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Interactive comment on "A major change in North Atlantic deep water circulation during the Early Pleistocene transition 1.6 million years ago" *by* N. Khélifi and M. Frank

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Dear Dr. Dutton,

We have carefully considered the reviewers remarks and all suggestions were incorporated into our revised manuscript. We thank the reviewers for their efforts and constructive comments which were indeed very helpful to improve the quality of our manuscript. Below you will find our point-by-point answers to their comments copied into this letter.

1. Response to comments of Referee #1

– Issue #1 (. . .A more interesting question, of course, is how this change in circulation

impacts or is impacted by climate and I think the authors could do a better job of setting up that point and making the connections between circulation and climate.):

We now improved this issue by including more complete information on long-term paleoceanographic changes and their impact and link with global climate throughout the Plio-Pleistocene global cooling (e.g. the onset of major Northern Hemisphere glaciation, early and mid-Pleistocene climate transitions). The discussion of these relationships and their wider implications has significantly improved the new version of our manuscript as we carefully detail below in this letter.

– Issue #2 (. . .the main point of the paper is that changes in the climate system. . .led to changes in circulation. . .speculate in the conclusions that the resulting change in circulation may have set up the Late Pleistocene Transition, but other than timing I missed the argument for that connection.):

We thank Ref. #1 for his valuable point regarding the circulation change we observe in the Northeast Atlantic after 1.4 Ma and its contribution to more pronounced Late Quaternary style cycles of glacial/interglacial climates. We now rewrote our conclusions as follows:

"Based on bottom-water radiogenic neodymium isotope (εNd) variability our study suggests a major reorganization of deep circulation in the Northeast Atlantic after 1.6 Ma. The overflow of deep waters from the Nordic Seas significantly decreased, which had implications for the evolution of overturning in the North Atlantic. We argue that the surface water changes in the Arctic and sub-Arctic source areas (e.g. increased sea-ice expansion and enhanced surface water stratification) most likely ultimately triggered the reorganization of North Atlantic deep water circulation towards a more stratified water column and more distinct water masses after 1.4 Ma, which occurred distinctly before the mid-Pleistocene transition and the onset of more pronounced Late Quaternary style cycles of glacial/interglacial climates that still prevail today. This major circulation change in the middle deep Atlantic at $\sim$1.6 Ma may have affected the deep ventilation rates and thus altered the ocean carbon storage. Further evidence documenting past changes in pCO2 and ice sheet dynamics are required to better understand the exact cause and implications of this important transition at ∼1.6–1.4 Ma.".

– Issue #3 (. . .The manuscript would be significantly improved by a clearer statement in both the abstract and introduction about why they undertook this study over this time interval in this area. Clearly they were targeting something more specific than the global link between climate and circulation.):

We now define more clearly the goals for undertaking our study near the region of the Nordic Seas overflow over the Plio-Pleistocene global cooling in the introduction and rewrote the Abstract as follows:

"The global ocean-climate system has been highly sensitive to the formation and advection of deep overflow water from the Nordic Seas as integral part of the Atlantic meridional overturning circulation (AMOC) but its evolution over the Pliocene-Pleistocene global cooling is not fully understood. In particular, changes in the sources and mixing of prevailing deep waters that were involved in driving overturning throughout the Plio-Pleistocene climate transitions are not well constrained. Here we investigate the evolution of a substantial deep southward return overflow of the AMOC over the last 4 million years. We present new records of the bottom-water radiogenic neodymium isotope (εNd) variability obtained from three sediment cores (ODP sites 980/981 and 900, DSDP Site 610) at water depths between 2,100 and 5,000 m in the Northeast Atlantic. We find that prior to the onset of major Northern Hemisphere Glaciation (NHG) ∼3 million years ago (Ma) εNd values primarily oscillated between –9 and –11 at all sites, consistent with enhanced vertical mixing and weak stratification of the water masses during the warmer-than-today Pliocene period. From 2.7 Ma to ∼2.0 Ma the εNd signatures of the water masses gradually became more distinct and documents a significant advection of Nordic Seas overflow deep water coincident with the intensification of NHG. Most markedly, however, at ∼1.6 Ma the εNd signatures at all sites synchronously shifted to about 3εNd units to less radiogenic values at different

water depths. Since then the difference between glacial and interglacial εNd values has been similar to the Late Quaternary at each site. This major εNd change at 1.6 Ma reflects a significant reorganization of the overturning circulation in the Northeast Atlantic paving the way for the more stratified water column with distinct water masses prevailing thereafter.".

