Atlantic Ocean circulation during the Younger Dryas: Insights from a new Cd/Ca record from the western subtropical South Atlantic

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[1] Benthic foraminiferal Cd/Ca from an intermediate depth, western South Atlantic core documents the history of southward penetration of North Atlantic Intermediate Water (NAIW). Cd seawater estimates (Cd_W) for the last glacial are consistent with the production of NAIW and its export into the South Atlantic. At ~14.5 ka concurrently with the onset of the Bølling-Allerød to Younger Dryas cooling, the NAIW contribution to the South Atlantic began to decrease, marking the transition from a glacial circulation pattern to a Younger Dryas circulation. High Cd_W in both the deep North Atlantic and the intermediate South Atlantic imply reduced export of deep and intermediate water during the Younger Dryas and a significant decrease in northward oceanic heat transport. A modern circulation was achieved at ~9 ka, concurrently with the establishment of Holocene warmth in the North Atlantic region, further supporting a close linkage between deepwater variability and North Atlantic climate. *INDEX TERMS:* 4267 Oceanography: General: Paleoceanography; 4875 Oceanography: Biological and Chemical: Trace elements; 4870 Oceanography: Biological and Chemical: Stable isotopes; *KEYWORDS:* Cd/Ca, $\delta^{13}C$, Younger Dryas, intermediate water, foraminifera

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1. Introduction

[2] A large body of evidence suggests that several abrupt millennial-scale climate changes occurred during the last deglaciation [*Dansgaard et al.*, 1993; *Bond et al.*, 1993; *Lehman and Keigwin*, 1992]. The most notable of these deglacial climate events was the Younger Dryas, a brief return to near-glacial temperatures in the North Atlantic that began ~13,000 years ago and lasted ~1500 years. The Younger Dryas cooling has been observed in many North Atlantic climate proxies, including oxygen isotopes in Greenland ice cores [*Dansgaard*, 1984] and the faunal assemblages of planktonic foraminifera in the North Atlantic [*Ruddiman and McIntyre*, 1981].

[3] Major changes in the Atlantic Ocean's meridional overturning cell (MOC) may amplify millennial-scale climate variations in the North Atlantic. A decrease in the strength of the MOC would cause a reduction in the amount of heat transported by the upper ocean to the North Atlantic and therefore would cool the northern high latitudes [*Broecker et al.*, 1985a]. Models predict that a large decrease in the strength of the MOC also warms the surface and thermocline of the lower latitudes as a result of the reduced northward export of heat [*Manabe and Stouffer*, 1997; *Rahmstorf*, 1994; *Marchal et al.*, 1999]. Alkenone-derived temperature estimates from the tropics suggest that such a warming did occur during the Younger Dryas, with sea surface temperatures increasing by 1.2°C [*Rühlemann et al.*, 1999]. However, recent modeling studies [*Manabe and Stouffer*, 1997; *Marchal et al.*, 1999] suggest that only dramatic reductions in MOC could cause tropical warming. Thus a very large reduction in MOC would be consistent with the evidence suggesting a warming of the tropics during the Younger Dryas.

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[4] Nutrient proxies may be used to trace changes in ocean water mass geometry. In the modern ocean, North Atlantic Deep Water (NADW) forms in the northern Atlantic Ocean when surface water loses heat, becomes extremely dense, and sinks to great depths. Because surface water is relatively nutrient depleted, the NADW that originates from it is also nutrient depleted, causing a southward penetrating tongue of nutrient-depleted deep water. By contrast, Circumpolar Deep Water forms in the Southern Ocean from relatively nutrient enriched waters that upwell from great depth [e.g., *Broecker et al.*, 1985b]. Thus the pattern of nutrient distributions in the Atlantic Ocean reflects deepwater circulation patterns.

[5] Cd and $\delta^{13}C$ are two nutrient proxies used to trace deepwater circulation [*Boyle and Keigwin*, 1982; *Curry and Lohman*, 1982; *Boyle*, 1988; *Curry et al.*, 1988; *Duplessy et al.*, 1988]. Cd is a trace metal incorporated into organisms proportionately to other nutrients, resulting in a positive

