values can be observed in the Atlantic (Lippold et al., 2012a; Ng et al., 2018).

Further, the ^{230}Th normalized sediment flux is lowest when $^{231}Pa/^{230}Th$ is highest and vice-versa (Fig. 5) arguing against a major influence of particle flux on the temporal evolution of the $^{231}Pa/^{230}Th$ record. This observation is further corroborated by the ^{230}Th normalized vertical sediment-accumulation rate of around 3 to 7 g/cm^2/ka for the time periods of highest $^{231}Pa/^{230}Th$. Similar vertical fluxes have been reported from sites of circulation dominated $^{231}Pa/^{230}Th$ records (McManus et al., 2004; Gherardi et al., 2009; Roberts et al., 2014). Roberts et al. (2014) also conclude that fluxes of ~5 g/cm^2/ka are not capable of significantly increasing the $^{231}Pa/^{230}Th$ ratio in a circulation controlled setting. Interestingly, when the ^{230}Th normalized sediment flux is greatest, reaching values up to 20 g/cm^2/ka, ^{231}Pa/^{230}Th is lowest with values clearly below the production ratio. The section featuring the overall highest ^{231}Pa/^{230}Th corresponds to the LGM (around 29 cm) and is characterized by a massive change in sedimentary composition as well as in the environmental boundary conditions. Due to the high abundances of preserved foraminifera and high IRD counts, a certain particle effect on the ^{231}Pa scavenging behavior cannot be excluded but is considered to be of subordinate relevance since these particle types are not of primary importance for the scavenging of protactinium (Chase et al. 2004).

4.3. The effect of sediment winnowing on ^{231}Pa/^{230}Th

For large parts of the ^{231}Pa/^{230}Th profile the sediment core experienced enhanced sediment winnowing (Fig. 5c). Hence, besides the particle type also effects of sediment sorting and selective removal of different sediment phases and grain sizes may have influenced the measured sedimentary ^{231}Pa/^{230}Th ratio (Geibert and Usbeck, 2004; Kretschmer et al., 2010; Kretschmer et al., 2011). Kretschmer et al. (2011) investigated the effect of winnowing (removal) of the fine fraction (< 20 µm) with and without opal-rich particles on the retained sedimentary ^{231}Pa/^{230}Th ratio, since protactinium is characterized by a high affinity to particles built up from biogenic opal while thorium is preferentially scavenged by fine sized particles like clay (e.g. Chase et al., 2002; Geibert and Usbeck, 2004; Rutgers van der Loeff et al., 2016). From opal-rich sediments in the Southern Ocean Kretschmer et al. (2011) found that the removal of the fine fraction (< 20 µm) alone would result in a slightly increased sedimentary ^{231}Pa/^{230}Th ratio since the lost fine particles like clay are a major carrier phase of scavenged ^{230}Th. In contrast, if opal-rich particles, the main carrier phase of scavenged ^{231}Pa, is lost by winnowing the retained ^{231}Pa/^{230}Th ratio can clearly decrease (Kretschmer et al., 2011 and their Fig. 4). Indeed, SU90-I02 shows sediment winnowing prior the Holocene (Fig. 5c) a period which exhibited low ^{231}Pa/^{230}Th markedly below the production ratio. However, since the sedimentary setting of SU90-I02 with its very low opal concentrations (Fig. 3) is very different to the Southern Ocean, winnowing would rather have removed ^{230}Th rich clay particles which should be evident in high ^{231}Pa/^{230}Th. This is not observed here with exception of a short excursion during the LGM. While this excursion could be explained by the removal of clay particles it contradicts the observation of generally low ^{231}Pa/^{230}Th during strong winnowing. Correlations between winnowing and ^{231}Pa/^{230}Th are thus considered too ambiguous for explaining the observed variations in ^{231}Pa/^{230}Th. Furthermore, the effect of sediment sorting on ^{231}Pa/^{230}Th has not been observed yet for winnowing sites and is inferred from findings of Southern Ocean sediments (Kretschmer et al., 2011).

