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The closing of a seaway: ocean water masses and global climate change

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Abstract

The Late Neogene witnessed various major paleoceanographic changes that culminated in intense Northern Hemisphere Glaciation (NHG). The cause and effects of these changes are still debated. We use a multiproxy approach to determine the relative timing of the closure of the Panama gateway, changes in Atlantic circulation, global cooling and ice sheet growth. Benthic foraminiferal Mg/Ca records from a Pacific and an Atlantic Site have been produced and are interpreted in terms of bottom water temperatures. These Mg-temperature records are combined with published benthic $\delta^{13}C$, $\delta^{18}O$ and erosion records to reconstruct the flow of proto-North Atlantic Deep Water (proto-NADW) over the past 12 Ma. The results suggest that between 12.5 and 10.5 Ma, and again between about 8.5 and 6 Ma, a nutrient-depleted water mass that was colder (by 1–2°C) and fresher than the intervening deep water mass filled the Atlantic basin. This proto-NADW became warmer (by $\sim$1°C) and saltier between 6 and 5 Ma, coincident with the restriction of surface water flow through the Central American Seaway. The Mg-temperature records define a subsequent global cooling trend of $\sim$3.5°C between 5 Ma and today. Early NHG in the late Miocene was perhaps related to the formation of the relatively cold, fresh proto-NADW. The formation of the warmer and saltier proto-NADW in the early Pliocene may have initially limited Northern Hemisphere ice growth. However, the increased moisture released at high northern latitudes associated with formation of 'warm' proto-NADW, coupled with the global temperature decrease of deep (and hence polar surface) waters, likely helped initiate the intense NHG of the Plio–Pleistocene.

Keywords: North Atlantic Deep Water; benthic foraminifera; Mg/Ca; ocean gateway; Ocean Drilling Program

1. Introduction

Ocean circulation patterns affect global climate via the distribution of heat, moisture and CO_2. Today, the evaporative cooling associated with the formation of North Atlantic Deep Water (NADW) supplies heat and moisture to high northern latitudes, thereby affecting the stability of Northern Hemisphere ice sheets [1]. Traditionally, reconstructions of past deep water circulation are based on the carbon isotopic composition

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($\delta^{13}C$) of benthic foraminifera, which record inter-basin differences in $\delta^{13}C$. Site-to-site $\delta^{13}C$ gradients are related to ocean circulation patterns via nutrient distribution by water mass aging and/or mixing of different water masses. This method can be complicated by the fact that the carbon isotopic composition of deep waters is also affected by changes in the global carbon cycle, the total deep ocean nutrient inventory, and the overall rate of oceanic overturn. Using integrated bio-, magneto-, and isotope stratigraphies, these complications were minimized, showing that deep waters sourced from the North Atlantic probably formed during much of the late Miocene and probably during the latter part of the middle Miocene [2,3].

The key to understanding how deep waters formed and hence their effect on climate lies in reconstructing their relative densities. While carbon isotopes may point to source regions and circulation paths, it has not been possible to determine the physical properties (i.e. temperature and salinity) of proto-NADW using traditional paleoceanographic proxies such as the oxygen isotopic composition ($\delta^{18}O$) of benthic foraminiferal calcite. Although a robust and valuable proxy, the $\delta^{18}O$ of fossil calcite reflects both the temperature and $\delta^{18}O$ of seawater, so for example modern benthic foraminifera bathed in NADW have similar $\delta^{18}O$ to those bathed in Antarctic Bottom Water (AABW), despite the $\sim$2°C temperature difference between the two water masses. Mg/Ca-paleothermometry in benthic foraminifera is a relatively new tool that has been shown to have potential in providing salinity-independent estimates of past bottom water temperatures (BWTs) [4–7]. Here we use this tool to compare the physical properties of the water masses bathing an Atlantic and a Pacific site over the last 12 Myr. Our working hypothesis is that parallel variations in Mg/Ca reflect global temperature change whereas differences between the two sites reflect changes in ocean circulation. We link changes in the physical properties of NADW to the tectonic closure of the Panama Gateway and global climatic change.

2. Methods

2.1. Site selection and age models

Ocean Drilling Program (ODP) Site 806 (2500 m) on the Ontong Java Plateau (OJP) in the western equatorial Pacific was chosen to represent average global ocean temperatures. Conversely, ODP Site 926 (3500 m) on the Ceara Rise (CR) in the eastern equatorial Atlantic was chosen as a site that is today within the mixing zone between NADW and AABW, and therefore would be sensitive to changes in the flow of proto-NADW (Table 1). Samples were obtained from these two sites covering 0–12 Ma at a temporal resolution of roughly one sample per 0.2 Myr. An age model suitable for this low resolution was obtained for Site 806 using linear regressions between the depths of biostratigraphic events [8] and ages for these events that were compiled from the literature by the ODP Leg 199 Shipboard Scientific Party [9] (Fig. 1). An orbitally tuned timescale [10] was used for dating the 926 samples for the 4–11 Ma interval. The same method as used for Site 806 was used to date the 0–4 Ma interval of Site 926.