– Issue #4 (. . .Part of my dissatisfaction with the very general climate-circulation set up is that the introduction never specifically explains what the goals of the project were. . .I had never heard the phrase "Early Pleistocene Transition" before and assumed I'd find out what it is, why it is important and what is known about it and what are the outstanding issues in the introduction. . .I had to work fairly hard to understand the major contribution is of this work and its relevance because they never laid it out specifically in the paper. A stronger Introduction would resolve that problem.):

To follow the suggestion of Ref. #1 we now deleted the slightly confusing term "Early Pleistocene Transition" – A terminology previously used by some colleagues to specify the timing of major transition in climate system dynamics at 1.4 Ma (e.g. Lisiecki and Raymo, Quaternary Science Reviews 2007). We changed the title as follows: "A major change in North Atlantic deep water circulation 1.6 million years ago". Moreover, we now significantly refocused the introduction and included more useful information related to the scope of our study as follows:

"The reconstruction of past changes in ocean circulation enables the assessment of the role of the ocean in the develÂňopment of the global climate system. In particular, changes in the cold, dense overflow from the Greenland-Iceland-Norwegian (GIN) Seas into the deep North Atlantic and the compensating northward flow of warm, saline surface waters as part of the Gulf Stream/North Atlantic Current (NAC) system forming the Atlantic meridional overturning circulation (AMOC) and the global thermohaline circulation have had a significant impact on regional and global climate. It is therefore crucial to constrain past changes of this conveyor belt system and to evaluate its role in North Atlantic and global circulation and climate, especially over the Plio-

Pleistocene global cooling, during which the modern feedbacks and mechanisms driving the global climate system developed. In fact, the long-term climatic cooling during the Plio-Pleistocene climate transitions and increased glacial/interglacial cyclicity are suggestive of important changes in the global climate system (e.g. Lisiecki and Raymo, 2007). It has been reported that changes in ocean circulation, in particular in the northern North Atlantic near the sites of deepwater formation have played an important role in these global climate changes (e.g. Raymo et al., 1998; Ravelo et al., 2004; Hodell and Venz-Curtis, 2006; Sarnthein et al., 2009; Etourneau et al., 2010; Lawrence et al., 2010, 2013; Lisiecki, 2014).

It is the aim of this study to reconstruct the distribution and mixing of water masses in the northern Northeast Atlantic in an attempt to reconstruct the evolution of the deep return overflow limb of the AMOC during the Plio-Pleistocene climate transitions. In particular, we aim to investigate when and how the transition to the more pronounced 100 kyr Late Quaternary style cyclicity of glacial/interglacial climates and closely linked deep ocean circulation occurred, which still prevails today. To reach this goal we focus on a region near the deep water convection sites of the GIN Seas due its sensitivity and capability of propagating climate signals regionally and around the globe throughout the ocean and atmosphere system (e.g. Imbrie et al., 1993; Ganopolski and Rahmstorf, 2001).

