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Subsurface North Atlantic warming as a trigger of rapid cooling events: evidences from the Early Pleistocene (MIS 31–19)

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Abstract

Subsurface water column dynamics in the subpolar North Atlantic were reconstructed in order to improve the understanding of the cause of abrupt IRD events during cold periods of the Early Pleistocene. We used Mg / Ca-based temperatures of deep-dwelling (*Neogloboquadrina pachyderma* sinistral) planktonic foraminifera and paired Mg / Ca-δ^{18}O measurements to estimate the subsurface temperatures and δ^{18}O of seawater at Site U1314. Carbon isotopes on benthic and planktonic foraminifera from the same site provide information about the ventilation and water column nutrient gradient. Mg / Ca-based temperatures and δ^{18}O of seawater suggest increased temperatures and salinities during ice-rafting, likely due to enhanced northward subsurface transport of subtropical waters during periods of AMOC reduction. Planktonic carbon isotopes support this suggestion, showing coincident increased subsurface ventilation during deposition of ice-rafted detritus (IRD). Warm waters accumulated at subsurface would result in basal warming and break-up of ice-shelves, leading to massive iceberg discharges in the North Atlantic. Release of heat and salt stored at subsurface would help to restart the AMOC. This mechanism is in agreement with modelling and proxy studies that observe a subsurface warming in the North Atlantic in response to AMOC slowdown during the MIS3.

1 Introduction

Rapid climate events in marine and continental sediments, as well as ice-core records are a pervasive feature during the Last Glacial period (Dansgaard et al., 1993; Heinrich, 1988). Millennial-scale oscillations are characterized by abrupt shifts between warm/cold conditions, associated to ice-sheet oscillations, as evidenced by major ice-rafting events recorded in the North Atlantic sediments (Grousset et al., 2001; Heinrich, 1988). The mechanism responsible for these fluctuations is not fully understood. Most accepted hypotheses relate rapid oscillations in the Atlantic Meridional Overturning Circulation (AMOC) to insulating effect of extensive ice-shelves and sea-ice and/or through freshwater perturbations causing changes in the dynamics of the North Atlantic subpolar gyre that controls the meridional heat and salinity transport (Ganopolski and Rahmstorf, 2001; Clark et al., 2001; Hátún et al., 2005; Li et al., 2005).

More recently, a number of studies and climate models have proposed that increased iceberg discharge during cold stadial events may have resulted from the destabilization of marine ice-shelves by a strong subsurface melting caused, in turn, by enhanced subsurface oceanic warming (Alvarez-Solas et al., 2010; Shaffer et al., 2004; Rasmussen and Thomsen, 2004; Liu et al., 2009; Marcott et al., 2011; Mignot et al., 2007; Moros et al., 2002; Peck et al., 2008; Jonkers et al., 2010b). This mechanism involves the coupling of the AMOC with ice-sheet dynamics, by an increase of the heat and salt export from low latitudes, warming of subsurface waters that would act as a positive feedback in the ice-shelf collapse. General agreement between model and proxy evidences support this explanation for abrupt climate events such as Heinrich and Dansgaard–Oeschger (D-O) cycles.

Application of Mg / Ca paleothermometry to deep-dwelling planktonic foraminiferal species constitutes a potential recorder of subsurface conditions (Kozdon et al., 2009; Simstich et al., 2003; Volkmann and Mensch, 2001) to test the feasibility of this hypothesis. Moreover, as foraminiferal δ^{18}O is controlled by temperature and δ^{18}O of seawater (δ^{18}O$_{sw}$), combining foraminiferal Mg / Ca temperature reconstructions with d^{18}O from the same species and samples allow to reconstruct δ^{18}O$_{sw}$ as a proxy for salinity (Schmidt et al., 2004). However, only few paleoceanographic studies using these proxies have been produced (Jonkers et al., 2010b; Peck et al., 2008, 2006). Therefore, more studies with a similar approach are still required to understand subsurface temperature and circulation changes linked to AMOC reorganizations, especially for time periods out of the MIS 3.