From the observations as outlined in paragraph 4.2. and 4.3. it is concluded that the main features of the $^{231}Pa/^{230}Th$ record of SU90-I02 and the huge variations in absolute $^{231}Pa/^{230}Th$ values cannot have been primarily controlled by variations in particle fluxes, particle compositions or winnowing, but are best explained by large-scale AMOC variations imprinted in the sedimentary $^{231}Pa/^{230}Th$. The uncorrelated or even anti-correlated evolution of $^{231}Pa/^{230}Th$ with sediment fluxes in turn points towards variations in both $^{231}Pa/^{230}Th$ and sedimentation history along with changes in the circulation regime.

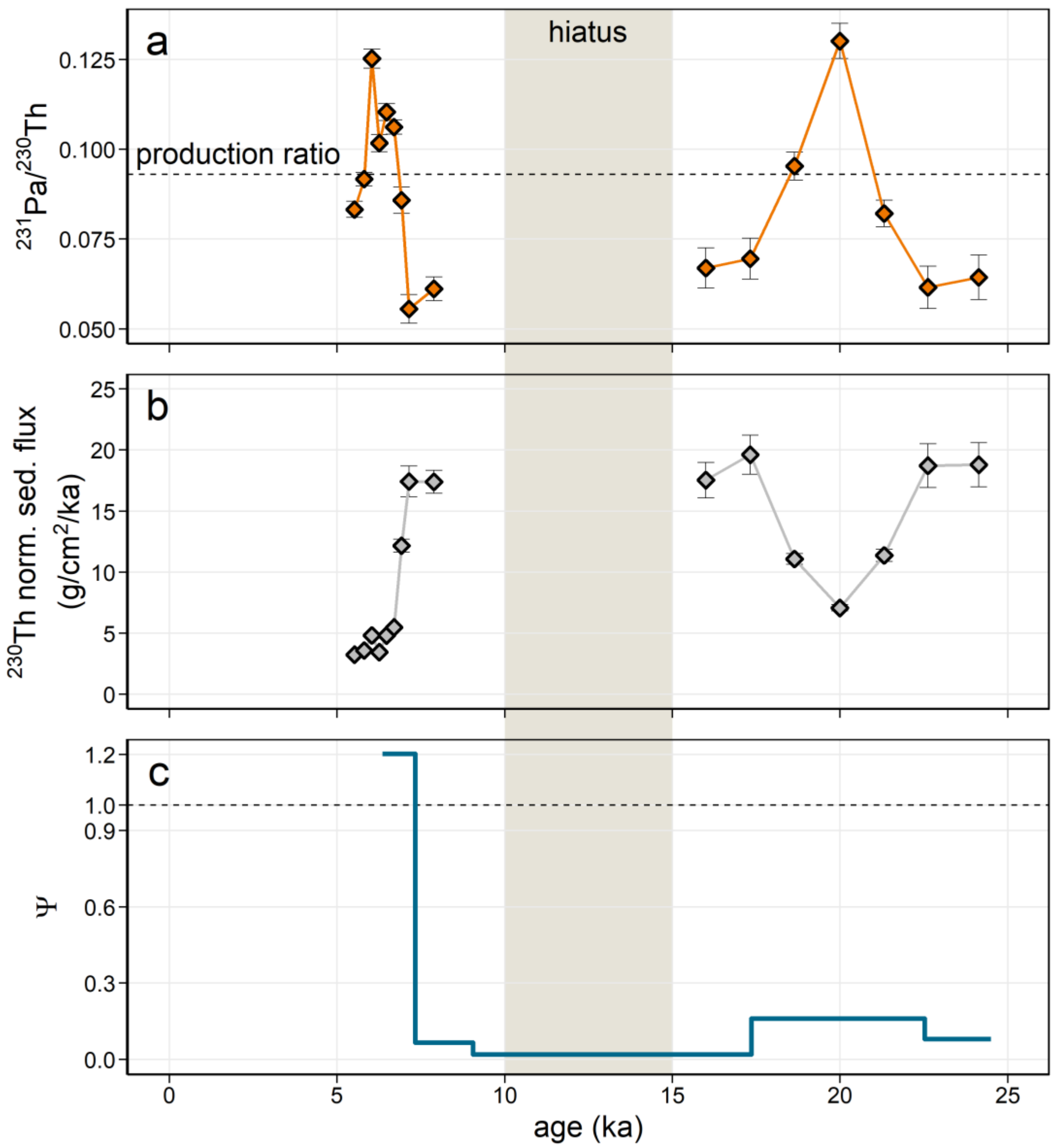

Fig. 5 The $^{231}Pa/^{230}Th$ (a) record of SU90-I02 compared to the ^{230}Th normalized sediment flux given in g/cm²/ka (b) and the sediment focusing factor Ψ (c) calculated from $^{230}Th_{xs0}$ concentrations (Francois et al., 2004). High sediment fluxes correlated with the $^{231}Pa/^{230}Th$ activity ratios, indicative for a subordinate effect of the sediment flux on sedimentary $^{231}Pa/^{230}Th$. The dashed line in panel (a) indicates the production ratio of $^{231}Pa/^{230}Th$. The brown bar (hiatus) delineates the missing interval of the Deglacial in SU90-I02. The dashed line in panel (c) indicates a focusing factor of one which would indicate that now sediment is transported to or form this site. The strongest winnowing (sediment removal) is observed during the period of the proposed hiatus and is therefore in accordance with this finding.

4.4. The SU90-I02 $^{231}Pa/^{230}Th$ record interpreted in terms of reflecting AMOC variations

The here observed pattern of high Holocene and low Heinrich Stadial 1 and 2 $^{231}Pa/^{230}Th$ ratios is inverted and at first glance contradicting compared to the prominent $^{231}Pa/^{230}Th$ profiles from the deep northwestern Atlantic below 3000 m water depth (e.g. from the Bermuda Rise: McManus et al., 2004; Blake-Bahama Outer Ridge: Süfke et al., 2019; Ceara Rise: Lippold et al., 2016; Ng et al., 2018; Researchers Ridge: Ng et al., 2018) and time slice integrating compilations (Lippold et al., 2012a; Bradtmiller et al., 2014; Burckel et al., 2016).