Table 1
Locations of sites (new and published data)

Site	Ocean region	Latitude	Longitude	Present water depth (m)
DSDP 289	Pacific	0°29.9′S	158°30.7′E	2206
DSDP 563	North Atlantic	33°38.5′N	43°46.0′W	3786
DSDP 608	North Atlantic	42°50.2′N	23°5.3′W	3526
ODP 806	Pacific	0°19.1′N	159°21.7′E	2521
ODP 926	Equatorial Atlantic	3°43.1′N	42°54.5′W	3598

2.2. Sample preparation and analysis

Sediments were disaggregated by shaking for 48 h in de-ionized water and wet-sieved through 60 µm mesh. Samples were dry-sieved to obtain around 10–15 benthic foraminifera from the 250–355 µm size fraction. Occasionally, and where necessary, foraminifera were picked from the > 355 µm size fraction to increase sample size. The same species (*Cibicidoides wuellerstorfi*, *Cibicidoides mundulus* (= *C. kullenbergi*), and *Oridorsalis umbonatus*) were picked from each site. Foraminiferal tests were cleaned using a protocol to remove clays, organic matter, metal oxides [11], although about half of the CR samples were cleaned without the reducing step that removes metal oxides, and with only one weak acid leach as opposed to four separate leaches (Fig. 2). After cleaning, the foraminifera were gradually dissolved in trace metal clean 0.065 N HNO_3 (Seastar, Vancouver, BC, Canada) and 100 µl of this solution was diluted with 300 µl trace metal clean 0.5 N HNO_3 to obtain a Ca concentration of 3 ± 1 mmol l^{-1}. Measured Mg/Ca varies slightly with Ca concentration of the solution and this matrix effect was corrected for as described in [12]. These samples were analyzed for Mg/Ca, Sr/Ca and Mn/Ca by Finnigan MAT Element Sector Field inductively coupled plasma mass spectrometer (ICP–MS) operated in low resolution ($m/\Delta m$ = 300) following the method outlined in [13] and modified by [12]. Benthic foraminiferal Sr/Ca ratios are presented here to assess diagenetic alteration and are discussed in more detail in a separate publication [14]. In both sites, benthic foraminiferal Mn/Ca increases between the seafloor and about 10 m burial depth and subsequently decreases down-core. The shorter cleaning technique results in higher and more variable Mn/Ca, presumably reflecting the presence of Mn oxides. The Mn/Ca profiles bear no resemblance to those of Mg/Ca and Sr/Ca and in this case are not regarded as a useful indicator of compromised Mg/Ca data.

The long-term (several months) precision of a consistency standard with Mg/Ca of 1.10 mmol mol^{-1} was ±3.7% (r.s.d.), the precisions of consistency standards with Mg/Ca of 2.40 mmol mol^{-1} and 6.10 mmol mol^{-1} were ±1.5% and

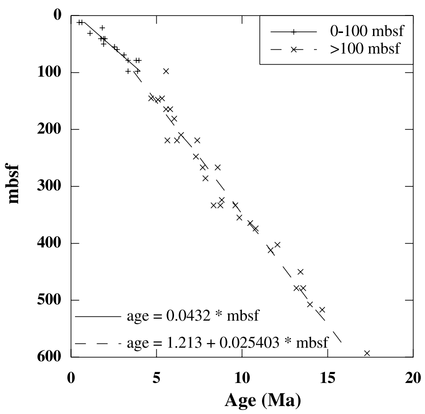

Fig. 1. Age model for ODP Site 806. Biostratigraphic events recorded by [8] are tied to assigned ages from literature compiled by the ODP Leg 199 Shipboard Scientific Party [9] (mbsf = meters below seafloor).