correlation between Cd seawater (Cd_W) concentrations and oceanic PO_4 concentrations. Benthic foraminifera incorporate Cd into their $CaCO_3$ tests in direct proportion to the Cd concentration in the water in which they calcify. Thus the Cd/Ca ratio of the tests can be used as an indicator of the concentration of Cd (and thus PO_4) in the water at the time the foraminifera tests formed [*Hester and Boyle*, 1982]. The $\delta^{13}C$ distribution is the result of the isotopic fractionation of carbon associated with photosynthesis, which favors ^{12}C over ^{13}C. The remineralization at depth of low-$\delta^{13}C$ organic material produces a negative correlation between the $\delta^{13}C$ of dissolved inorganic carbon ($\delta^{13}C_{DIC}$) and PO_4 [e.g., *Kroopnick*, 1985]. Like Cd_W, the oceanic $\delta^{13}C_{DIC}$ signal is recorded in the tests of benthic foraminifera. Thus benthic foraminifera can be used to infer past water mass geometry: Low Cd and high $\delta^{13}C$ are indicative of a nutrient-depleted northern source, while high Cd and low $\delta^{13}C$ are indicative of a nutrient-enriched southern source.

[6] The $\delta^{13}C$ distribution, however, is complicated by the influence of the $\delta^{13}C$ air-sea exchange signature ($\delta^{13}C_{AS}$). When ocean water has contact with the atmosphere, a temperature-dependent fractionation of the carbon isotopes in CO_2 occurs [*Mook et al.*, 1974]. For a given atmospheric $\delta^{13}C$, colder temperatures result in higher $\delta^{13}C_{DIC}$. However, since different parcels of water spend varying amounts of time in contact with the atmosphere, the degree to which a parcel equilibrates with the atmosphere also varies. High wind speeds increase exchange rates, bringing the $\delta^{13}C_{DIC}$ closer to equilibrium with the atmosphere [*Liss and Merlivat*, 1986; *Broecker and Maier-Reimer*, 1992].

[7] Changes in Cd/Ca and $\delta^{13}C$ have been used to trace the past changes in the ocean's subsurface geometry. During the last glacial, deep waters of the North Atlantic were nutrient enriched relative to the present, and intermediate waters were nutrient depleted, suggesting a reduction in NADW formation and an increase in Glacial North Atlantic Intermediate Water (GNAIW) formation [*Boyle and Keigwin*, 1987]. Many studies have confirmed this glacial subsurface geometry of GNAIW overlying waters of southern origin [*Duplessy et al.*, 1988; *Oppo and Lehman*, 1993; *Marchitto et al.*, 2002]. There are conflicting interpretations for the subsurface geometry during the Younger Dryas. It has been suggested that deepwater formation decreased [*Boyle and Keigwin*, 1987] and intermediate water formation increased, signifying a glacial-like stratification for the Younger Dryas [*Marchitto et al.*, 1998; *Zahn and Stüber*, 2002]. Alternatively, *Sarnthein et al.* [2001] have suggested that MOC during the early Younger Dryas was similar to the modern mode, with significant NADW formation and little NAIW formation. They suggest that deepwater reduction occurred late, near the end of the Younger Dryas. Because the production of NADW at high latitudes results in greater heat loss to the atmosphere than the production of intermediate water at lower latitudes, the above interpretations predict very different roles of the MOC in cooling the North Atlantic during the Younger Dryas. Thus it is clear that a better understanding of changes in subsurface geometries is necessary in order to understand how oceanic heat transport changes on millennial timescales. In this study, we present a new record of intermediate depth variability using Cd/Ca data from a South Atlantic core to determine the response of North Atlantic Intermediate Water during the Younger Dryas.

2. Study Area

[8] Sediment core KNR159-5-36GGC (36GGC) was taken from the Brazilian margin at 27°31′S and 46°28′W, 1268 m (Figure 1). Today, the core site lies within waters that are a mixture of Upper Circumpolar Deep Water, Antarctic Intermediate Water (AAIW), and Labrador Sea Water [*Oppo and Horowitz*, 2000]. During the last glacial, water at this location consisted of at least one-third GNAIW but may have been entirely GNAIW (aged) [*Oppo and Horowitz*, 2000]. This core is ideally situated: It is directly in the flow path of GNAIW if this water mass exits the North Atlantic.

3. Methods

[9] Cd, Mn, and Ca concentrations were measured in the shells of the benthic foraminifera *Hoeglundina elegans*. This aragonitic species faithfully records bottom water Cd concentrations with a partition coefficient $D_P = [(Cd/Ca)_{foram}/(Cd/Ca)_{water}] \approx 1.0$ [*Boyle et al.*, 1995]. The partition coefficient of the aragonitic *H. elegans* is constant with depth, unlike the partition coefficients of calcitic foraminifera, which are depth dependent [*Boyle*, 1992]. A constant seawater Ca concentration of 0.01 mol kg^{-1} was assumed to estimate Cd seawater concentrations.