We trace changes of deep-water formation and of the distribution and mixing of water masses in the deep Northeast Atlantic using the radiogenic neodymium (Nd) isotope composition of past bottom waters extracted from the authigenic ferromanganese (Fe-Mn) coatings of deep sea sediment particles and of foraminiferal shells at three DSDP/ODP core sites near the GIN Seas overflow over the last 4 million years. In their source areas water masses are imprinted with the Nd isotope signature of the rocks of the adjacent landmasses through weathering processes. The Nd isotope signatures are expressed as εNd values corresponding to the deviation of the measured 143Nd/144Nd ratio of a sample from that of the chondritic uniform reservoir (CHUR

= 0.512638), multiplied by 10,000 (Jacobsen and Wasserburg, 1980). Old continental rocks contribute much lower εNd values than younger mantle-derived material (e.g. Goldstein and O'Nions, 1981). Given that Nd has an average global oceanic residence time of $\sim$400–700 yr (Rempfer et al., 2011) and differences in εNd between water masses are large enough to be detectable (cf. Frank, 2002), Nd isotopes have been used as a quasi-conservative tracer to infer changes in past deep-water sources and their mixing within the North Atlantic basin on different time scales (e.g. O'Nions et al., 1998; Burton et al., 1999; Roberts et al., 2010; Crocket et al., 2011; Piotrowski et al., 2012).".

– Issue #5 (. . .the evidence that specific positive excursions in the Site 980 record correlate to specific glacial events was a bit tenuous. . .Do they really have an age model for Site 980 that is robust enough to support those correlations? Is there anything that is actually unique about the intervals they refer to as "key glacials" in the figure caption? Some do stand out as more dramatic events, but several of them (G20, 70, 58) do not. Why did these glacials produce especially strong overflow of Nordic waters and why does that overflow appear to last longer than the glacial interval?):

As we mentioned on page 6499 (line 25) of our initial manuscript we used the well-established isotope stratigraphy for Site 980/981 of Raymo et al. (2004) and Lisiecki and Raymo (2005). We also carefully correlated the benthic δ18O isotope record of Site 980/981 to the stacked benthic δ18O (ice volume) LR04 record of Lisiecki and Raymo (2005). Our test did not reveal marked differences from the original age model published by these authors. Accordingly, the specific positive εNd excursions at Site 980/981 do indeed correspond to distinct glacial stages as now clearly displayed in new Fig. 5 of our revised manuscript (see the Supplement to this letter).

We now omitted the wording "key glacials" in the figure caption. Moreover, based on our new Fig. 5 we revised our general statement on strong overflow in the Nordic Seas during glacial intervals since indeed some interglacials (e.g. MIS KM6, 99, 71) also show positive εNd excursions. Instead we now focus on our major finding of glacial and interglacial εNd values oscillating around –9/–10 prior to 1.6 Ma. Subsequently, we now demonstrate that the significant negative εNd shift indeed occurred both during glacial and interglacial intervals (see new Fig. 5 in the Supplement).

– Issue #6 (...I didn't follow why the changes in obliquity would lead to reduced overflow...unless there was significant sea ice development, why would cooling reduce overturning and overflow? ...cooling in the Southern Ocean would be expected to produce more southern sources waters. Why isn't the same true for northern sourced waters?):

We now removed our speculation on a reduction of the overflow from the Nordic Seas as a response to an increase in the amplitudes of the 41-kyr obliquity cycle (also following the advice of Ref. #2). As we mentioned in the text on page 6502 (line 15) new findings by Martínez-Garcia et al. (2010) show that indeed over the 1.8–1.4 Ma transition the sub-Arctic region underwent a substantial cooling directly associated with sea-ice expansion during glacial and interglacial climate stages. In agreement with the statement of Ref. #1 the significant sea ice development and the increased advection of polar waters led to a major weakening of deep-water production at the Nordic Seas convection centres and consequently of Nordic Seas overflow during both glacial and interglacial intervals, as can now better be followed in our new Fig. 5 (see the Supplement). This was mainly a consequence of surface stratification near the Nordic Seas convection centres (as we mentioned in page 6502, line 23). In line 27 of the same page we suggested that a reduction in the formation of deep water in the North Atlantic would be expected to result in the advection of southern source waters following the well established idea of diminished NADW influence and enhanced AABW inflow in the deep Atlantic basin during glacial times of the Late Quaternary (e.g. Duplessy et al., Paleoceanography 3, 1988; Sarnthein et al., Paleoceanography 9, 1994; Marchitto et al., Paleoceanography 17, 2002). We now also cite these references in our discussion.