However, the course of the SU90-I02 $^{231}Pa/^{230}Th$ matches the general glacial to Holocene evolution recorded by mid-depth North Atlantic site MD95-2037 at 2159 m (Gherardi et al., 2009; Fig. 1, 6). Both cores from shallower water depths share the same general pattern in their $^{231}Pa/^{230}Th$ profile with low values during prolonged cold periods (e.g. Heinrich Stadials) and a sharp increase to high Holocene values at ~ 8 ka. This pattern is inverted to the $^{231}Pa/^{230}Th$ profiles from the deep northwestern Atlantic (McManus et al., 2004; Lippold et al., 2009; Fig. 6) (low Holocene – high Glacial). Furthermore, the timing of the early Holocene circulation change is earlier (between 11 to 10 ka) in the deep compared the mid-depth Atlantic (see paragraph 4.5.; Fig. 6).

The position of a sediment core within one distinct overturning cell (in particular in terms of water depth) has been identified as a crucial parameter for $^{231}Pa/^{230}Th$, as suggested by simple box model approaches and observations (Luo et al., 2010; Lippold et al., 2011; Lippold et al., 2012a; Burckel et al., 2016). Further, the depth dependency of $^{231}Pa/^{230}Th$ is amplified with increasing circulation strength. A hypothetical static ocean would generate $^{231}Pa/^{230}Th$ deviations from the production ratio only due to large-scale diffusion caused by gradients in the particle fluxes between the margins and the inner ocean (boundary scavenging; Anderson et al., 1983; Hayes et al., 2015). But under a strong advection regime low $^{231}Pa/^{230}Th$ in deep waters predominantly result from the increasing vertically integrated deficit of ^{231}Pa relative to ^{230}Th. In shallower waters this deficit cannot build up efficiently due to the smaller water column above. Instead, dissolved ^{231}Pa is supplied from upstream while ^{230}Th is effectively scavenged to deeper waters leading to the observed decrease of $^{231}Pa/^{230}Th$ with water depth. However, shallower water depths alone seem not to be a sufficient condition for high $^{231}Pa/^{230}Th$. The Holocene $^{231}Pa/^{230}Th$ record at the Carolina Slope in a water depth of 1790 m (core KN140-2-51 GGC in the direct flow path of the Atlantic Deep Western Boundary Current; Hoffmann et al., 2018) displays constant values around 0.075 not exceeding the production ratio.

