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Widespread and synchronous change in deep-ocean circulation in the North and South Atlantic during the Late Cretaceous

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[1] Modern thermohaline circulation plays a role in latitudinal heat transport and in deep-ocean ventilation, yet ocean circulation may have functioned differently during past periods of extreme warmth, such as the Cretaceous. The Late Cretaceous (100–65 Ma) was an important period in the evolution of the North Atlantic Ocean, characterized by opening ocean gateways, long-term climatic cooling and the cessation of intermittent periods of anoxia (oceanic anoxic events, OAEs). However, how these phenomena relate to deep-water circulation is unclear. We use a proxy for deep-water mass composition (neodymium isotopes; ε_{Nd}) to show that, at North Atlantic ODP Site 1276, deep waters shifted in the early Campanian (~78–83 Ma) from ε_{Nd} values of ~−7 to values of ~−9, consistent with a change in the style of deep-ocean circulation but >10 Myr after a change in bottom water oxygenation conditions. A similar, but more poorly dated, trend exists in ε_{Nd} data from DSDP Site 386. The Campanian ε_{Nd} transition observed in the North Atlantic records is also seen in the South Atlantic and proto-Indian Ocean, implying a widespread and synchronous change in deep-ocean circulation. Although a unique explanation does not exist for the change at present, we favor an interpretation that invokes Late Cretaceous climatic cooling as a driver for the formation of Southern Component Water, which flowed northward from the Southern Ocean and into the North Atlantic and proto-Indian Oceans.

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1. Introduction

[2] During the Late Cretaceous (early Turonian), sedimentation in the abyssal North Atlantic changed from dominance by organic-carbon-rich shales and mudstones to organic-carbon-poor, varicolored mudstones [e.g., *Arthur*, 1979; *Jansa et al.*, 1979; *Tucholke et al.*, 1979, 2004]. This facies shift has been ascribed to more oxygenated bottom waters, resulting from the progressive opening of the Central Atlantic Gateway (CAG) and enhanced deep-water mixing [*Poulsen et al.*, 2001]. Furthermore, the lithological transition marks the end of the major, but periodic, OAEs and the capacity of the North Atlantic basin to act as a major sedimentary organic carbon sink [*Jenkyns*, 1980], implying that it was of significance to the long-term evolution of the Cretaceous carbon cycle. In addition to the changing paleogeographic conditions, global climate cooled from the mid-Turonian onwards [*Huber et al.*, 2002], particularly in high southern latitudes, and this may have driven the onset of high-latitude deep-water formation [*Poulsen et al.*, 2001; *Huber et al.*, 2002; *Robinson et al.*, 2010]. Whether such changes can be linked to changes in deep-water paleoenvironments in the North Atlantic during the Late Cretaceous is not yet clear. More generally, the response of circulation patterns and deep-water formation to the background changes in Late Cretaceous climate and geography is also not fully understood.

[3] Previous studies have sought to reconstruct Late Cretaceous deep-water circulation using benthic foraminiferal stable-isotopes [e.g., *Frank and Arthur*, 1999; *D'Hondt and Arthur*, 2002; *Friedrich et al.*, 2012], but dissolution below the carbonate compensation depth (CCD) and the effects of major lithological changes on carbonate preservation limit the use of such proxies in the Late Cretaceous North Atlantic. In contrast, the neodymium-isotopic composition (ε_{Nd}) of fish teeth and bones ("fish debris") can be used to reconstruct past bottom water ε_{Nd} across a range of paleowater depths and lithologies. Neodymium has a seawater residence time comparable to the mixing time of the ocean and, consequently, is isotopically heterogeneous in the modern ocean so that different water masses can be distinguished on the basis of their Nd-isotopic composition [*Goldstein and Hemming*, 2003]. Though it is theoretically possible that the residence time of Nd could have been significantly different in the geological past, it is generally assumed that it has remained constant through time, and there is no obvious reason why it would have changed dramatically. The ε_{Nd} of seawater is determined by the inputs of Nd from the local geology into the region of water mass formation [*Goldstein and Hemming*, 2003], with young, primitive volcanic rocks being more radiogenic than old continental

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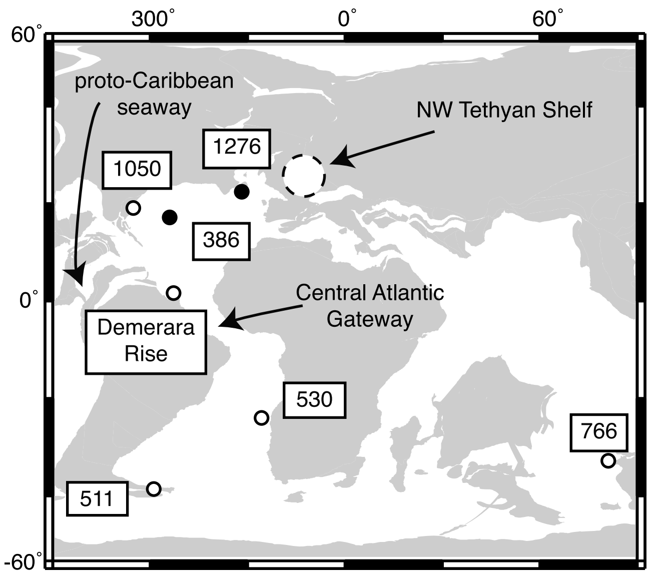