Although the paleo-community has extensively studied climate disruptions during most recent time scales, relatively little attention has been devoted to high-frequency climate variability in earlier periods when large Northern Hemisphere (NH) ice-sheets were same size as in the Late Pleistocene. Part of the gap of the study of these rapid climate oscillations in older time scales was due to the absence of high-quality/resolution paleoclimate records. However, during the last years, several studies carried out in International Ocean Drilling Project (IODP) cores have found robust evidences of abrupt climate events, (Bolton et al., 2010; Ferretti et al., 2010; Kleiven et al., 2011; Hernández-Almeida et al., 2012; Bartoli et al., 2006), with similar structure transitions between cold (stadial) and warm (interstadial) phases of the D-O cycles as those found during the Last Glacial period.

To further evaluate the relationship between subsurface ocean temperature and ice-sheet instabilities during the Early Pleistocene, we present here a new millennial-scale reconstruction of the temperature and $\delta^{18}O_{sw}$ of the subsurface Atlantic inflow using paired Mg / Ca and $\delta^{18}O$ measurements on the planktonic foraminifera *Neogloboquadrina pachyderma* sinistral (sin.) from IODP Site U1314. This is the first Mg / Ca temperature record produced in the subpolar North Atlantic for the Early Pleistocene. Previous paleo-sea surface temperatures (SST) records in the region are derived from planktonic foraminifera-based transfer functions (Hernández-Almeida et al., 2012) or alkenones (McClymont et al., 2008), but none of them give information about the thermocline conditions. The location of this core is at ideal latitude for monitoring changes in ice-sheet mass balance, and Mg / Ca values derived from *N. pachyderma* sin. allows to record changes in the subsurface temperatures (base of the thermocline, ~ 200 m depth) (Nürnberg, 1995) associated with oscillations in the AMOC. Our data suggest subsurface warming and salinity increases preceding and during the iceberg events, indicating clear evidence of coupling between basal melting and ice-sheet collapse as a mechanism controlling the millennial-scale events in the Early Pleistocene.

2 Study site and materials

Records were made using sediments from IODP Site U1314 (56.36° N, 27.88° W, 2820 m depth) from the southern Gardar Drift in the subpolar North Atlantic (Fig. 1a).

Sedimentation rates average 9.3 cm kyr^{-1} from 1069–779 ka, dated by tuning our benthic δ^{18}O curve to the benthic isotope stack of Lisiecki and Raymo (2005) (hereinafter referred to as LR04) by using AnalySeries 2.0 software (Paillard and Yiou, 1996) (See Hernández-almeida et al., 2012, for further details).

Site U1314 lies in the path of an extension of the North Atlantic Current (NAC), the Irminger Current (IC), which splits from the NAC and turns toward the Greenland coast. The core of this relatively warm (3–8 °C) and salty (~ 35 ‰) water mass is distinguishable by its properties vertically down to 700 m depth. As the IC travels eastwards it mixes with the colder (≤ 0 °C) and fresher (< 34.4 ‰) waters of the East Greenland Current (EGC) (Krauss, 1986).

Although today the limit of winter sea-ice (Arctic Front) lies north of Site U1314, it is known to have migrated southward during glacials of the Pleistocene bringing much cooler waters and potentially also sea-ice south of 60° N. (Ruddiman, 1977). Today, modern hydrographic conditions at Site U1314 are characterized by seasonal water temperatures ranging between 11.7 and 7.7 °C at 10 m depth and 8–7.4 °C at 200 m (Locarnini et al., 2013) with nearly constant salinity of 35.1–35.2 practical salinity units (p.s.u.) (Antonov et al., 2006) (Fig. 1b).

Winter convection of the cooled Atlantic surface waters in the Nordic Seas results in the formation of North Atlantic Deep Water (NADW), which flows south-ward as the Iceland–Scotland Overflow Water (ISOW) (Fig. 1a). This water mass flows at Site U1314 depth (Bianchi and McCave, 2000).