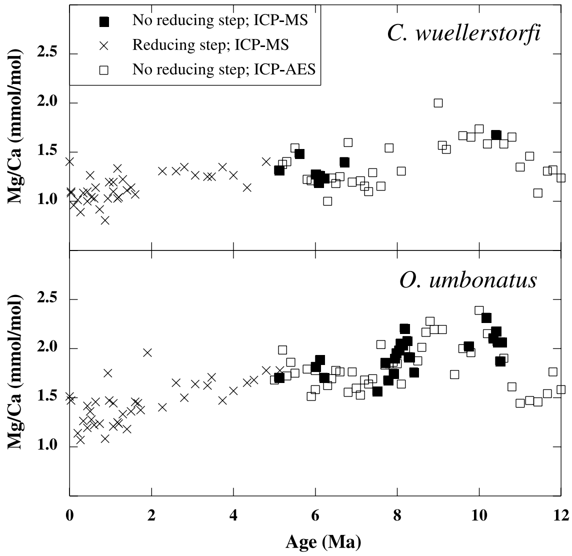

Fig. 2. Mg/Ca of benthic foraminifera (top panel, *C. wuellerstorfi*; bottom panel, *O. umbonatus*) from ODP Site 926 (CR). Mg/Ca values appear unaffected by choice of cleaning technique or method of analysis. Square symbols represent samples cleaned without the reducing step at Cambridge University. Of these samples, the open symbols were analyzed by ICP–AES at Cambridge University using Cambridge standards, and the closed symbols were analyzed by ICP–MS at Rutgers University using Rutgers standards. The crosses represent samples cleaned with the reducing step and analyzed at Rutgers University.

±1.6%, respectively. A portion of the CR record was prepared without the reducing step in the cleaning process, and was analyzed either by ICP-MS at Rutgers University or by simultaneous ICP-AES (inductively coupled plasma atomic emission spectroscopy) at Cambridge University. There is no systematic difference in benthic foraminiferal Mg/Ca resulting from either the different cleaning or analytical methods (Fig. 2).

2.3. Stable isotope analysis

Samples for isotope analysis were loaded into a Multi-prep peripheral device, reacted in 100% orthophosphoric acid at 90°C, and analyzed on an Optima mass spectrometer at Rutgers University. Seventy samples were analyzed in the Godwin Laboratory (University of Cambridge, UK). These samples were soaked in a 3% solution of hydrogen peroxide, ultrasonicated and dried overnight prior to reaction with 100% orthophosphoric acid at 90°C and analysis by a VG PRISM mass spectrometer. Values are reported versus V-PDB through the analysis of NBS19 with values of 1.95‰ and −2.20‰ for $\delta^{13}C$ and $\delta^{18}O$, respectively, as reported by [15]. The precision of the isotope analyses is better than ±0.06‰ for $\delta^{13}C$ and better than ±0.08‰ for $\delta^{18}O$. We use the species adjustment factors of [16] to convert $\delta^{18}O$ values to 'equilibrium' values.

2.4. Determination of Mg-paleotemperatures

We use the revised calibration equations for *C. wuellerstorfi* and *O. umbonatus* [12] to estimate BWT. Multispecies records clearly show a large offset between *C. mundulus* and *C. wuellerstorfi* Mg/Ca; for this reason *C. mundulus* Mg/Ca are not used in core-top *Cibicidoides* calibrations. For this study therefore, we have assumed that *C. mundulus* has the same temperature sensitivity as *C. wuellerstorfi* but a different pre-exponential constant. This is a reasonable assumption because there is a growing body of evidence that the incorporation of Mg into the calcite tests of most epibenthic and also planktonic foraminifera appears to have a temperature sensitivity of 10±1% per °C (e.g. [4,7,12,17–19]). We estimated the pre-exponential constant using the ratio of the mean *C. mundulus* Mg/Ca and mean *C. wuellerstorfi* Mg/Ca for the interval between 4 and 14 Ma at ODP Site 806 to obtain a temperature calibration for *C. mundulus*:

$$\mathrm{Mg/Ca} = 0.9\exp(0.11\times \mathrm{BWT}) \quad (1)$$

Assuming little or no change in seawater Mg/Ca, the temperature estimates calculated here should be accurate to within ±1°C (2 S.E.) [12].

3. Results

ODP Sites 926 (CR) and 806 (OJP) both display a general trend of increasing benthic foraminiferal Mg/Ca with sediment depth (Figs. 3 and 4). The Atlantic record displays a decrease in benthic foraminiferal Mg/Ca between 150 and 200 meters composite depth (mcd), followed by an interval of elevated Mg/Ca between 200 and 250 mcd. These features are not observed in the Pacific record at either the same burial depth or age. In the Atlantic core, the Mg/Ca of *C. mundulus* is more similar to *O. umbonatus* than *C. wuellerstorfi*, whereas the reverse is true for *C. mundulus* in the Pacific core. This is possibly

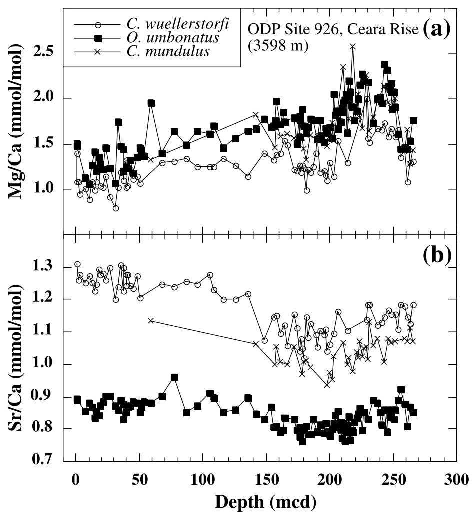

Fig. 3. Multi-species benthic foraminiferal trace metal data, Mg/Ca (panel a) and Sr/Ca (panel b), from ODP Site 926 (CR) versus depth in sediment (mcd = meters composite depth).