With adding this new mid-depth $^{231}Pa/^{230}Th$ record and reviewing the up-to-date available data base (McManus et al., 2004; Gherardi et al., 2009; Lippold et al., 2009,2011,2012a,2016; Bradtmiller et al., 2014; Böhm et al., 2015; Henry et al., 2016; Voigt et al., 2017; Mulitza et al., 2017; Ng et al., 2018;

Waelbroeck et al., 2018; Hoffmann et al., 2019; Süfke et al., 2019) on sedimentary $^{231}Pa/^{230}Th$ records from the western Atlantic, it becomes clear that even for a relatively constant mode of AMOC (as e.g. for the late Holocene) sedimentary $^{231}Pa/^{230}Th$ varies widely as a function of core location. As a consequence, predicting the behavior of $^{231}Pa/^{230}Th$ from a distinct position within a certain AMOC regime is unfortunately less intuitive. Accordingly, the use of adequate model approaches is necessary in order to better interpret $^{231}Pa/^{230}Th$ records (Luo et al., 2010; Rempfer et al., 2017).

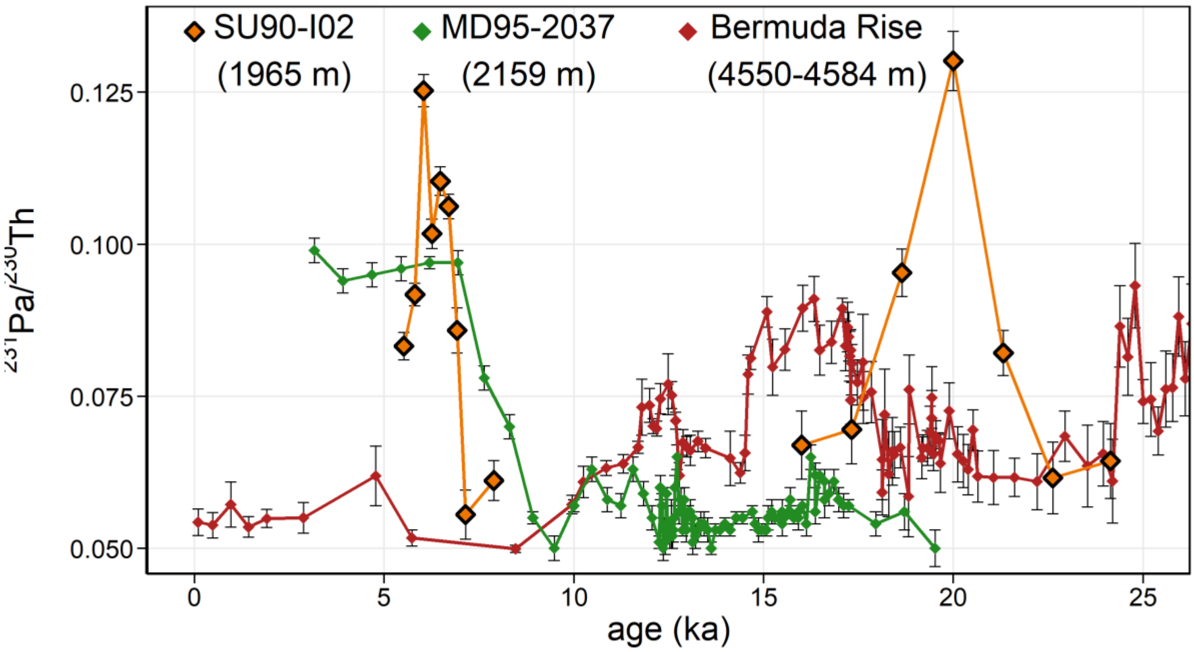

Fig. 6 $^{231}Pa/^{230}Th$ profiles of SU90-I02, MD95-2037 (Gherardi et al., 2009) and the Bermuda Rise (McManus et al., 2004; Lippold et al., 2009).