Subsurface water column conditions were determined through Mg / Ca ratios and stable isotopes measured on deep dwelling planktonic foraminifera *N. pachyderma* sin. inhabits and calcifies its shelf in the subpolar North Atlantic at water depths below the thermocline, at ~ 200 m, (Kohfeld et al., 1996; Simstich et al., 2003; Nürnberg, 1995; Volkmann and Mensch, 2001). Therefore we assume that *N. pachyderma* sin. δ^{13}C provides information on the ventilation rates of the subsurface water mass at the thermocline (Hillaire-Marcel et al., 2011), while Mg / Ca measurements reflect water temperature changes and combined with δ^{18}O provides a record δ^{18}O of seawater (sw) of the subsurface ocean (Peck et al., 2006).

Around to 50–60 well-preserved tests of planktic foraminifera *N. pachyderma* sin. were (> 150 µm size fraction) analysed in 542 samples for Mg / Ca ratio following Pena et al. (2005) procedure which includes the reductive cleaning step. Dissolved samples were analysed a Perkin Elmer Elan 6000 Inductively Coupled Plasma Mass Spectrometer (ICP-MS) at the Scientific and Technological Centers of the University of Barcelona (CCiT-UB). External reproducibility for Mg / Ca ratio is estimated at 1.8 % (2σ) based in the analysis of high-purity gravimetrically prepared standard solution (1.629 mmol mol^{-1}) measured routinely every four samples. Elemental ratios of Mn/Ca and Al/Ca ratios were analysed in parallel as quality controls for clay and Mn-rich mineral content. The recorded low values (Mn/Ca < 0.5 mmol mol^{-1}; Al/Ca < 0.15 mmol mol^{-1}) indicate that the cleaning protocol satisfactorily removed most of the contaminant phases. Final Mg / Ca values were converted into temperatures values according to Elderfield and Ganssen (2000) equation.

Stable isotopes were carried out on planktonic foraminifera *N. pachyderma* sin. and on benthic foraminifera *Cibicidoides* spp. (mainly *Cibicidoides wuellerstorfi*) and *Melonis pompilioides* when former was absent. An adjustment factor (–0.11 ‰ for δ^{18}O and +0.6 ‰ for δ^{13}C) calculated from replicates along the core was then applied to the *M. pompilioides* isotope values to produce a uniform isotope data set (Hernández-Almeida et al., 2012). Analyses were carried out on a Finnigan MAT 252 mass spectrometer fitted with a CarboKiel-II carbonate preparation device at the CCiT from the University of Barcelona. Calibration to the Vienna Pee Dee Belemnite (VPDB) standard scale (Coplen, 1996) was made through the NBS-19 standard, and the analytical precision was better than 0.06 ‰ for δ^{18}O and 0.02 ‰ for δ^{13}C. (Hernández-Almeida et al., 2012, 2013b). Oxygen isotope values were then ice-volume corrected by scaling to the sea-level curve of LR04 using an LGM to late Holocene sea-level change of 120 m (Bintanja and van de Wal, 2008). Seawater δ^{18}O was calculated following Shackleton (1974) from paired Mg / Ca–δ^{18}O on *N. pachyderma* sin.

It has been widely demonstrated that planktonic species do not always precipitate calcite in equilibrium. Based on the δ^{18}O measurements on seawater and *N. pachyderma* sin. tests from the Icelandic continental shelf, Smith et al. (2005) observed a δ^{18}O disequilibrium offset of 0.25 ‰. Others authors have also observed a disequilibrium offset in the oxygen isotope composition of *N. pachyderma* sin. of ~ 0.6 ‰ associated with post-gametogenic processes and thermal stratification of the water column in the Nordic Seas (Nyland et al., 2006). However, Jonkers et al. (2010a) did not find any offset in sediment trap samples from the Irminger Sea. Taking into account that samples used in this study are very close to Site U1314, we did not apply any correction factor to our calculated $\delta^{18}O_{sw}$. Contradicting studies indicate that this issue is not well constrained, with a need for further studies. Due to the uncertainties in *N. pachyderma* sin. vital effect and low SST during the Mid-Pleistocene Transition that may overestimated the $\delta^{18}O_{sw}$ values, we suggest caution when interpreting in absolute terms.