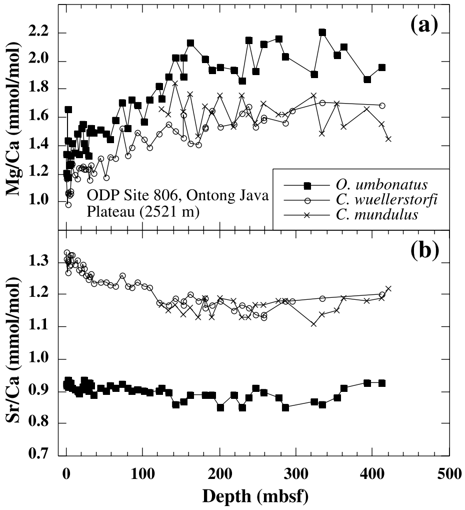

Fig. 4. Multi-species benthic foraminiferal trace metal data, Mg/Ca (panel a) and Sr/Ca (panel b), from ODP Site 806 (OJP) versus depth in sediment (mbsf = meters below seafloor).

a result of genetic differences that may occur between the 'same' species across both time and space. These differences are responsible for some of the scatter in the Mg-temperature records.

Unlike Mg/Ca, benthic foraminiferal Sr/Ca from each site generally decreases with increasing sediment depth, reaching a broad minimum at around 200 m burial depth, (~ 6–8 Ma), although the minimum is more pronounced in the Atlantic site than in the Pacific site (Figs. 3 and 4). Subsequently, Sr/Ca slowly increases. Sr/Ca of *O. umbonatus* is low relative to the *Cibicidoides* species. As with Mg/Ca, *C. mundulus* appears to have a slightly different inter-species offset for Sr/Ca in the Atlantic compared to the Pacific (Figs. 3 and 4).

Benthic foraminifera were analyzed for $\delta^{18}O$ to complement published [16,20] stable isotope records (Fig. 5). The Pleistocene is characterized by large amplitude oscillations in $\delta^{18}O$ on the order of 1.0‰ at each site. The CR record also displays large oscillations in $\delta^{18}O$ prior to the Pleistocene, but the different resolution of the records prevents comparison of the magnitude and frequency of these oscillations. However, both sites display a broad maximum on the order of 0.5‰ between 7 and 5 Ma and a general increase of 0.8–1.0‰ through the Pliocene.

4. Discussion

4.1. Geochemical preservation and changes in seawater Mg/Ca

We will address the issue of post-depositional alteration of calcite Mg/Ca and the effect of secular variations in seawater Mg/Ca. Descriptions of foraminifera from Sites 926 and 806 in addition to the quality of published isotope records show that the foraminifera at these sites have not undergone wholesale recrystallization (e.g. [8,16,21]). It has been argued that calcite saturation state may potentially affect the trace metal content of benthic foraminifera, either through dissolution or through a precipitation effect (e.g. [22]). The effect of post-depositional dissolution on the trace metal content of benthic foraminifera is still a matter of debate (e.g. [4,23]). However, the contrast between the trends in the benthic foraminiferal Mg/Ca and Sr/Ca records presented here suggests that the major features have not been caused by calcite saturation-related processes (Figs. 3 and 4). Measured foraminiferal calcite chemistry may be affected by adhering inorganic calcite cements. Such cements would result in an increase in Mg/Ca and a decrease in measured Sr/Ca cements [24]. No such cements were visible through inspection by binocular microscope. Nevertheless, using a mass balance approach assuming cement Mg/Ca of ~ 8 mmol/mol (Lear, unpublished data), inorganic cements comprising up to 1% of the total calcite could introduce an uncertainty in the accuracy of the Mg temperatures of around 1°C, and Sr/Ca values could decrease by ~ 1%.