– Issue #7 (...the correlation between Nd isotopes from different sites...and between foram and bulk sediment leaches is convincing evidence that the data are recording

seawater. Therefore it was surprising to see that they were using Sr isotopes to make that argument...Sr isotopes are not a particularly good test for preservation of the seawater signal...the data in the supplement don't hurt their argument, but I don't think the Sr argument is a particularly useful argument for a seawater signal.):

We agree with Ref. #1 that the Sr isotopes do unfortunately not provide an unambiguous proof of the seawater origin of the Nd isotope signal and in the text deleted our respective argument using Sr isotopes. However, we decided to keep the Sr isotope data in Supplementary Table 1 given that these data still at least support a seawater origin of the Nd isotopes.

– Issue #8 (minor comments):

With thanks to the reviewer we incorporated almost all suggestions for minor changes into our text as follows:

- P. 6500, line 8: The Holocene signature at Site 610 is now clearly described as follows "The late Holocene εNd signature at Site 610 which was also extracted from ferromanganese coatings of bulk sediments is -11.5 ± 0.2. This value is within error identical...".

- P. 6500, line 26: We clarified our slightly confusing text on the origin of the more radiogenic values of near modern samples at Site 900 by writing "This suggests that the more radiogenic εNd signature extracted from the bulk surface sediment Fe–Mn coatings at Site 900, most likely due to loss of the Holocene sediment section during drilling...".

- P. 6501, line 15: We now omitted describing the $\sim3\varepsilon$Nd shifts after 1.4 Ma as "glacial/interglacial" oscillations and now simply write "This major εNd shift was followed by pronounced oscillations of up to $\sim3\varepsilon$Nd units between glacial and interglacial climate states at both sites...".

- P. 6501, line 21: Following the very useful constructive suggestion of Ref. #1 our statement on the general similarity of the εNd records at Sites 610 and 980 has now been extended to include a short discussion on the origin and implications of the offset between those two records during the intensification of Northern Hemisphere Glaciation between ∼2.5 and 2.0 Ma as follows:

"Only after about 2.7 Ma (glacial MIS G6/G4) until 2.0/1.8 Ma the offset between the two εNd records at Sites 980/981 and 610 significantly increased to reach on average 1.5 to 2εNd units difference during a time interval when the stacked benthic δ18O (ice volume) LR04 record started to oscillate for the first time above the present interglacial level (Fig. 3; Lisiecki and Raymo, 2005). This significant offset in εNd signatures was mainly a consequence of the shift towards more radiogenic εNd values at Site 980/981. This shift points to enhanced advection of more radiogenic deep overflow from the Nordic Seas after 2.7 Ma, closely associated with the onset of major NHG (Shackleton et al., 1984). This close association is in agreement with previous findings on strengthened deepwater convection in the Nordic Seas accompanying the intensification of NHG (summarized in Sarnthein et al., 2009). Accordingly, the εNd difference after 2.7 Ma documents an enhanced North Atlantic deep overturning. These results complement the available deep ocean δ13C data which did not clearly show a major change of NADW ventilation with the intensification of NHG ∼2.7 Ma (e.g. Raymo et al., 1992; Haug and Tiedemann, 1998). We propose that the increase in the formation of newly ventilated and nutrient-depleted Nordic Seas deep waters may have helped to maintain an enhanced ventilation of the Atlantic Ocean and in turn a strong biological pump in the global ocean (e.g., Sigman et al., 2010). This was crucial notably during a time of major reduction in Antarctic-sourced ventilation of the deep ocean over the ∼2.7 Ma transition (Hodell and Venz-Curtis, 2006). The enhanced global ocean biological pump may have increased the quantity of carbon dioxide (CO2) sequestered in the abyssal basins and thus overprinted the apparently absent ventilation signature in the Atlantic δ13C data. This is fully consistent with the relatively rapid decline in atmospheric CO2 that was observed during the severe deterioration of global climate over the intensification of the NHG (Seki et al., 2010).".