[10] Each sample consisted of approximately five individuals and was cleaned according to the methods of *Boyle and Keigwin* [1985] with a reversal of the oxidative and reductive steps to improve the removal of authigenic Cd deposits [*Boyle and Rosenthal*, 1996; *Rosenthal*, 1994; *Rosenthal et al.*, 1995]. Measurements were made using a Hitachi Z8200 atomic absorption spectrophotometer (AAS) tandem flame and graphite furnace. Cd and Mn were measured using graphite furnace AAS, and Ca was measured using flame AAS. Mn/Ca ratios were measured when possible in order to verify that manganese carbonate overgrowths are not a source of contamination at this site. Manganese carbonate overgrowths are a potential source of contamination in many species of benthic foraminifera [*Boyle*, 1983]. However, the species *H. elegans* was chosen for this study because it does not suffer from the contamination caused by such overgrowths [*Boyle et al.*, 1995].

[11] In order to assess the precision of measurements on the AAS, three consistency standards were treated as samples in each of the six runs in which the data were generated. Mean Cd/Ca values for the three consistency standards were 0.037, 0.089, and 0.127 μmol mol^{-1}. Standard deviations were 0.005, 0.004, and 0.007 μmol mol^{-1}, respectively. For *H. elegans*, which has a partition coefficient of 1, the resulting Cd_W errors range from 0.04 to 0.07 nmol kg^{-1}. Consistency standard data and sample data are available electronically.[1]

[1] Auxiliary consistency standard data and sample data are available electronicallly at World Data Center-A for Paleoclimatology, NOAA/NGDC, 325 Broadway, Boulder, CO 80303, USA. (paleo@mail.ngdc.noaa.gov; URL: http://www.ngdc.noaa.gov/paleo)

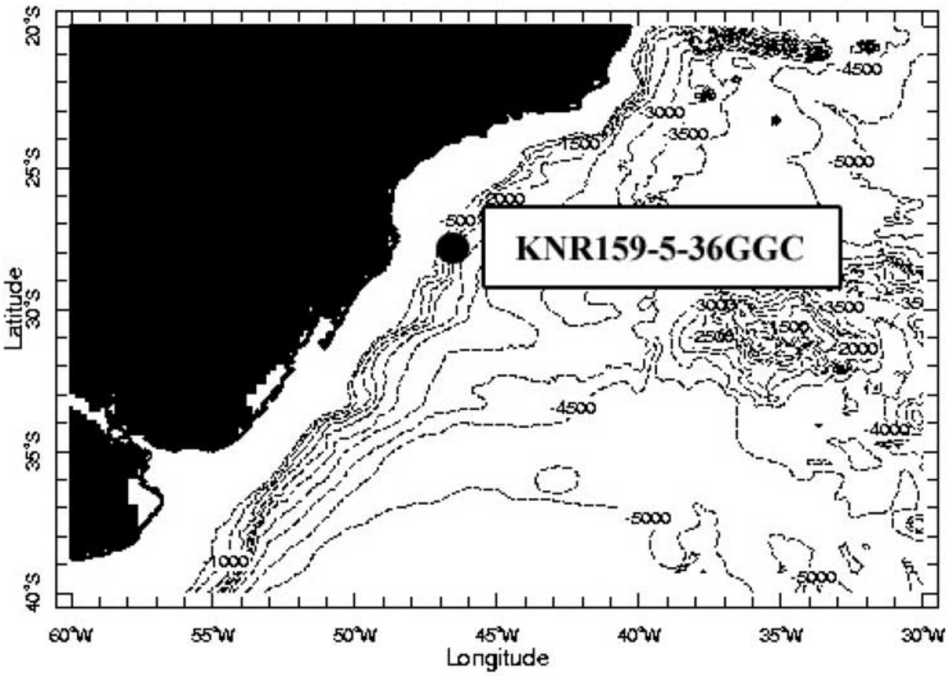

Figure 1. Map of the study area showing the location of core KNR159-5-36GGC (27°31′S, 46°28′W; 1268 m).

[12] For $\delta^{13}C$ determinations, *Oppo and Horowitz* [2000] used the species *Cibicidoides pachyderma* and a species that closely resembles *C. wuellerstorfi*. At one depth interval in this core (4 cm), $\delta^{13}C$ values were determined for both *C. wuellerstorfi* and the species that resembles it, and these values were found to be the same [*Oppo and Horowitz*, 2000]. In the western subtropical Atlantic, *C. pachyderma* and *C. wuellerstorfi* have the same $\delta^{13}C$ values as well [*Slowey and Curry*, 1995]. *Oppo and Horowitz* [2000] therefore concluded that the two species used for $\delta^{13}C$ measurements in this core are equivalent.