Seawater Mg/Ca is assumed to be constant between 0 and 12 Ma. However, it should be noted that if the benthic foraminiferal Sr/Ca records reflect changes in seawater Sr/Ca, it is likely that Mg/Ca has changed over the same interval, as Ca has the shortest residence time in the ocean of all three elements. The largest change in benthic foraminiferal Sr/Ca is a 10–15% increase

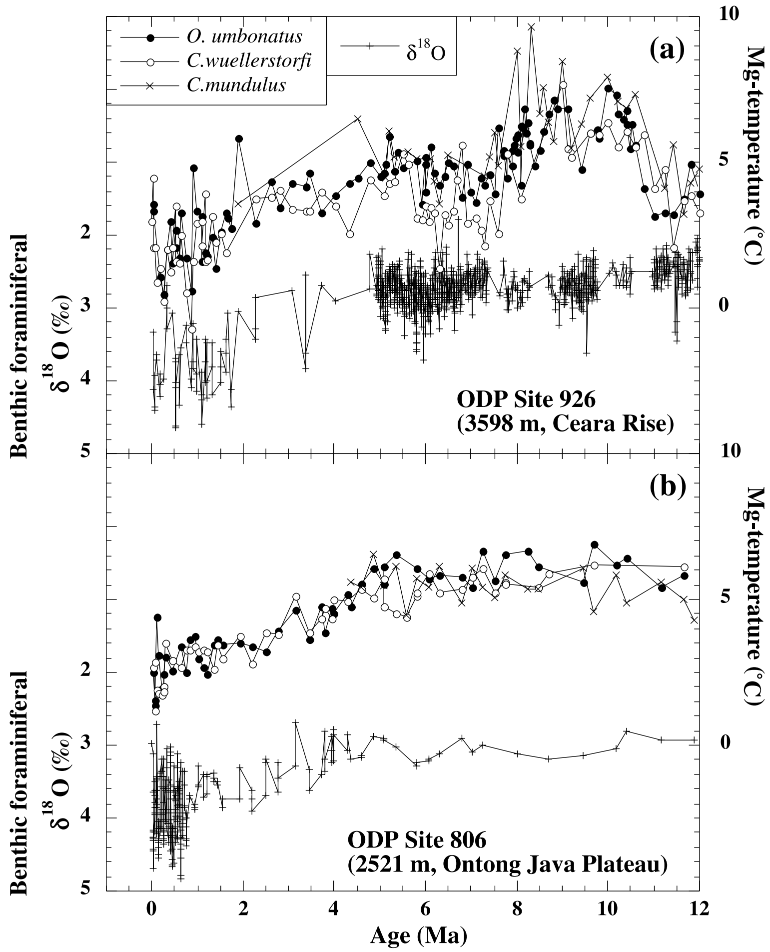

Fig. 5. Mg-temperatures from three benthic foraminiferal species and composite benthic foraminiferal $\delta^{18}O$ for (a) ODP Site 926 cored on the CR, Atlantic and (b) ODP Site 806 cored on the OJP, Pacific. Published stable isotope data [16,20] are supplemented with new data (this study). Benthic foraminiferal oxygen isotope data have been adjusted to 'equilibrium values'.

between 5 and 0 Ma. If this change were caused by only a change in seawater Ca concentration, it would result in an underestimation of the Mg-temperature decrease of about 1°C over the 5 Myr interval.

4.2. Temperatures

The benthic foraminiferal Mg/Ca data are interpreted solely in terms of variations in BWT (Fig. 5). Using the species-specific temperature calibrations [12] results in more consistent temperature estimates (generally ±1°C) than the 'constant offsets' method [5]. Much like $\delta^{18}O$ paleothermometry, the 'constant offsets' method normalizes all Mg/Ca data to a single species before using a generic temperature calibration. However, the inter-specific offsets in Mg/Ca appear to be sensitive to changes in temperature. Differences between species-specific temperatures estimated from a single sample could be the result of natural Mg/Ca variability, sampling resolution (one sample represents ~5 cm of core), imperfect calibrations, evolutionary changes within a species, or changes in seawater Mg/Ca. We combine the temperatures derived from all three species to avoid any species bias and produce a robust record of the temperature variations at each site. We use the Kaleidagraph® weighted fit function (10%) which uses the locally least-squared error method to fit the best smooth curve through the compiled data (Fig. 6). The accuracy of these temperature estimates is ±1°C (2 S.E.) given minimal changes in seawater Mg/Ca [12].

The Atlantic and Pacific Mg-temperatures are indistinguishable within the limits of the method for most of the past 12 Ma (Fig. 6). However, there are two intervals (12–11 Ma and 8.5–6 Ma) over which the Atlantic Mg-temperatures were appreciably lower (by 1–2°C) than the Pacific Mg-temperatures. BWT estimates from Pacific Site 806 were relatively stable between around 11 and 5 Ma, at about 5.5°C. In contrast, the deep Atlantic Site 926 displays fluctuations in benthic foraminiferal Mg/Ca, which cannot be interpreted in terms of global temperature or seawater Mg/Ca change. BWTs calculated from benthic foraminiferal Mg/Ca at ODP Site 926 increased about 3°C across the Serravallian–Tortonian boundary, from ~3°C at 11.5 Ma to ~6°C at 10 Ma. The Mg-temperatures remained at around 6°C until 8.5 Ma, except for a ~1°C temperature decrease centered at 9.5 Ma. Subsequently, Site 926 BWT decreased towards the Tortonian–Messinian boundary, reaching around 3.5°C at 7.1 Ma. Temperatures gradually increased by around 1.5°C throughout the Messinian, reaching ~5°C at 5.3 Ma. We interpret these Atlantic temperature changes in terms of changing ocean circulation, in particular changes in the flow of proto-NADW. Both the Atlantic and the Pacific sites display a concurrent decrease in benthic foraminiferal Mg/Ca through the Plio–Pleistocene. We interpret this trend as reflecting a global decrease in BWT of around 3.5°C (Fig. 6).