4.5. Modeled versus observed $^{231}Pa/^{230}Th$ at the mid-depth North Atlantic

There have been model approaches clearly pointing towards the importance of the core location on $^{231}Pa/^{230}Th$ (Siddall et al., 2007; Luo et al., 2010; Lippold et al., 2012; Rempfer et al., 2017; Van Hulten et al., 2018), but the observational $^{231}Pa/^{230}Th$ data hardly reaches the required coverage for unambiguous AMOC reconstructions.

With the Bern3D Earth System Model Rempfer et al. (2017) showed in transient experiments, in which the strength of the AMOC has been varied by changing freshwater forcing, a strong statistical anti-correlation between variations in AMOC strength and the particle-bound $^{231}Pa_p/^{230}Th_p$ in great depths in the Northwest Atlantic region (i.e. low AMOC produces high $^{231}Pa/^{230}Th$ and vice versa; Fig. 7). The authors improved the simulation of the protactinium and thorium cycle from older versions by taking additional sink processes into account (bottom scavenging; boundary scavenging; with/without particle redissolution at depth). They found the relationship between AMOC and $^{231}Pa/^{230}Th$ to be robust across these parametrizations, indicating that on larger spatial and temporal scales the relationship between $^{231}Pa/^{230}Th$ and AMOC is not fundamentally affected by uncertainties in the sink processes (e.g. bottom/boundary scavenging).