[13] Accelerator mass spectrometer (AMS) radiocarbon dates were obtained for 17 samples of the planktonic foraminifer *Globigerinoides ruber* and 1 sample of the benthic foraminifer *C. pachyderma*. AMS radiocarbon dates were converted to calendar age using the calibration program of *Stuiver and Reimer* [1993] (Table 1 and Figure 2). Overall, the data indicate a relatively constant sedimentation rate of slightly greater than 6 cm kyr^{-1} at this location, which is sufficient for resolution of the Younger Dryas. There is an age reversal in the chronology at 148 cm, where the age of the planktonic foraminifer *G. ruber* is ~14 kyr. However, the age of the benthic foraminifer *C. pachyderma* from the same sample (148 cm) is glacial, in close agreement with neighboring AMS dates. Benthic $\delta^{18}O$ and $\delta^{13}C$ values at this core depth are also typical of the last glacial and are distinctly different from those at ~14 kyr age (~90 cm) (Figure 2). Hence, while the benthic AMS date is not included in the determination of the age model, we proceed under the assumption that the *C. pachyderma* date more closely approximates the age of the sediment at this core level. We also note that the age reversal does not affect the deglacial portion of this core and hence our conclusions of the Younger Dryas.

[14] Additional AMS radiocarbon dates were obtained for deep North Atlantic core EN120-GGC1 (33°40′N, 57°37′W; 4450 m) and intermediate depth North Atlantic core OC205-2-103GGC (26°04′N, 78°03′W; 965 m) (Table 1). A new age model was developed for OC205-2-103GGC using the new and previously published dates [*Marchitto et al.*, 1998; *Curry et al.*, 1999]. The ages at 99.5 and 100 cm were averaged for the age model calculation.

4. Results and Discussion

[15] Average Cd_W values in core 36GGC range from a minimum value of 0.26 nmol kg^{-1} at 160 cm (19.4 kyr) to a maximum of 1.02 nmol kg^{-1} at 14 cm (2.9 kyr) (Figure 2). We have no explanation for the three anomalously high values that occur in the upper portion of the core, and a lack of sufficient *H. elegans* in this portion prevents further analysis. If the anomalously high values are removed, a maximum value of 0.64 nmol kg^{-1} is observed at 25.5 cm (4.3 kyr). Average glacial (0.40 nmol kg^{-1}) and Holocene (0.55 nmol kg^{-1}) Cd_W values determined using *H. elegans* are consistent with the previously published glacial *Uvigerina* spp. estimate of 0.43 nmol kg^{-1} and the modern seawater estimate of 0.67 nmol kg^{-1} [*Oppo and Horowitz*, 2000].

[16] The Cd_W data from Brazilian margin core 36GGC reveal an overall glacial-interglacial trend of increasing Cd_W values (Figures 2 and 3). The increase in Cd_W values at this intermediate depth site is indicative of increased nutrient concentrations and thus an overall decrease in the relative influence of northern source waters since the last glacial. These data are consistent with the work of *Boyle and Keigwin* [1987], who suggested that intermediate