Figure 1. Plate tectonic reconstruction at 80 Ma (map from ODSN plate tectonic reconstruction: http://www.odsn.de/odsn/services/paleomap/paleomap.html), showing the localities discussed in the text. Numbers refer to DSDP/ODP sites. Solid circles represent sites for which new data are presented here; unfilled circles and the large dashed circle represent sites for which published data already exist [*Pucéat et al.*, 2005; *MacLeod et al.*, 2008; *Jiménez Berrocoso et al.*, 2010; *Robinson et al.*, 2010].

rocks. Fish debris acquire very high concentrations of Nd (>100 s ppm) during an early reaction at the sediment-water interface, thereby recording bottom water ε_{Nd} values [*Martin and Scher*, 2004]. Furthermore, they are resistant to subsequent burial diagenesis and are found in a variety of deep-sea sediments, which can be well-dated using conventional bio-, chemo- and magneto-stratigraphic techniques.

[4] Existing Cretaceous Nd-isotope records suggest that both spatial and temporal variability in ε_{Nd} were features of the Cretaceous oceans [e.g., *Frank et al.*, 2005; *Pucéat et al.*, 2005; *MacLeod et al.*, 2008, 2011; *Jiménez Berrocoso et al.*, 2010; *Robinson et al.*, 2010]. Therefore, Nd-isotopes have great potential to explore the relationships between deep-water mixing of the North Atlantic during the Cretaceous, which may provide insights into the controls on bottom water oxygenation. However, North Atlantic records are currently restricted to intermediate water depth (<1500 m) sites on the Demerara Rise and Blake Nose (Figure 1) [*MacLeod et al.*, 2008, 2011; *Jiménez Berrocoso et al.*, 2010]. A remarkable finding at the Demerara Rise sites is the very unusually non-radiogenic Nd-isotope values recorded there, thought to derive from Nd sourced from the Guyanan shield and carried to depth by low-latitude, warm saline intermediate-water formation (so-called "Demerara Bottom Water," DBW) [*MacLeod et al.*, 2008]. The extent to which this water mass influenced the rest of the intermediate and deep North Atlantic is, as yet, unclear. Demerara Rise remained a locus of significant organic-carbon accumulation into the Santonian [*Erbacher et al.*, 2004], implying, perhaps, a different paleoceanographic history there compared to the main North Atlantic basins. Additional Nd-isotope data from elsewhere should establish what connections existed between different geographic areas and paleodepths in the North Atlantic, and how deep-ocean circulation evolved in response to the changing climatic and tectonic boundary conditions. The object of this paper, therefore, is to constrain temporal variability in Nd-isotope values in the deep North Atlantic in order to ascertain the source and variability of deep-waters during the Cretaceous, and to determine whether changes in circulation occurred synchronously with major changes in deep-water facies.

2. Materials and Methods

[5] Deep Sea Drilling Project (DSDP) Site 386 and Ocean Drilling Program (ODP) Site 1276 (Figure 1) were chosen as suitable sites for this study as both span much of the Late Cretaceous and, critically, the Turonian transition from largely dysoxic to more oxygenated facies. Furthermore, they provide a northeast-trending transect away from Demerara Rise toward the Tethyan shelf region, thereby providing the opportunity to test whether low-latitude warm, saline water production on the shelves impacted the deep North Atlantic. Modern water depths at Sites 386 and 1276 are in excess of 4.5 km. The paleowater depths of the sites are estimated to be >3 km for Site 386 [*Tucholke et al.*, 1979] and >2 km for Site 1276 [*Tucholke et al.*, 2004; *Urquhart et al.*, 2007]. Given these paleowater depths both sites record sedimentation within lower-intermediate to deep water masses. Samples were selected generally from fine-grained (and in places laminated) sediments in order to avoid, as much as possible, inclusion of redeposited materials from shallower water depths. Biostratigraphic age models were constructed for each site; full details are given in Text S1 and Tables S1 and S2 in the auxiliary material.[1] The samples studied range from the Albian to the Maastrichtian. For Site 386, age constraints for Turonian–Maastrichtian samples are problematic due to the absence of conventional biostratigraphic markers and so the age constraints are based upon benthic foraminifera [*Kuhnt et al.*, 1996]. Consequently the numerical ages assigned to these samples are best estimates but with significant (possible multimillion year) uncertainty. Nd-isotopic analysis was conducted in the laboratories of the Bristol Isotope Group, University of Bristol. A full description of the preparatory and analytical methods is given in the auxiliary material.