- P. 6501, line 27: We now describe the ∼2εNd unit shift from 1.65–1.35 Ma at Site 900 as follows "At the deepest Site 900, the εNd values display a similar but stepwise decrease of about ∼2εNd units from 1.65 to 1.35 Ma…".

- P. 6502, line 23: We now specify which bottom water is referred to as follows "Assuming that the bottom water signature at Sites 610 and 980/981 was derived primarily…".

- P. 6503, line 20: We deleted the sentence starting with "In contrast" and the speculation about obliquity forcing on the observed circulation change following Ref. #2. We also deleted the preceding possibly confusing sentence starting with "Accordingly, it seems unlikely…". We then carefully rephrased the complete paragraph starting at line 15 on the same page (please also see our response to Ref. #2 below).

- P. 6504, line 7: Here we prefer to stick to our sentence because a "diminished admixture of Nordic waters" may confuse the reader with the Nordic Seas (overflow) waters, which have a more radiogenic Nd isotope signature and given that the trend we observe after 1.35 Ma at Site 900 is towards more positive εNd values.

– Issue #9 (…the authors…need to set up the problem clearly and concisely in the introduction and make sure that the abstract and conclusions then focus on the issues presented in the introduction…they need to highlight why we want to understand circulation specifically at this time in this place rather than in vague, general terms. Several of the other points of confusion are probably a matter if rephrasing to make it a concept clearer and more accurate.):

As mentioned above we carefully considered these important suggestions and included them in the revised manuscript. We thank Ref. #1 for his constructive review.

2. Response to comments of Referee #2 (D. Hodell)

– Issue #1 (…Although the shift in εNd in the North Atlantic at 1.6-1.5 Ma is an important observation that merits publication, the discussion of the cause of the event and especially the comparison to benthic δ13C records are misleading. In the body of the manuscript the authors are careful to note that the shift in εNd occurred primarily during INTERGLACIAL intervals. Indeed, this is clear in Figure 4 as there is no change in εNd for the glacial periods. This is a vital piece of evidence that governs the interpretation and comparison of the Nd results with other proxy records, yet it is absent from the abstract and title of the paper.):

With thanks to Ref. #2 we now rectified our statement and included new Fig. 5 which shows more clearly that the major εNd shift occurred indeed during both interglacial (MIS 71–49) and glacial (MIS 56–48/44) intervals. Moreover, we now take care to properly interpret this change in comparison to other published records in our revised discussion (e.g. Raymo et al., 2004).

– Issue #2 (The discussion is confusing because the authors have conflated two events at 1.5 Ma, which may have had different causes; i.e., the INTERGLACIAL shift in εNd demonstrated in this paper and the primarily GLACIAL shift in benthic δ13C values observed in deep Atlantic and Southern Ocean carbon isotope records. The paper implies the two were related but they are occurring in fundamentally different climate states. To explain the Nd results, a discussion focused on deep-water processes during INTERGLACIAS would be more appropriate than comparison to circulation changes associated with dominantly GLACIAL periods (e.g., see Raymo et al. 2004. . .for a discussion of interglacials.):

We thank Ref. #2 for his valuable point on the glacial shift in benthic δ13C values observed in deep Atlantic and Southern Ocean carbon isotope records. As mentioned we now devote a more careful investigation in our discussion section to deep water changes during both glacials and interglacials (based on new Fig. 5, see the Supplement). We now directly compare our mid-depth negative εNd shift throughout the glacial/interglacial transitions at 1.8/1.6–1.4 Ma to the pronounced North Atlantic mid-depth low-δ13C water mass signatures, which also clearly comprise both the glacial and interglacial climate states at $\sim$1.8–1.2 Ma (please see Figs. 4 and 5 in Raymo et al., 2004). These findings are indeed in agreement with the reduced Nordic Seas

overflow we observe in our εNd records.