Table 1. Accelerator Mass Spectrometer (AMS) Dates and Calendar Ages

Depth, cm	NOSAMS Number[a]	AMS Date	AMS Error	Calendar Age B.P.	Species	Source
				KNR159-5-36GGC		
1	OS-22674	1,740	30	1,283	*G. ruber*	this study
16	OS-25478	3,170	60	2,946	*G. ruber*	this study
28	OS-22675	4,450	40	4,606	*G. ruber*	this study
28	OS-22681	4,480	55	4,647	*G. ruber*	this study
40	OS-23216	6,000	35	6,402	*G. ruber*	this study
56	OS-22676	8,510	50	8,965	*G. ruber*	this study
60	OS-27350	9,450	50	10,262	*G. ruber*	this study
64	OS-25479	10,750	90	12,047	*G. ruber*	this study
68	OS-23210	10,600	45	11,683	*G. ruber*	this study
80	OS-23211	11,400	50	12,945	*G. ruber*	this study
88	OS-23212	12,200	50	13,674	*G. ruber*	this study
92	OS-22677	12,450	60	13,927	*G. ruber*	this study
104	OS-23318	13,550	60	15,691	*G. ruber*	this study
112	OS-23317	13,650	60	15,808	*G. ruber*	this study
141	OS-23213	14,850	120	17,192	*G. ruber*	this study
148	OS-22678	12,350	65	13,832	*G. ruber*	this study
148	OS-23214	16,050	65	18,573	*C. pachyderma*	this study
200	OS-22679	19,300	95	22,313	*G. ruber*	this study
				EN120-GGC1		
93	OS-33623	9,040	50	9,694	*G. ruber*	this study
107	OS-33624	10,850	60	12,212	*G. ruber*	this study
115	OS-33625	11,250	60	12,874	*G. ruber*	this study
115	OS-33626	11,200	65	12,838	*G. ruber*	this study
				OC205-2-103GGC		
10	OS-10523	920	35	518	*G. sacculifer*	*Marchitto et al.* [1998]
28	OS-26154	2,970	50	2,739	*G. sacculifer*	this study
42	OS-26155	3,850	35	3,815	*G. sacculifer*	this study
61	OS-26785	5,280	45	5,622	*G. sacculifer*	this study
62	OS-10524	5,290	45	5,636	*G. sacculifer*	*Marchitto et al.* [1998]
73	OS-26786	6,500	45	6,988	*G. sacculifer*	this study
88	OS-15376	7,630	45	8,073	*G. sacculifer*	*Curry et al.* [1999]
90	OS-33629	7,890	45	8,350	*G. ruber*	J. F. McManus, unpublished data, 2003
95.5	OS-33630	9,260	60	9,842	*G. ruber*	J. F. McManus, unpublished data, 2003
99.5	OS-33631	9,800	60	10,456	*G. ruber*	J. F. McManus, unpublished data, 2003
100	OS-26787	9,410	50	10,218	*G. sacculifer*	this study
105.5	OS-33632	10,400	55	11,334	*G. ruber*	J. F. McManus, unpublished data, 2003
113	OS-10526	11,000	50	12,472	*G. sacculifer*	*Marchitto et al.* [1998]
121	OS-10525	12,200	55	13,674	*G. sacculifer*	*Marchitto et al.* [1998]
134	OS-10527	17,100	100	19,781	*G. sacculifer*	*Marchitto et al.* [1998]

[a]NOSAMS is the National Ocean Sciences Accelerator Mass Spectrometer facility.

water formation was greater during the last glacial than it is today.

[17] Millennial-scale oscillations are superimposed on the glacial-interglacial trend. At ~14.5 ka, Cd_W values began to increase in concert with the gradual cooling observed in the Greenland Ice Sheet Project 2 (GISP2) ice core record (Figure 3). At ~12.8 ka a sharp depletion in the $\delta^{18}O$ of Greenland ice marks the rapid Northern Hemisphere cooling of the Younger Dryas. Concurrently, a more gradual increase is seen in the Cd_W concentration recorded in core 36GGC, culminating in peak values of 0.55 nmol kg^{-1} during the Younger Dryas, almost as high as interglacial values. These high values suggest an increase in nutrient concentrations at this intermediate depth site during the Younger Dryas, consistent with a decrease in the influence of northern source waters. Following the Younger Dryas, one lower Cd_W value at 36GGC suggests a possible resumption of northern source ventilation. Cd_W values soon increased, indicating a Holocene-like circulation with the contribution of nutrient-rich southern source waters.

[18] Comparison of the new Cd_W data with published data from the intermediate depth North Atlantic [*Marchitto et al.*, 1998] and from a deep North Atlantic site [*Boyle and Keigwin*, 1987] provides additional insight into the evolution of deep water since the last glacial. Figure 3 reveals three separate water mass geometries. During the period 14–20 ka both intermediate water sites were lower in Cd_W (and hence nutrients) than the deep North Atlantic, consistent with the interpretation of decreased NADW formation and increased GNAIW formation during the last glacial [*Boyle and Keigwin*, 1987]. At ~14 ka the deep North Atlantic became more nutrient depleted than the intermediate depth South Atlantic, marking an important transition between glacial and interglacial circulation. From ~9 to 14 ka, highest Cd_W values occurred in the intermediate depth South Atlantic, intermediate values occurred in the deep North Atlantic, and the lowest values occurred in the intermediate depth North Atlantic. At ~9 ka the modern geometry was firmly established: The North Atlantic deep and intermediate sites were both nutrient depleted, while the