3. Results

[6] The Nd-isotopic values ($\varepsilon_{Nd(t)}$) of fish debris from DSDP Site 386 range from approximately −7.5 to −6.4 during the Albian to Coniacian (Figure 2 and Table S3). A single horizon from the Maastrichtian yields an average value of −8.7 (n = 2). At ODP Site 1276 $\varepsilon_{Nd(t)}$ values fluctuate between −7.6 and −5.8 during the Cenomanian to Santonian (Figure 2 and Table S4) but from 78 Ma onwards are more negative (−9.4 to −7.6; average of −8.7), with the exception of two samples ($\varepsilon_{Nd(t)}$ of −0.5 and −4.9). At both sites there is no significant discernible change in Nd-isotopic values across the switch in sedimentation from low-oxygen facies, dominated by green,

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011PA002240.

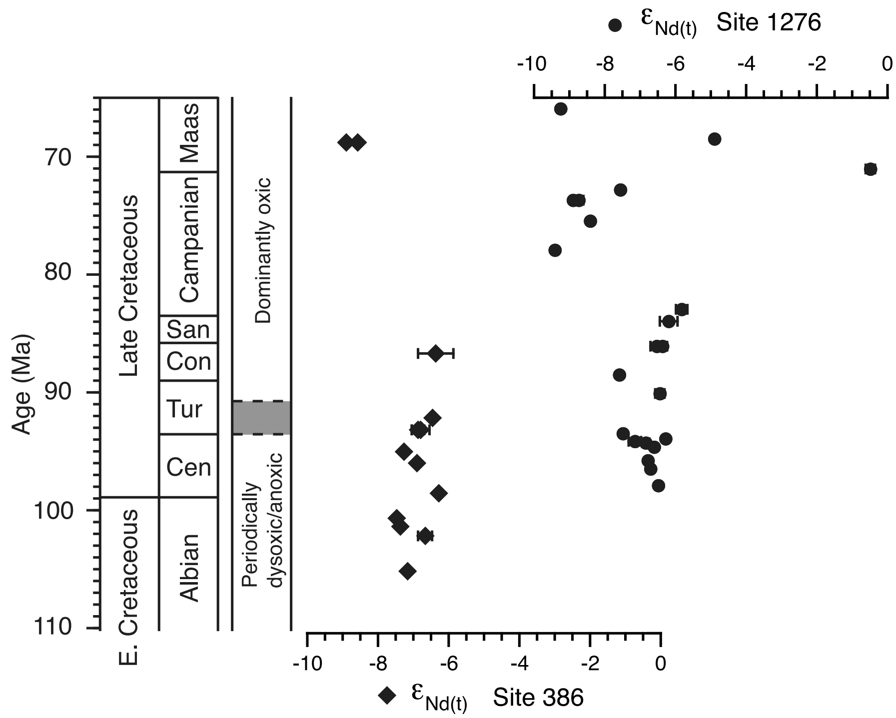

Figure 2. Nd-isotopic data from DSDP Site 386 and ODP Site 1276. North Atlantic oxygenation is based on Sites 386 and 1276 and taken from *Tucholke et al.* [1979, 2004]. Error bars show 2 sigma uncertainties (see auxiliary material for details). Where no error bar is shown, it is less than the size of the symbol. Note that the ages assigned for Turonian–Maastrichtian samples from Site 386 likely have considerable uncertainty (see section 2). Cen = Cenomanian; Tur = Turonian; Con = Coniacian; San = Santonian; Maas = Maastrichtian.

grey and black colored lithologies, to better oxygenated facies dominated by red colored lithologies (Figure 2).