– Issue #3a (The resolution of the Nd records in the three sites is very low and likely don't fully capture the full range of glacial-to-interglacial values. I would therefore advise caution when stating that the "glacial/interglacial" amplitude of the Nd signal increased after 1.5 Ma.):

As mentioned in our response to Ref. #1 regarding Issue #8 (minor comments) we followed recommendations of Ref. #2 and avoided the statement of an increase in the "glacial/interglacial" amplitude of the Nd signal after 1.5 Ma. We rather prefer to add to the text that in view of the low resolution of our data we cannot be sure that the amplitude between glacial and interglacial εNd values represents the full glacial/interglacial range.

– Issue #3b (. . .How were the samples chosen (based on O18)? Do they come for peak glacial and interglacial periods? If so, which ones? For example, Raymo et al. (2004) showed that extreme interglaciations of the late Pleistocene (including the Holocene) had anomalous δ13C profiles, albeit their shift occurs at $\sim$0.6 Ma rather than 1.5 Ma.):

As mentioned in our response to Ref. #1 (issue #5) we now plot a new Fig. 5 which shows more clearly that we chose the samples based on peak glacial and interglacial marine isotope stages following Lisiecki and Raymo (2005). The εNd shift that we observe between MIS 71 and MIS 45 (new Fig. 5) actually occurred within the period of time of pronounced North Atlantic mid-depth low-δ13C from 1.8–1.2 (Figs. 4 and 5 in Raymo et al., 2004).

– Issue #4 (. . .The authors attribute their change in εNd at 1.5 Ma to an increase in the amplitude of the obliquity cycle but they don't have the time series needed to rigorously test this hypothesis. A recent paper by Lisiecki (2014. . .) reported cross-spectral analysis of benthic δ13C with obliquity and precession signals and concluded the phase between benthic δ13C and obliquity were the same before and after 1.6 Ma, whereas the phase with precession differs considerably after 1.6 Ma. They found 41-

kyr power in benthic δ13C peaks during a maximum obliquity forcing at 1.4 Ma but also at 0.8 Ma during a minimum in obliquity forcing. I think the speculation about obliquity forcing should be removed from the paper and the results of Lisiecki (2014) cited.):

We agree with Ref. #2 arguments and removed this speculation about obliquity forcing on the major change in deep water circulation in the Northeast Atlantic. Moreover we now included and discuss the new important study of Lisiecki (2014) that we had not initially included because it was not published when we submitted our manuscript. This new study indeed provides great support to our conclusions.

3. Response to comments of C. Zeeden and S. Kaboth

– Issue #1 (You refer to Laskar et al., 1993 (p. 6503, l.21), while Laskar et al. 2004 provide the most recent and most precise solution for obliquity (and precession) though differences are small.):

We just aimed to cite the first and original publication by these authors. We admit that we should have also cited their most recent precise solution for obliquity. However, after a careful check we now reconsidered our speculation about obliquity forcing on North Atlantic change in circulation and decide to remove this statement (see also our response to Issue #4 of Ref. #2).

– Issue #2 (You discuss an 'event near 1.65 Ma'. . .At 1.6 Ma, a long term (0.4 Ma) eccentricity minimum occurs with lowest precession amplitudes. . .Huybers (2007) suggested that at 1.6 Ma (and also 1.2 Ma) at least some δ18 O records 'skip' an obliquity cycle. This probably leads Meyers Hinnov (2010) to discuss a relatively high ratio of deterministic (vs. stochastic) energy at 1.6 Ma during a minimum in eccentricity. . .. . .Generally, because of the low precession amplitudes and the relatively strong obliquity component in the time interval from 1.50 Ma to 1.65 Ma, a relatively strong obliquity component in high latitudinal insolation is present in the insolation. . ...data according to Laskar et al. 2004. . .. . .At 1.68 Ma both eccentricity and obliquity amplitude are exceptionally low; at 1.45 Ma both eccentricity and obliq-

uity amplitude are relatively high. This combination may make a clear statement on the orbital cause of a climate change 'around this time' difficult.).