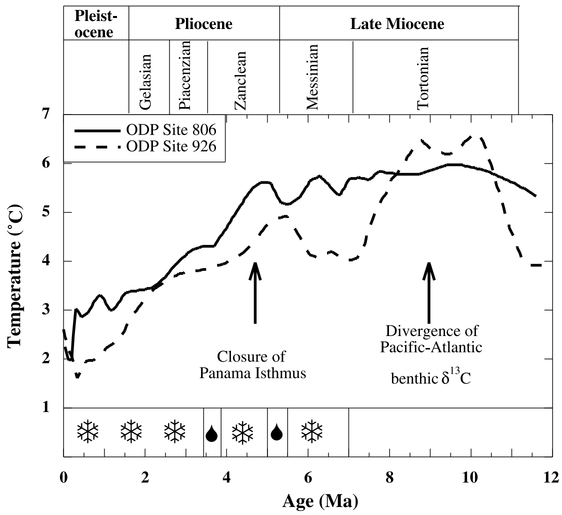

Fig. 6. 10% weighted fit through the compiled Mg-temperatures (Fig. 5) for ODP Sites 806 and 926. Accuracy of temperature estimates is about ±1°C (2 S.E.) given minimal change in seawater Mg/Ca over this interval (see Section 4). The snowflakes and water droplets indicate increased and reduced occurrences of IRD, respectively, on the Iceland and Vøring plateaus [42].

4.3. Nature and cause of circulation change

A seismic erosion reflector 'Merlin' has been identified along the western margin of the North Atlantic, and its age constrained to be between 13 and 10.5 Ma [25]. This reflector has been correlated to an increase in the flux of proto-NADW during the late middle Miocene [3]. Carbon isotope data indicate that this phase of proto-NADW production began about 12.5 Ma [3]. This erosion event was also coincident with the initiation of drift accumulation on the Hatton and Snorri drifts [26] and relatively low (~4°C) Mg-temperatures at CR Site 926 (Fig. 6). Site-to-site $\delta^{13}C$ reconstructions have shown that between 10 and 8.5 Ma there was little difference between the North Atlantic, Pacific and Southern oceans, indicating little to no flow of proto-NADW. During this interval, CR Mg-temperatures rose by ~2°C to temperatures similar to those at the Pacific site. Between 8.5 and 7 Ma, the inter-ocean $\delta^{13}C$ gradients increased, recording the flow of proto-NADW to the south [27,28], and CR ODP Site 926 Mg-temperatures decreased by ~2°C (Fig. 7). Several seismic reflectors of late Miocene to early Pliocene age have been identified in the northern North Atlantic by various authors [29,30].

The limited spatial and temporal resolution of the paleoceanographic records coupled with the uncertainties inherent in each of the various prox-

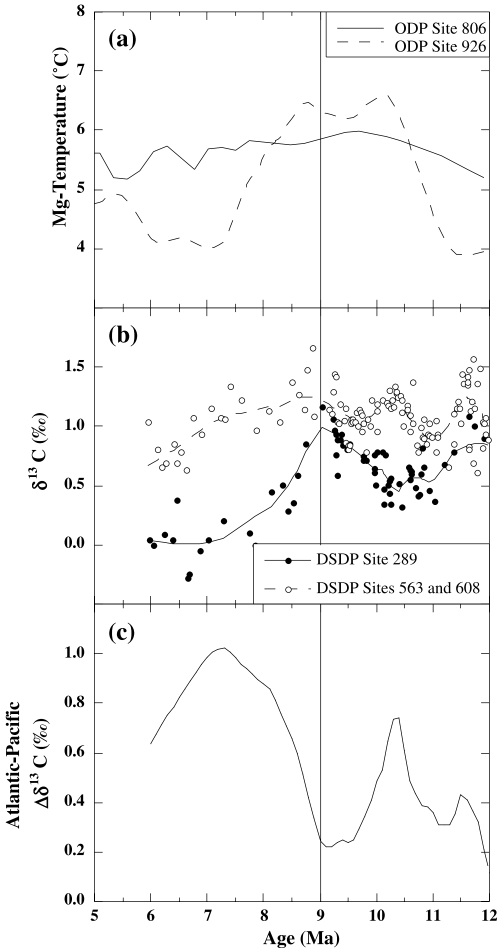

Fig. 7. (a) Mg-temperature records from CR Site 926 (dashed line) and OJP Site 806 (solid line). (b) Published benthic foraminiferal $\delta^{13}C$ records from ODP Sites 563 and 608 (dashed line) in the North Atlantic and DSDP Site 289 (solid line) on the OJP, Pacific (Table 1) [27]. (c) Difference between the Atlantic and Pacific $\delta^{13}C$ records in panel b.