4. Discussion

4.1. Albian–Santonian Nd-Isotopes and Oxygenation of the North Atlantic

[7] The similarity in Cenomanian–Santonian Nd-isotopic values at both sites suggests a common water mass existed at 2–3 km depth in the North Atlantic at that time, with an average $\varepsilon_{Nd(t)}$ value of ~ -6.7. Albian-age samples from Site 1050 (deposited at 800–2000 m paleowater depth) have an average value of -5 [*MacLeod et al.*, 2008], suggesting that compositionally differentiated water masses may have existed at different depths in the North Atlantic. Nonetheless, all three sites are remarkable for their relatively radiogenic values, in comparison to modern Atlantic intermediate or deep-waters. It is unlikely that weathering or exchange with sediments (so-called boundary exchange) was the source of radiogenic Nd as the pre-Cenozoic rocks of the modern North Atlantic margins are generally dominated by lithologies with less radiogenic $\varepsilon_{Nd(0)}$ values in the range of -12 to -10 [*Jeandel et al.*, 2007]. An appealingly simple explanation is that Pacific Ocean intermediate–deep waters with $\varepsilon_{Nd(t)}$ values of -5 to -3 [*Frank et al.*, 2005; *MacLeod et al.*, 2008; *Robinson et al.*, 2010] flowed through a deep (>2 km) proto-Caribbean seaway into the North Atlantic basin and some ocean models suggest that this was possible [e.g., *Trabucho Alexandre et al.*, 2010]. However, various interpretations of the paleogeographic and paleobathymetric history of this seaway exist [e.g., *Meschede and Frisch*, 1998; *Pindell and Kennan*, 2009] so that a more restricted, shallower gateway that prevented deep-water mixing is also possible. Intriguingly, Nd-isotope data from the southern hemisphere are also relatively radiogenic during the Albian–Santonian (Figure 3) [*Robinson et al.*, 2010], including before the Central Atlantic Gateway was open to deep-water flow. It is unlikely that Pacific-sourced deep water could have filled both the North and South Atlantic with the constrained paleogeography of the time, nor could weathering have resulted in a very similar $\varepsilon_{Nd(t)}$ value throughout the Atlantic and Indian Ocean [*Robinson et al.*, 2010]. If ocean circulation was more sluggish [e.g., *Poulsen et al.*, 2001] then it may have been possible that seawater-particle-exchange with volcanic dust from arcs in the Pacific and Caribbean regions supplied more radiogenic Nd than in the modern ocean (in a manner analogous to the modern North Pacific [*Goldstein and Hemming*, 2003; *Jones et al.* 2008; *Siddall et al.*, 2008]). As previously suggested [*Robinson et al.*, 2010], this mechanism could provide an alternative explanation for the relatively radiogenic, and somewhat similar, Nd-isotope values found in North Atlantic, South Atlantic and Indian Ocean deep-waters prior to the Santonian.

[8] There is no discernible change in Nd-isotopic composition across the transition in the Turonian from dysoxic to well-oxygenation facies at Sites 386 and 1276 (Figure 2). This is perhaps surprising, given that other marked changes in the deep-ocean environment are recorded at this time, including an increase in the diversity of deep-water agglutinated benthic foraminifera [*Kuhnt et al.*, 1996], interpreted as a switch to better-oxygenated bottom waters. If this switch were associated