Please see our response to Issue #1 and also to Issue #6 of Ref. #1 and Issue #4 of Ref. #2.

– Issue #3 (When discussing a major climatic change at 1.6 Ma, it may also be worth including the discussion about a change in the marine carbon cycle at 1.6 Ma (Wang et al. 2010.)):

We now included a brief discussion on the reported change of marine carbon cycle near 1.6 Ma.

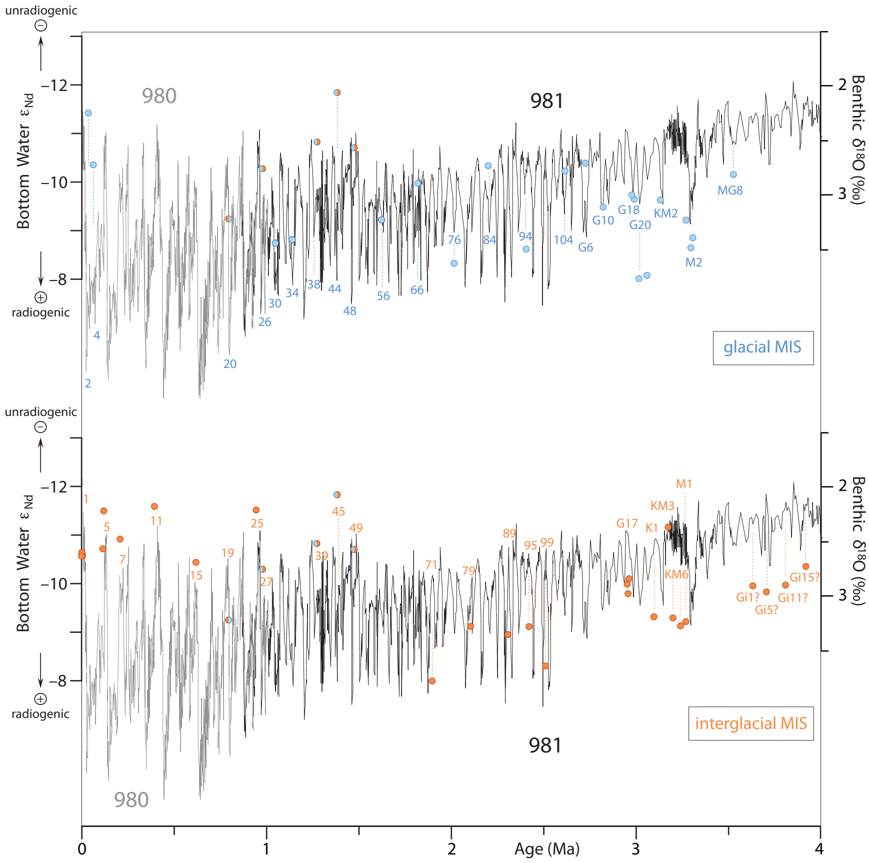
Finally we like to thank the reviewers for their efforts and valuable advice.

Sincerely,

N. Khélifi and M. Frank

Fig. 5. Comparison between changes in bottom water εNd signatures and benthic foraminiferal δ18O values at Site 980/981 for glacial (blue dots) and interglacial (red dots) marine isotope stages (MIS) during the last 4 million years (benthic δ18O data from Raymo et al., 2004; Lisiecki and Raymo, 2005 and references therein). Samples reflecting the transition from glacial to interglacial condition are shown in dots coloured in blue and red.

Interactive comment on Clim. Past Discuss., 9, 6495, 2013.



unradiogenic
radiogenic
Bottom Water ε_{Nd}
Benthic $\delta^{18}O$ (‰)
980
981
glacial MIS
interglacial MIS
Age (Ma)

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