3 Results

Mg / Ca ratio ranges between 0.7–1.25 mmol mol^{-1} and Mg / Ca derived paleotemperatures range between 1.9 and 12.3 °C (Fig. 2). The Mg / Ca and $\delta^{18}O_{sw}$ records show different patterns after and before MIS 25. From MIS 31 to MIS 25, the amplitude of the glacial-to-interglacial changes is low; temperatures and $\delta^{18}O_{sw}$ are stable, only punctuated by frequent millennial-scale oscillations, with temperature decreases of ~ 3 °C and $\delta^{18}O_{sw}$ increases up to 1 ‰. Since MIS 25, $\delta^{18}O_{sw}$ increased by ~ 0.5 ‰ and temperature by only 0.5 °C, with large changes at orbital-scale (between 5–9 °C) (Fig. 2). During this interval, there is also a pervasive suborbital variability, especially during glacial onset and during MIS 21. Ice-rafting episodes are characterised by relatively warm and saltier subsurface waters at the Gardar Drift. Rapid temperature and $\delta^{18}O_{sw}$ increases are observed before the IRD deposition, e.g. at 1060, 995, 924, 880 ka, or shortly after iceberg discharge the iceberg started (Fig. 3).

The most important feature of the difference between benthic and planktonic δ^{13}C ($\Delta\delta^{13}$C) are the abrupt decreases of ~ 1 ‰ during IRD events, when values are around 0 ‰. During warmer periods, $\Delta\delta^{13}$C ranges between +1–1.4 ‰ (Fig. 4).

4 Discussion

Paleotemperature estimates based on Mg / Ca of *N. pachyderma* sin. at Site U1314 indicate that many of the IRD events were characterised by an abrupt subsurface warming (Fig. 2). The magnitude of this warming is not always the same across the studied interval, ranging between 2.5–8 °C. The $\delta^{18}O_{sw}$ shows repeatedly higher values, indicating saltier waters during IRD deposition. Although these changes in temperature and salinity were simultaneous to the IRD events, in some cases (e.g. at 995 ka), subsurface waters started to warm up and to become saltier even before the ice-rafting. The positive excursions of the δ^{13}C signal from *N. pachyderma* sin. during these events were interpreted to indicate increasing subsurface ventilation in the North Atlantic (Hernández-Almeida et al., 2013b) (Fig. 2). Similar conditions of better ventilation at intermediate depths during IRD deposition are also evident from benthic δ^{13}C in Site 982 on the Rockall Plateau (Venz et al., 1999), which was suggested to be related to changes in the production of GNAIW (Fig. 2). Strong coupling between the Mg / Ca temperatures and $\delta^{18}O_{sw}$ fluctuations and subsurface circulation may reflect a change in the AMOC.

The accumulation of subsurface warming during ice-rafting events would correspond with a rapid development of the thermocline that stabilizes the water column and via intense basal melting and thinning of marine ice-shelves provokes a large-scale instability of the ice-sheets and retreat of the grounding line. With destruction of ice-shelves, ice streams may surge, leading to increased iceberg production. The ice-sheets located in regions with relatively mild conditions and high precipitation rates, such as Scandinavia and Iceland, are indeed very sensitive to millennial climate variability, and then exhibit a brief and rapid increase in iceberg flux during warmings (Marshall and

Koutnik, 2006). The difference between benthic and planktonic δ^{13}C ($\Delta\delta^{13}$C), used to indicate the nutrient gradient between subsurface and bottom water (Charles et al., 2010), gives additional information about the ventilation of subsurface and deep waters. The short-term periods of low $\Delta\delta^{13}$C values (~ 0 ‰) during IRD discharges suggest water column vertical mixing and formation of Glacial North Atlantic Intermediate Water (GNAIW) south of the Arctic Front.