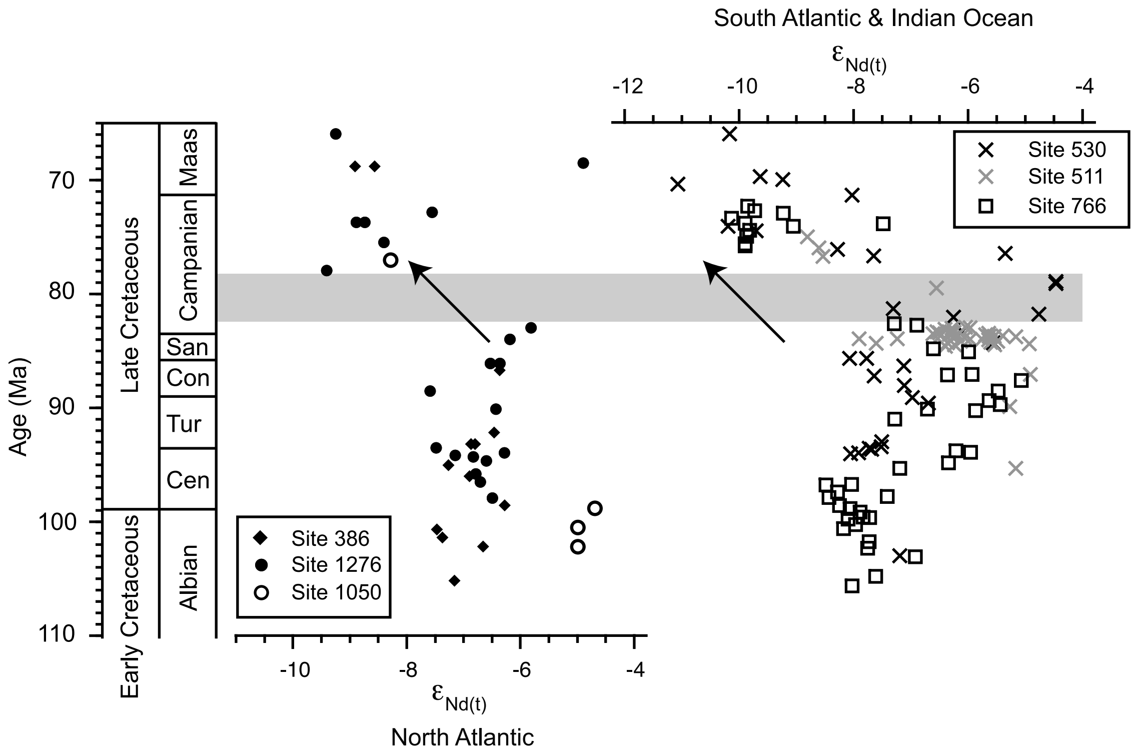

Figure 3. Nd-isotopic data from intermediate and deep-water North Atlantic, South Atlantic and Indian Ocean sites including new data from Sites 386 and 1276. The Site 1050 data from *MacLeod et al.* [2008] have been calibrated to the same timescale used for Site 386 and 1276 and the $\varepsilon_{Nd(t)}$ values have been corrected accordingly. South Atlantic and Indian Ocean data from *Robinson et al.* [2010]. Arrows indicate synchronous shift in Nd-isotopic values in both Northern and Southern Hemisphere records. Grey horizontal bar represents period during which SCW is hypothesized to have become a dominant feature in the Atlantic basins.

with a change in deep-water source, then the Nd-isotopic composition of the new source must have been very similar to the pre-Turonian source. Given the broad similarity in Nd-values in the North and South Atlantic during the Albian–Santonian, we cannot rule out mixing with South Atlantic waters at this time. Alternatively (or perhaps additionally) the oxygen content of North Atlantic deep-water masses could have been increased by cooling, enhanced flow rates or a decline in export production; such mechanisms would not have required any fundamental change in the origin of deepwater.

4.2. Implications for Mixing Between Shelf and Deep-Water Regions

[9] During the mid-Cretaceous it has been hypothesized that evaporation over low-latitude shelf seas could have led to the formation of warm, saline bottom waters that contributed to intermediate and deep-water masses [*Brass et al.*, 1982]. Stable- and Nd-isotopic evidence from Demerara Rise [*Friedrich et al.*, 2008; *MacLeod et al.*, 2008] strongly support the existence of such a water mass in the southern part of the North Atlantic in the Cretaceous (so-called "Demerara Bottom Water," DBW). The $\varepsilon_{Nd(t)}$ value of this water mass was dominantly extremely non-radiogenic (typically -11 to -16) implying that warm saline deep-water persisted on Demerara Rise until the Maastrichtian [*MacLeod et al.*, 2008, 2011]. The Late Cretaceous Nd-isotope data from Demerara Rise stand in marked contrast to the data from Blake Nose [*MacLeod et al.*, 2008] and the new data presented here. This observation supports the suggestion that DBW existed at intermediate water depths of <1 km, in a manner analogous to Mediterranean outflow water [*MacLeod et al.*, 2008, 2011; *Jiménez Berrocoso et al.*, 2010] and, thus, did not significantly influence the deep-water masses in the abyssal North Atlantic during the Late Cretaceous.

[10] *Voigt et al.* [2004] suggested that warm saline dense water masses may also have formed on the NW Tethyan shelf and sunk to intermediate-deep depths in the North Atlantic during the Albian–Cenomanian. However, Nd-isotopic data range from ~ -8.8 to -10.3 on the NW Tethyan shelf during that time [*Pucéat et al.*, 2005], less radiogenic than the values reported from contemporaneous samples from Sites 386, 1050 and 1276. Consequently, it seems unlikely that any intermediate water masses sourced from the Tethyan shelf-seas were capable of reaching below 2 km water depth in the North Atlantic (Sites 386 and 1276). This does not, of course, preclude the existence of Tethyan sourced waters in locations, or at depths, that have not yet been sampled.

[11] Nd-isotope data from the NW Tethyan region show a trend toward less radiogenic (-10 to -12) values during the Coniacian–Campanian which *Pucéat et al.* [2005] interpreted as the result of an increased contribution of deep-water upwelling from the North Atlantic onto the Tethyan shelf, based on the assumption that North Atlantic deep-waters would be less radiogenic (as in the modern). Clearly, the deep North

Atlantic, as sampled by Sites 386 and 1276, was probably not the source, as upwelling of these waters would result in an opposite shift to the one observed by *Pucéat et al.* [2005]. A Lower Campanian sample from Sweden has an $\varepsilon_{Nd(t)}$ value of -17 [*Pucéat et al.*, 2005], raising the possibility that higher-latitude waters would have had non-radiogenic Nd-isotopic signatures that could be transported south by changes in surface ocean circulation, possibly caused by Coniacian–Campanian cooling. In the Campanian–Maastrichtian, the NW Tethyan shelf values return to ~-8 to -9 [*Pucéat et al.*, 2005], similar to those in the deep North Atlantic at that time. Whether this has paleoceanographic significance, or is a coincidence, is not yet clear.