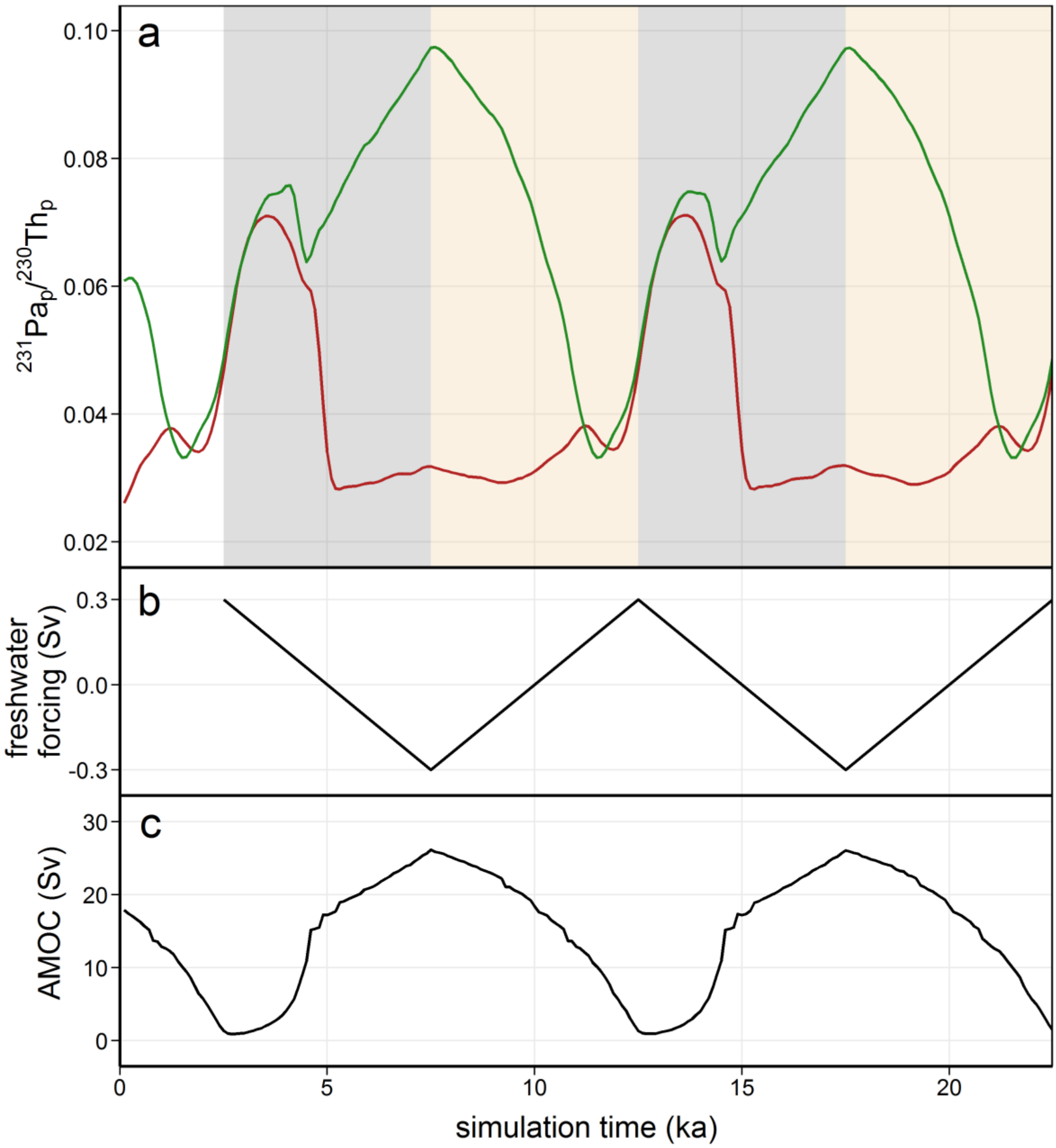

Fig. 7 (a) Bern3D model output of the $^{231}Pa/^{230}Th$ signal from simulation Re3d_Bd_Fw of Rempfer et al. (2017) for the grid cells closest to the core location of SU90-I02 (green) and for the deeper Bermuda Rise (red), which is also called Northwest Atlantic in Rempfer et al. (2017). (b) Amplitude of the North Atlantic freshwater forcing used by Rempfer et al. (2017), which causes the AMOC to fluctuate between 2 and 25 Sv. (c) The AMOC periodically fluctuates between practically no AMOC (2 Sv; e.g. at 2.5 ka) and a strong AMOC (25 Sv; e.g. at 7.5 ka) with a 10 kyr period. Gray bars indicate periods of increased AMOC strength (decreasing freshwater forcing), while light brown bars indicate decreasing AMOC (increasing freshwater forcing). The supplementary Fig. S4 indicates the used grid cells and shows the sign of $^{231}Pa/^{230}Th$ response to AMOC in different regions throughout the whole North Atlantic.

While the authors put emphasis on comparing the model outputs to the large observational data base available from the northwestern Atlantic (more specific the Bermuda Rise; McManus et al., 2004; Lippold et al., 2009; Henry et al., 2016), their model also reproduced observational features in other regions which have not yet received much attention. The figure 8a of Rempfer et al. (2017) shows a section plot of the North Atlantic (water depth versus latitude) indicating the correlation between AMOC strength and $^{231}Pa_p/^{230}Th_p$. For the northwestern Atlantic up to ~40°N and below ~2500 m water depth the negative model correlation corresponds to the classical picture as found in the Bermuda Rise sediment cores. Interestingly, for the region north of ~40°N and above ~2500 m water depth this correlation becomes inverted (strong AMOC causes higher $^{231}Pa/^{230}Th$). In this way, the modelling study of Rempfer et al. (2017) already predicted that sediment cores north of ~40°N should show a pattern of $^{231}Pa/^{230}Th$ vs. AMOC opposite to the expected, just as the results present in this study for core SU90-I02. For this study the model output of simulation Re3d_Bd_Fw of Rempfer et al. (2017) was revisited (see their Table A2 for parameters) without running new simulations. Thus, the AMOC fluctuations in our Figure 7c are equal to these presented in Rempfer et al. (2017) in their Figure 7a. The location of SU90-I02 indeed reveals a pattern highly sensitive on AMOC strength but asynchronous to the Bermuda Rise (Fig. 7). The main reason for this inverted behavior is grounded by the prevailing effect of import of ^{231}Pa over ^{230}Th from the upstream deep water formation zones as seen from the increase of $^{231}Pa_p$ with virtually unchanged $^{230}Th_p$ levels (Rempfer et al., 2017). Subsequently, further downstream and with increasing depth the ^{231}Pa deficit takes control due to meridional advection.