After iceberg calving decreased, sudden release of heat accumulated at subsurface, broke the upper stratification and destabilized the water column (Mignot et al., 2007). Saltier and warmer water brought to the surface from below resulted in an intensified AMOC, characterized by deeper and stronger deep-water circulation (Schmidt et al., 2006; Liu et al., 2009). Onset of deep convection in the Nordic Seas and NADW production led to a shut-down of GNAIW production (Venz et al., 1999). The nutrient gradient profile shows rapid increases up to 1.4 ‰ reflecting the establishment of a strong nutricline between deep and intermediate waters (Fig. 4). The switch to deep convection and a strong AMOC overshooting caused a decrease in subsurface temperatures and $\delta^{18}O_{sw}$, suggesting the return toward a “normal water column” state.

We are still uncertain about the driving mechanism that enhanced northward transport of warm and salty subsurface waters during episodes of weak AMOC. We suggest that analogous mechanisms involving ice-shelf and sea-ice expansion in the NH that are invoked to explain D-O cycles during the Last Glacial period (Petersen et al., 2013), operated also during the Early Pleistocene. Growing ice-shelves in the subpolar North Atlantic during the onset of glaciations would change land surface albedos producing a reduction of air sea temperature (Broccoli and Manabe, 1987). This cooling would increase the extent and thickness of sea-ice, resulting in a higher insulation of the surface ocean (Li et al., 2005; Kaspi et al., 2004), causing convection shutdown in the high latitude North Atlantic. A weakened subpolar gyre circulation would supply less cold and fresh water to the Atlantic inflow, making it saltier (Thornalley et al., 2009; Hátún et al., 2005). Warm and salty waters accumulating at the subsurface would be eventually transported poleward, causing a temperature inversion and salt inflow in the North Atlantic (Shaffer et al., 2004). Alternatively, abrupt slowdown of the AMOC may respond to different mechanisms including internal oscillation regulated via atmospheric CO_2 concentration and Southern Ocean wind intensiffcations (Banderas et al., 2012; Alvarez-Solas et al., 2011).

Several modelling and paleoclimate studies also show intermediate or subsurface warming in the North Atlantic during IRD events as a response to AMOC reorganizations (Liu et al., 2009; Mignot et al., 2007; Brady and Otto-Bliesner, 2011), accompanied by a southward shift in the convection cell from the Nordic Seas to the subpolar North Atlantic (Brady and Otto-Bliesner, 2011; Venz et al., 1999; Voelker et al., 2010; Oppo and Lehman, 1993). This scenario characterized by a temperature inversion, would represent an analogous situation to modern conditions in Arctic Ocean. In this region, Atlantic waters flowing via the West Spitsbergen Current cause an Atlantic-derived temperature and salinity maximum at 200–500 m water depth, under the permanent sea-ice cover (Bauch et al., 1997).

Temperature sensitive proxies from other North Atlantic sites display similar features that are interpreted as subsurface warming conditions prior to ice-rafting events and deglaciations during the Last Glacial period and the Holocene. Risebrobakken et al. (2011) documented intensified subsurface warming in the Nordic Seas using planktonic foraminifera faunas as a response to a reduced strength of the AMOC through the deglaciation and the early Holocene. Mg / Ca derived temperatures from *N. pachyderma* sin. in two cores from the Northeast Atlantic also support the inferred warming during Heinrich events. These records show upper ocean stratification and high subsurface temperatures initiated during ice-rafting events (Jonkers et al., 2010b; Peck et al., 2008). Jonkers et al. (2010b) explained the low planktonic $\delta^{13}C$ values of *N. pachyderma* during these events as a result of reduced ventilation of subsurface waters due to the insulating effect of a meltwater lens and/or a sea-ice layer. Our high planktonic $\delta^{13}C$ values during these rapid cooling events, however, indicate that more intense subsurface ventilation and/or nutrient depleted subtropical waters were exported to the subpolar North Atlantic, which is supported by the similarity with the intermediate water δ^{13}C signal from Site 982 (Venz et al., 1999) (Fig. 2). We argue that such disagreement between planktonic δ^{13}C profiles could be explained by the southward shift of the Polar Front as far as 42° N during cold periods of the Late Pleistocene (Ruddiman and McIntyre, 1981a; Eynaud et al., 2009), limiting the fraction of nutrient depleted subtropical waters exported northward (Mix and Fairbanks, 1985) compared to the Early Pleistocene.