4.3. A Major Change in Deep Ocean Circulation During the Campanian?

[12] The most notable long-term feature of the data from Site 1276 is a shift from $\varepsilon_{Nd(t)}$ values between -8 and -6, typifying the Albian–Santonian, to values below -8 from the mid-Campanian onwards. A similar contrast between Albian–Santonian and Campanian–Maastrichtian data is observed at Sites 386 and 1050, albeit with fewer samples and lower sampling resolution due to poor spot-core recovery. Exceptions to the long-term pattern occur at Site 1276 where two samples at 71.0 and 68.5 Ma exhibit extremely radiogenic values of -4 and -0.5, contrasting with the general background value of <-8. The cores from which these samples came contain rare occurrences of volcanic glass and feldspars [*Tucholke et al.*, 2004], so it is likely that local volcanism was, at times, contributing radiogenic Nd. Similar associations have been noted in late Cretaceous and early Paleogene records from the Caribbean [*Thomas et al.*, 2003] and South Atlantic [*Robinson et al.*, 2010]. The presence of volcanic material in all these examples points to the possible source of radiogenic Nd, but the transfer mechanism could be by one of two pathways. Volcanic ash, dissolved or leached in the water column, may have caused a transient local change in seawater ε_{Nd} values, which was recorded by fish debris and teeth. Alternatively, release of radiogenic Nd from ash within the sediments during the time of apatite inversion could have led to the radiogenic values, but this seems unlikely. Recent work on a Late Quaternary North Atlantic site [*Roberts et al.*, 2010] showed that the $\varepsilon_{Nd(t)}$ of bulk-sediment leaches were consistently more radiogenic than those from fish teeth or uncleaned foraminifera. The difference in values was explained by volcanic ash (transported to the site by bottom water currents) being leached during bulk extractions. Despite significant ash within the host sediments, there appears to have been no effect on the fish teeth Nd-isotope values, which leads us to suggest that the radiogenic values recorded at Site 1276 (and other sites) are more likely the result of localized changes in seawater ε_{Nd} driven by the supply of volcanic material to the water column, rather than a later diagenetic effect caused by the presence of volcanic material in the host sediments.

[13] Any explanation of the origin of the Campanian shift in North Atlantic $\varepsilon_{Nd(t)}$ values, must be mindful of three observations. First, the timing of the shift is coincident with a similar shift in the southern hemisphere (Figure 3). Second, during the Campanian–Maastrichtian the average $\varepsilon_{Nd(t)}$ values are very similar at North Atlantic (-8.7) and southern hemisphere sites (approximately -8.7 to -8.9 in the South Atlantic) [*Robinson et al.*, 2010]. Finally, the average values of the North Atlantic during the Campanian–Maastrichtian are very similar to those of the Late Paleocene–early Eocene at nearby sites (Figure 4) [*Thomas et al.*, 2003]. For the Paleogene, the similarity in deep-water $\varepsilon_{Nd(t)}$ values between the Southern Ocean and Southern Hemisphere sites (all ~-9) strongly suggests the existence of Southern Component Water (SCW) [*Thomas et al.*, 2003]. On the basis of near identical $\varepsilon_{Nd(t)}$ values, *Robinson et al.* [2010] suggested that a similar mode of deep-water circulation also existed in the Southern Hemisphere during the Late Cretaceous. It seems unlikely that a change in Atlantic-wide weathering and continental runoff, or in exchange with sediments, would result in similar $\varepsilon_{Nd(t)}$ values being recorded throughout the Atlantic in the Campanian. By analogy with the modern, it is likely that there was great variability in the Nd-isotopic composition of continental rocks exposed around the margins [*Jeandel et al.*, 2007]. Consequently, a change in deep-ocean circulation provides a more plausible explanation for the Campanian transition.

[14] Previous authors have suggested that deep-water sourced in the northern North Atlantic (in some cases termed Northern Component Water, or NCW) may have been a local, possibly transient, feature of Late Cretaceous ocean circulation [e.g., *Frank and Arthur*, 1999; *D'Hondt and Arthur*, 2002; *Friedrich et al.*, 2012; *MacLeod et al.*, 2011]. However, various lines of evidence suggest that NCW was not the dominant source of deep-water ventilation in the Atlantic basins from the Campanian onwards. The broad synchroneity in the timing of the shift to $\varepsilon_{Nd(t)}$ values <-8 in the North Atlantic, South Atlantic and proto-Indian Ocean would suggest a common driving mechanism affecting circulation in both hemispheres. In contrast, a Nd-isotopic shift from Demerara Rise [*MacLeod et al.*, 2011], used to argue for NCW in the latest Cretaceous–early Paleocene, occurs $\sim$10 Myr after the transition to $\varepsilon_{Nd(t)}$ values < -8 in the deeper water sites of the North and South Atlantic [*Robinson et al.*, 2010; this study]. The existence of NCW at Demerara Rise was postulated on the basis of an assumed early Cenozoic North Atlantic $\varepsilon_{Nd(t)}$ value of -11 from Fe-Mn crusts [*MacLeod et al.*, 2011], yet dating of such crusts is extremely problematic for the Cenozoic, with potential for considerable stratigraphic error (can be >10 Myr) [see *Klemm et al.*, 2008]. In contrast, well-dated Late Paleocene–early Eocene fish-teeth suggest deep-water $\varepsilon_{Nd(t)}$ values of ~-9 in the North Atlantic [*Thomas et al.*, 2003]. These data and the data from Site 1276, would suggest that the excursion on Demerara Rise in the Maastrichtian [*MacLeod et al.*, 2011] does not represent a replacement of DBW by a northerly sourced deep-water mass and that some other, perhaps, intermediate-water circulation change must be invoked. Future depth transects in the North Atlantic basin may be able to resolve this. The tectonic configuration of the North Atlantic during the Late Mesozoic–early Cenozoic provided a major constraint on the significant production of NCW. The Greenland-Iceland-Faeroes Ridge deepened in the early Oligocene, which only then allowed the southward movement of water masses from the Nordic Seas, and marked the onset of drift sedimentation in the North Atlantic [*Wold*, 1994, *Davies et al.*, 2001, *Howe et al.*, 2001]. Finally, many ocean climate models do not support significant deep-water production in the northern hemisphere during the Late Cretaceous and, instead, suggest that the southern hemisphere was the dominant source of deep-water ventilation in the North Atlantic from the latest