Furthermore, the model predicts a different response time of $^{231}Pa/^{230}Th$ variations in the deep (Bermuda Rise) and mid-depth Atlantic (e.g. SU90-I02) during increasing AMOC strength. After 2.5 ka of decreasing freshwater forcing (after 5 ka of simulation time in Fig. 7) $^{231}Pa/^{230}Th$ in the deep Atlantic reacts by a sharp decline from higher to lower values quickly reaching lowest levels which stays constant even during ongoing freshwater forcing. In contrast, after transient concordant behavior the mid-depth Atlantic shows a gradual increase in $^{231}Pa/^{230}Th$ after 2.5 ka of decreasing freshwater forcing with overall highest values at the lowest point of freshwater forcing and therefore strongest AMOC. This time lag between circulation change and $^{231}Pa/^{230}Th$ response at the mid-depth Atlantic compared to the deep Atlantic is reflected by the patterns seen in SU90-I02 and MD95-2037. Both cores show low $^{231}Pa/^{230}Th$ values during the early Holocene while the deep Atlantic already shows low $^{231}Pa/^{230}Th$ values (Fig. 6) indicating a strong circulation (the mid-depth cores are supposed to show high values during a strong AMOC, Fig. S5). The time lag between decreasing $^{231}Pa/^{230}Th$ values in the deep Atlantic and increasing values in the mid-depth Atlantic is in the order of 2-4 ka (Fig. 6) which is similar to the model findings (Fig. 7). Therefore, the model findings do not only predicts the general direction of $^{231}Pa/^{230}Th$ change under variations in AMOC strength at a given position in the West Atlantic Overturning cell but also the relative timing.

Conclusions

Sedimentary analyses of the mid-depth North Atlantic core SU90-I02 result in a classical picture of IRD dominated sediments for Heinrich Stadials 1 and 2. Changes in sedimentology corresponding to the climatic periods of Heinrich Stadial 1 and 2, the LGM and the Holocene are clearly resolvable. The new established $^{231}Pa/^{230}Th$ down core profile from SU90-I02 reveals $^{231}Pa/^{230}Th$ values higher than the production ratio during periods of strong AMOC, such as the Holocene. The effect of the particle flux and enhanced scavenging of protactinium is found minor during these periods. Hence, the sedimentary $^{231}Pa/^{230}Th$ of this core at 45°N shows an opposite behavior compared to deep Atlantic sites (e.g. the Bermuda Rise) with values clearly below the production ratio during cold phases, like Heinrich Stadials 1 and 2. However, findings from the Bern3D model (e.g. Rempfer et al., 2017) confirm such an oppositional behavior in $^{231}Pa/^{230}Th$ between the deep northwestern and the mid-depth northern Atlantic north of 40°N. This model predicts that $^{231}Pa/^{230}Th$ from mid-depth sites north of 40°N correlate positively with the AMOC strength. This study adds a further downcore profile to the still sparse Atlantic $^{231}Pa/^{230}Th$ data-base and highlights the importance of considering the core position for interpretations of $^{231}Pa/^{230}Th$ ratios, even inside the same overturning cell. By combining spatially distributed, well dated and synchronized $^{231}Pa/^{230}Th$ records in the Atlantic Ocean much tighter constraints can be placed on changes in deep ocean circulation pathways and water mass distributions.

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