Similar warm conditions during Heinrich events and stadials are also evident from benthic faunas and Mg / Ca ratios in benthic foraminifera from the Nordic Seas, indicating that warming was probably extended to intermediate depths (below 1000 m) by downward diffusion of subtropical ocean heat during times of slow North Atlantic overturning (Rasmussen and Thomsen, 2004; Marcott et al., 2011). These results are in agreement with subsurface warming events at the subtropics during Heinrich 1 (Schmidt et al., 2012). All of these observations suggest that subsurface warming was a basin-wide phenomenon during periods of reduced AMOC in response to a reduction in the AMOC during MIS3. To better evaluate this scenario for the Early Pleistocene, more subsurface marine records situated in key regions from the North Atlantic are required. The proposed scenario is in agreement with modelling studies that reveal basal melting of the ice-shelf and periodic pulses of iceberg discharge as a response to strong reduction of the AMOC (Mignot et al., 2007; Shaffer et al., 2004; Alvarez-Solas et al., 2010; Manabe and Stouffer, 1997).

Finally, from the similarity of the paleoclimatic records with the model simulations and modern observations, we argue that observed increased subsurface ocean warming could play a leading role in the ice-sheet's increasingly negative mass imbalance over the next decades in the Arctic region, (Carmack et al., 1995; Grotefendt et al., 1998; Holland et al., 2008) and massive break-up of ice-shelves in the Antarctic Ocean (Vaughan and Doake, 1996; Rignot and Jacobs, 2002; MacAyeal et al., 2003).

5 Conclusions

The Mg / Ca derived paleotemperature and $\delta^{18}O_{sw}$ oscillations prior and during IRD discharges at Site U1314 across the Early Pleistocene (MIS 31–19) are related to changes in subsurface circulation. The mechanism operating during episodes of rapid-climate coolings consists in a reduction in the AMOC during periods of extensive ice-shelves and sea-ice in the subpolar North Atlantic. Enhanced poleward transport of warm and salty subsurface subtropical waters during these episodes would thin and destabilize ice-shelves creating pulses of ice-rafted debris. Deep water convection sites shifted south of the Polar Front and production of GNAIW would increase at expenses of NADW. Salt and heat accumulated at the subsurface would be suddenly released when the ice-sheet collapsed, resulting in an intensified AMOC. Analogous mechanisms based on subsurface warming as a trigger for millennial-scale climate variability were proposed for Heinrich events or D-O cycles recorded during Late Glacial period (Alvarez-Solas et al., 2010; Shaffer et al., 2004), reflecting that rapid switches of the AMOC also occurred before the establishment of the 100 kyr climate cycles of the Late Pleistocene.