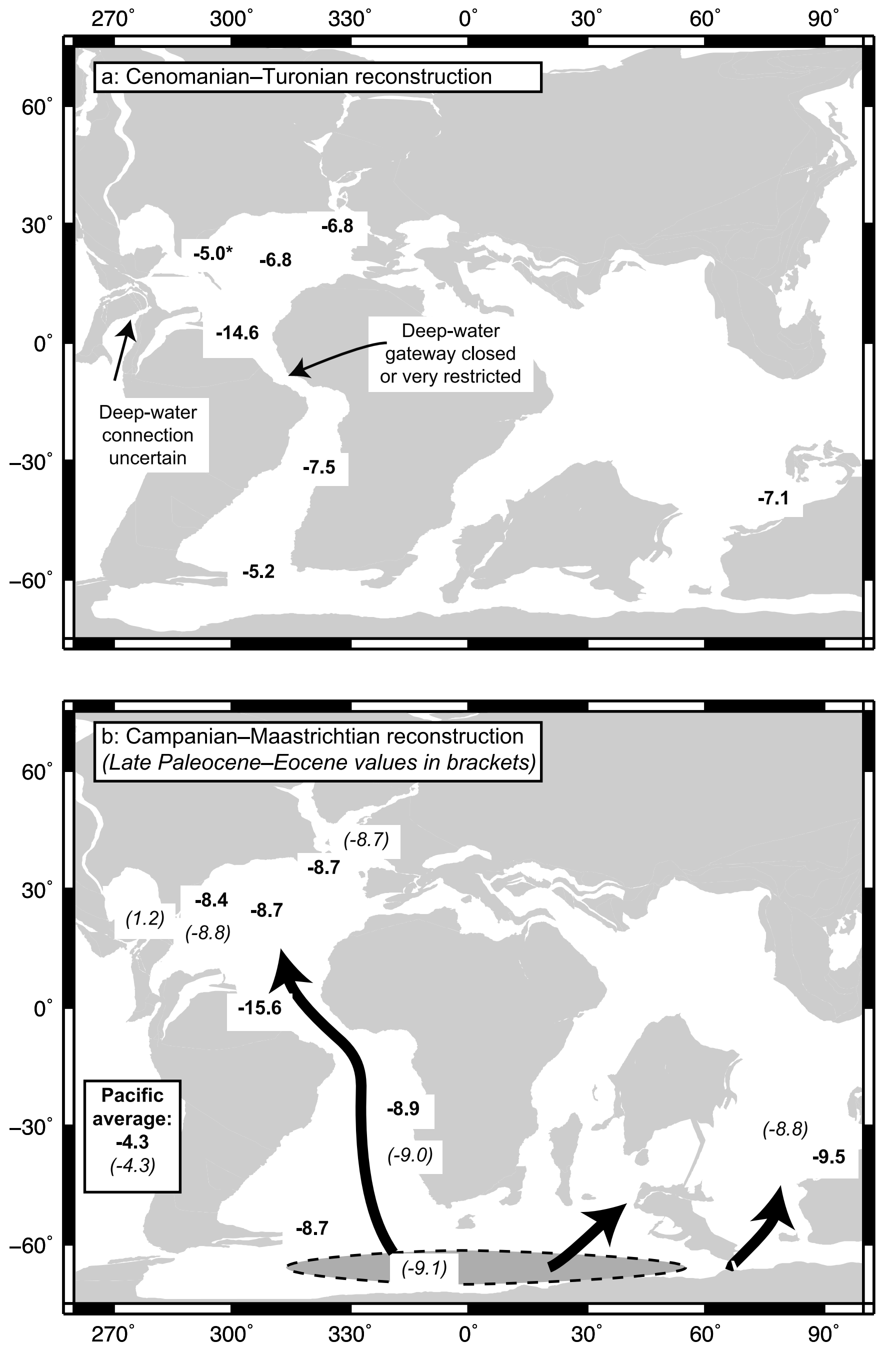

Figure 4. (a) Plate tectonic reconstruction of the Atlantic region at 100 Ma showing average Cenomanian–Turonian intermediate–deep water Nd-isotope values at different sites [*MacLeod et al.*, 2008; *Robinson et al.*, 2010; this study]. Data from Site 1050 (indicated by an asterisk) are from the Albian. (b) Plate tectonic reconstruction of the Atlantic region at 70 Ma showing average intermediate–deep water Nd-isotope values at different sites. Values in bold font are from the Campanian–Maastrichtian [*Frank et al.*, 2005; *MacLeod et al.*, 2008; *Robinson et al.*, 2010; this study]. Data italicized in parentheses are from the Late Paleocene–Eocene [*Thomas et al.*, 2003]. Schematic deep-water formation site and flow of Southern Component Water are shown in the grey ellipse and bold arrows, respectively. Plate tectonic reconstructions are from ODSN plate tectonic reconstruction (http://www.odsn.de/odsn/services/paleomap/paleomap.html).

Cretaceous until the end-Eocene [e.g., *Bice et al.*, 1997; *Brady et al.*, 1998; *Poulsen et al.* 2001; *Otto-Bliesner et al.*, 2002].

[15] An alternative explanation is that a shared water mass with a common origin, and an $\varepsilon_{Nd(t)}$ value of ~-9, bathed much of the deep Atlantic and southern proto-Indian Ocean in the latest Cretaceous and early Paleogene. The simplest mechanism would be for Southern Component Water, forming in the Southern Ocean, to fill the deep Atlantic basins via the Central Atlantic Gateway. The $\varepsilon_{Nd(t)}$ value of this water mass was different to the non-radiogenic values (typically -11 to

−16) recorded at Demerara Rise for most of the Cretaceous [*MacLeod et al.*, 2008, 2011; *Jiménez Berrocoso et al.*, 2010] and so, clearly, the common water mass bathing the deeper parts of the Atlantic basins must have flowed beneath the intermediate-depth DBW. Compilations of benthic carbon and oxygen isotopes spanning the Late Cretaceous provide support for our preferred interpretation of increasing influence of SCW in the Atlantic basins [e.g., *Huber et al.*, 2002; *Friedrich et al.*, 2012]. Alternative mixing paths into the North Atlantic may have been via the Pacific or Tethyan gateways [e.g., *Zhou et al.*, 2008], although the Pacific route seems unlikely on the basis of the Nd-isotopic evidence (i.e., the values in the North Atlantic in the Campanian are not especially radiogenic), whereas the Tethyan route requires deep-water to flow though a, potentially, complex Tethyan gateway [*Sewall et al.*, 2007].