ies complicate the paleoceanographic interpretation. However, there is one paleoceanographic scenario that is consistent with the erosion, carbon isotopic and Mg/Ca records described above, and which at present we believe is most likely to represent the evolution of proto-NADW over the past 12 Myr. This scenario invokes the flow of proto-NADW between 12.5 and 10 Ma, followed by an interval of little to no flow between 10 and 8.5 Ma, and the resumption of proto-NADW flow at ∼8.5 Ma. The Mg-temperature records presented here suggest that, unlike today, proto-NADW was colder (by about 2°C) and fresher (by an amount equivalent to $\delta^{18}O_w$ of 0.5‰) than the competing southern-sourced deep water in the late Miocene.

From around 9 Ma, the Pacific benthic $\delta^{13}C$ record decreases, while the North Atlantic $\delta^{13}C$ records remain relatively constant (Fig. 7). Relative (site-to-site) changes are more important than absolute changes in $\delta^{13}C$ in reconstructing circulation paths, as changes in the average isotopic composition of the global carbon reservoir are effectively canceled out. For example, the decrease in the Pacific deep ocean $\delta^{13}C$ record at ∼9 Ma likely reflects a global change in the ocean carbon reservoir that is masking a more localized increase in $\delta^{13}C$ at CR coincident with the resumption of proto-NADW. Interestingly, the increase in benthic $\delta^{13}C$ of the North Atlantic relative to the Pacific between ∼9 and 7 Ma (Fig. 7C) is coincident with an increase in the intensity of carbonate dissolution at CR Site 926 [31,32]. This observation implies that the increased dissolution intensity at CR Site 926 was the result of a global increase in the oceanic carbon inventory rather than the effect of water mass switching (as implied by [10]). This hypothesis is supported by the coincident decrease in the carbonate content and sediment accumulation rate of ODP Site 804, situated below the lysocline on the OJP, Pacific Ocean [33].

There are perhaps two major hypotheses for the cause(s) of the initiation of NADW. One is that the closure of the Panama Gateway finally allowed the North Atlantic to become saline enough for the formation of NADW [34]. The other hypothesis is that changes in the flux of NADW are directly linked to changes in the depth of the Greenland–Iceland–Scotland Ridge, which varies with the intensity of the mantle plume below Iceland [28]. These hypotheses are not incompatible. It has been shown that NADW formation may have been related to the closure of the Panama Gateway, but that its outflow was controlled by the topography of the Greenland–Scotland Ridge [35]. The same authors showed in their model that while NADW may form with a partially restricted Panama Gateway, convection in the Labrador Sea would be significantly reduced, or close to zero. There has been a great deal of effort aimed at determining the timing of both the initiation of convection in the Labrador Sea, and the initiation of NADW, in particular through the use of lead and neodymium isotopes (e.g. [36]). However, it has recently been shown that the isotopic composition of source sediments is greatly affected by changes in the weathering regimes that occurred at roughly the same time period under consideration [37].

Taken at face value, the CR Mg/Ca record suggests a cooling between 8.5 and 7 Ma on CR associated with the major divergence of the Pacific and Atlantic carbon isotope records (Fig. 7). This finding suggests that proto-NADW was cooler and fresher (by an amount equivalent to a decrease in $\delta^{18}O_w$ of about 0.5‰) than the competing southern-sourced deep water. Today, water temperatures in the Greenland–Iceland–Norwegian (GIN) seas are colder than average NADW, which is also largely influenced by deep water sourced from the warmer and saltier Labrador Sea [38]. Therefore, the cooling observed at Site 926 between 8.5 and 7 Ma is perhaps compatible with the resumption of proto-NADW prior to convection in the Labrador Sea, with the majority of this deep water sourced from the GIN seas. An alternative explanation for a relatively cold and fresh proto-NADW in the late Miocene is that the open Panama Gateway may have reduced the residence time of surface waters in this low-latitude region. This would prevent the surface water salinity from increasing as substantially as today prior to northward transport via the Gulf Stream. Consequently, the surface waters dense enough to sink at high northern latitudes to form proto-NADW would have been colder and fresher than today. Between 6 and 5 Ma, CR Site 926 BWTs gradually became warmer and saltier, likely related to further restriction of the Panama Gateway. Severe restriction of the Atlantic–Pacific connection as indicated by the sea surface salinity contrast either side of the isthmus occurred at ~4.7 Ma [39], coincident with the warmest BWT at Site 926 since 8 Ma, and the initiation of sediment drifts in the Labrador Sea [40].