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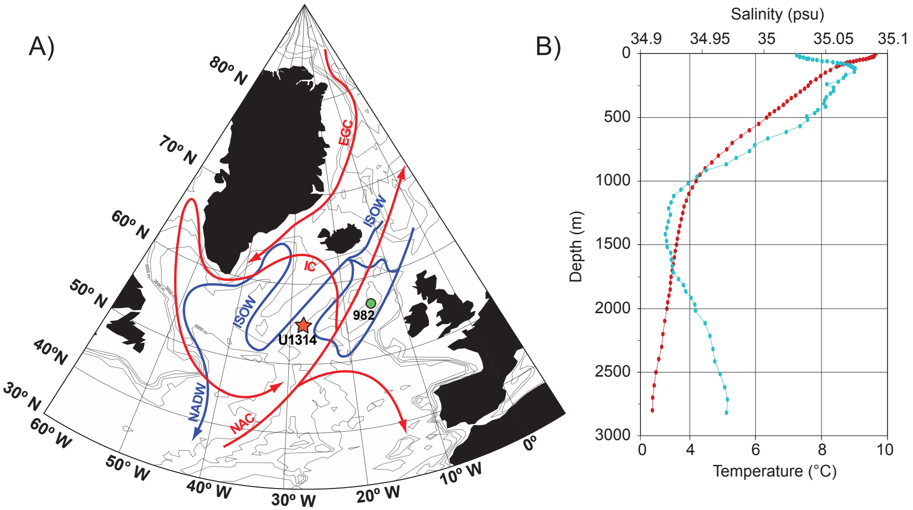

Figure 1. (a) Location of IODP Site U1314. Modern surface (red), and deep circulation (blue) in the North Atlantic: East Greenland Current (EGC), North Atlantic Current (NAC), Irminger Current (IC), Iceland Scotland Overflow Water (ISOW), North Atlantic Deep Water (NADW). **(b)** Plots of temperature (˚C) (red) and salinity (p.s.u.) (blue) vs. depth obtained from the World Ocean Atlas 2013 (Locarnini et al., 2013; Zweng et al., 2013). Map generated with Ocean Data View v.3.4.3. software (Schlitzer, 2008).

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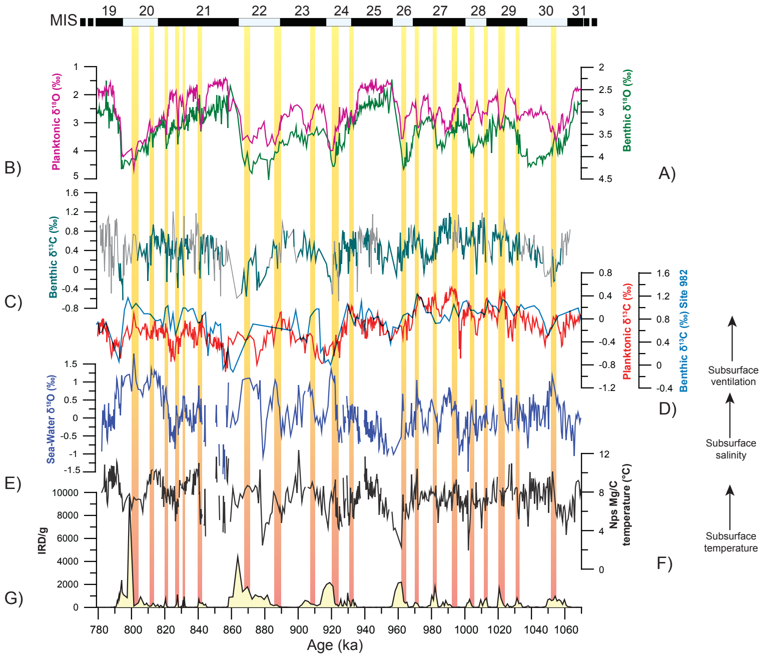

Figure 2. Data for IODP Site U1314 spanning marine isotope stages (MIS) 31–19 vs. age. From top to bottom: **(a)** benthic and **(b)** planktonic δ^{18}O (Hernández-Almeida et al., 2012); **(c)** benthic δ^{13}C **(d)** planktonic δ^{13}C (red) (Hernández-Almeida et al., 2013b) vs. benthic δ^{13}C from Site 982 (blue) (Venz et al., 1999); **(e)** $\delta^{18}O_{sw}$ reconstruction from paired Mg / Ca-δ^{18}O measurements on the planktonic foraminifera *Neogloboquadrina pachyderma* (sin.); **(f)** derived Mg / Ca-paleotemperature calculated using exponential temperature equation of Elderfield and Ganssen (2000); **(g)** IRD / g (Hernández-Almeida et al., 2012). Red vertical bars indicate IRD discharge associated with subsurface warming.