[16] As has been previously noted by *Robinson et al.* [2010], the shift in $\varepsilon_{Nd(t)}$ values in the Late Cretaceous is coincident with high-latitude southern hemisphere cooling [e.g., *Huber et al.* 2002], and, thus, this climatic change was ultimately the likely driver for the observed switch in deep ocean circulation. The new data from the North Atlantic suggest that the onset of SCW formation had a geographically widespread influence, and was the dominant mechanism of deep-water (>2 km water depth) formation in the Late Cretaceous Atlantic basins. The similarity with the Paleogene data, from both the North and South Atlantic (Figure 3), indicates that the new conditions established in the Late Cretaceous likely prevailed as the dominant mode of circulation until the early Oligocene, when Northern Component Water, sourced in the Nordic Seas, began to make a significant contribution to deep-waters in the main Atlantic basins [e.g., *Wold*, 1994; *Davies et al.*, 2001; *Howe et al.*, 2001; *Via and Thomas*, 2006].

5. Conclusions

[17] Nd-isotopes are emerging as a powerful tool with which to explore Cretaceous ocean dynamics and mixing, and can be applied across wide geographic areas and paleowater depths. Although multiproxy studies of deep-water North Atlantic sites will be required to assess whether Nd and stable-isotopes yield similar conclusions at shorter-time scales than those investigated here, the long-term trends in both types of data appear to be consistent. When considered in conjunction with other Nd-isotope data, the record from Site 1276, supported by data from Sites 386 and 1050, suggests that the early–mid Campanian represented a major, fundamental transition in deep-ocean history and circulation, affecting widely dispersed areas of the Atlantic and Indian Oceans. The similarity between the spatial pattern of intermediate–deep-water Nd-isotope values in the latest Cretaceous and data from the Paleocene–Eocene, indicates that the new mode of circulation established in the Campanian, and most likely dominated by Southern Component Water, may have been the major mechanism of deep-ocean ventilation until the latest Eocene, and the initial descent from a "greenhouse" to "icehouse" climate.

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