4.4. Caveats regarding the paleoceanographic interpretation

There are certain complications inherent in each of the proxy records mentioned here. Changes in seawater Mg/Ca will impact the absolute magnitude of the Mg-temperature changes, although the site-to-site temperature relationships are robust. We note that calcite saturation-related effects have been postulated to affect benthic foraminiferal Mg/Ca [7,22]. At present there is no definite evidence for, or quantification of, such effects. Therefore, we interpret the Mg/Ca records presented here in the most straightforward way (i.e. as representing a dominant temperature control). We note that the temperature changes observed at CR may have resulted from a vertical movement of the water masses. Rather than a 'switching on' or 'switching off' scenario for proto-NADW, the temperature changes at CR could be viewed more realistically as an intensification or reduction in the flow of proto-NADW. Lastly, it is not clear to what extent ODP Site 806, situated at 2500 m on the OJP, represents the average Pacific Ocean. In particular, it is possible that in the late Miocene, an open Panama Gateway may have allowed proto-NADW to pass into the Pacific, potentially reaching this site [41].

4.5. Changes in global ice volume

Between ~7 and 6 Ma, the Pacific and Atlantic benthic foraminiferal $\delta^{18}O$ records increase by about 0.5‰. This increase does not coincide with an excursion in the Mg-temperature record (Fig. 5). The simplest way to interpret this feature is therefore by a 0.5‰ increase in δw and hence global ice volume during this period, which is supported by an observed increase in Northern Hemisphere IRD (ice-rafted debris) at this time [42] (Fig. 6). Between ~6 and 5 Ma, there is an overall decrease of about 0.5‰ in the stable isotope record. The Mg-temperature records perhaps suggest ≤1°C warming associated with the decrease. Thus, the remaining portion of the $\delta^{18}O$ record (≥0.3‰) must be interpreted in terms of a decrease in ice volume, which is supported by a decrease in IRD content in the Iceland–Norwegian Sea between about 5.5 and 5.0 Ma [42] (Fig. 6). The benthic foraminiferal $\delta^{18}O$ records from Sites 806 and 926 increase through the Pliocene, and it appears that this increase is a result of both a decrease in BWTs (∼3.5°C assuming constant seawater Mg/Ca) and an increase in global ice volume.

4.6. Effect of circulation change on global climate

It is likely that either decreased polar temperatures and/or increased moisture flux to the Arctic region induced the initiation of intense Northern Hemisphere Glaciation (NHG). It has been suggested that closure of the Isthmus of Panama enhanced moisture transport to the Eurasian continent, leading to increased freshwater delivery to the Arctic and hence the NHG [43]. Our data suggest that although complete closure of the Panama Gateway occurred after NADW began to form, the closure may be responsible for the changes in the physical characteristics of NADW towards higher temperatures and salinity. Early NHG between 7 and 6 Ma evidenced by an increase in benthic $\delta^{18}O$ and Northern Hemisphere IRD records was perhaps associated with the initiation of a relatively cold proto-NADW. The subsequent warming of proto-NADW associated with the closure of the Panama Gateway may have caused the temporary decay of these ice sheets around 5 Ma (Fig. 6). Our Mg/Ca data document a significant cooling throughout the Pliocene in both the Atlantic and Pacific Sites, beginning about 2 Myr prior to major NHG (which is dated to 2.9 Ma at the Iceland Plateau [42]). The underlying cause of this global cooling is unclear.

5. Conclusions

The occurrence of IRD at high northern latitudes in the late Miocene coincides with a marked divergence between Atlantic and Pacific benthic $\delta^{13}C$ records and a lowering of deep water benthic foraminiferal Mg-temperatures by about 2°C at CR ODP Site 926. This early NHG was likely related to the initiation of a proto-NADW that was colder, fresher and nutrient-depleted relative to competing southern-sourced waters. Subsequent restriction of the Panama Gateway between 6 and 5 Ma coincided with proto-NADW becoming warmer and saltier, and a consequent decrease in Northern Hemisphere IRD. The extra heat released at high northern latitudes through formation of this 'warm' proto-NADW perhaps prohibited Northern Hemisphere ice growth in the early Pliocene. However, the increased moisture flux to the Arctic associated with formation of the 'warm' NADW, coupled with the subsequent global temperature decline through the Pliocene probably contributed to the major NHG in the late Pliocene. This study demonstrates the need for a multi-site approach when determining variations in global ice volume from benthic Mg/Ca and $\delta^{18}O$ records.

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