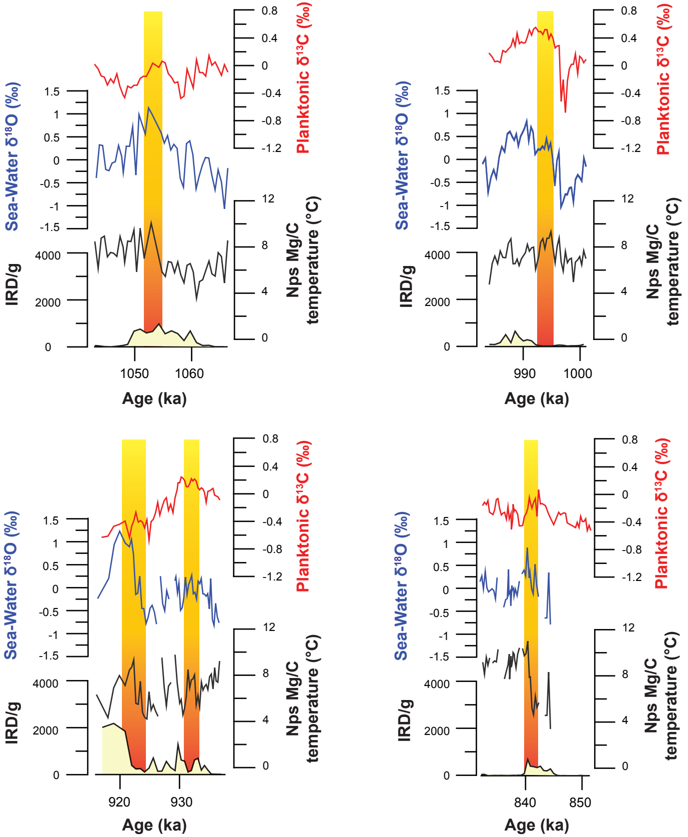

Figure 3. Comparison between Mg / Ca-paleotemperature, $\delta^{18}O_{sw}$, planktonic $\delta^{13}C$ and IRD / g for Site U1314 during specific intervals.

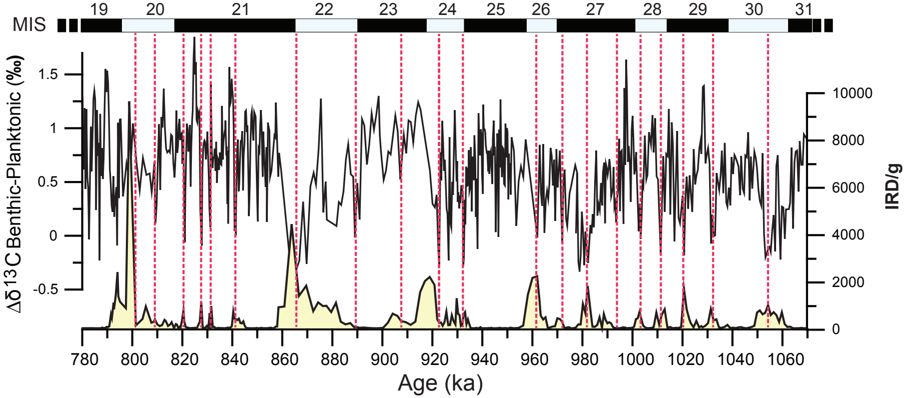

Figure 4. Data for IODP Site U1314 spanning marine isotope stages (MIS) 31–19 vs. age. **(a)** $\Delta\delta^{13}C_{b-p}$ (b-benthic, p-planktonic) (i.e. *C. wuellerstorfi*/*M. pompilioides*-*N. pachyderma* sin.); **(b)** IRD/g^{-1} (Hernández-Almeida et al., 2012).