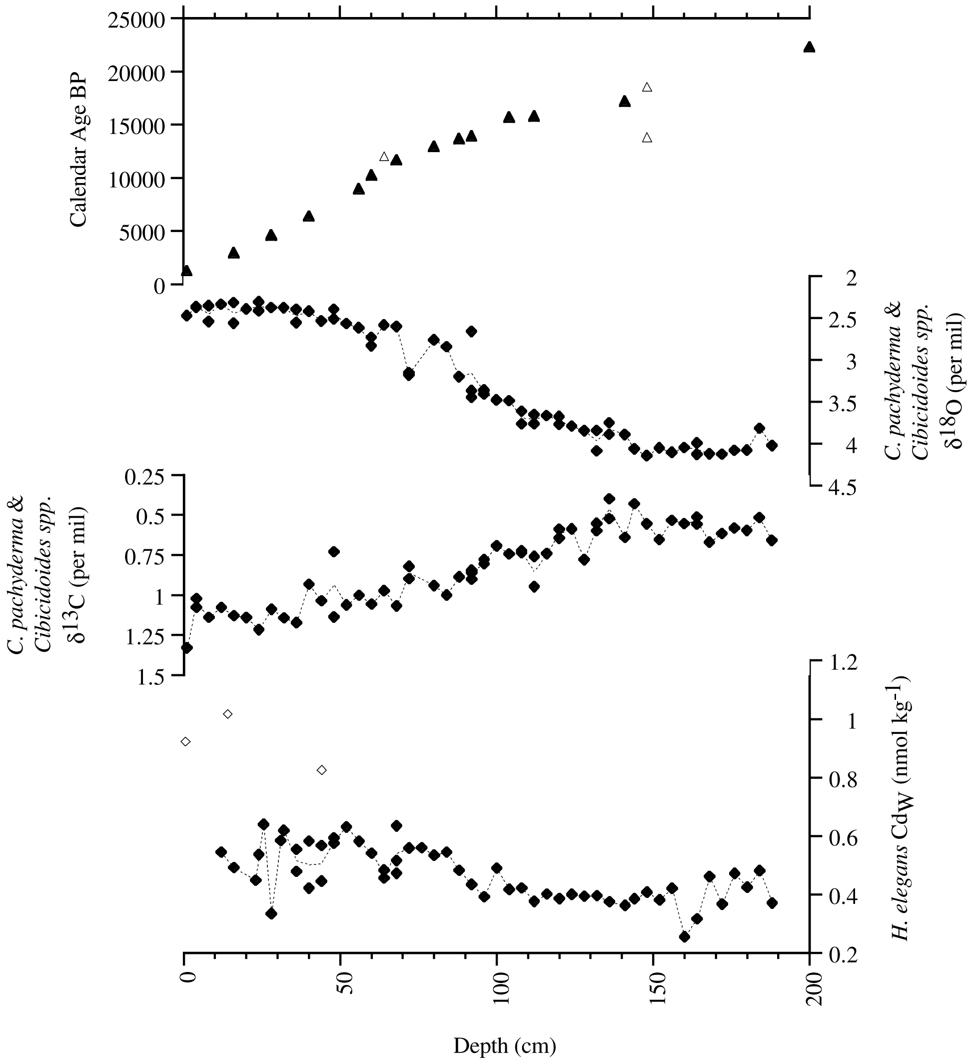

Figure 2. Data from core KNR159-5-36GGC (27°31′S, 46°28′W; 1268 m). At 148 cm a calendar age was obtained using the benthic foraminifer *C. pachyderma*; the rejected ages are open symbols (see text). Benthic foraminiferal $\delta^{18}O$ and $\delta^{13}C$ were obtained previously by *Oppo and Horowitz* [2000]. Benthic foraminiferal Cd seawater (Cd_W) estimates were obtained using the benthic foraminifer *H. elegans*. Rejected Cd_W values are open symbols.

intermediate South Atlantic remained high in nutrient concentrations (like today).

[19] Both North Atlantic sites show Cd_W increases at ~16.5 ka that may be associated with Heinrich event 1, an episode of massive iceberg discharge into the North Atlantic. This event is not clearly expressed in core 36GGC. As noted above, nutrients began to increase in the intermediate depth South Atlantic synchronously with the depletion in GISP2 $\delta^{18}O$ leading from the Bølling-Allerød into the Younger Dryas (Figure 3). A marked nutrient increase at the deep North Atlantic site began later, after the onset of GISP2 depletion in $\delta^{18}O$ but synchronously with the abrupt depletion in $\delta^{18}O$ at the onset of the Younger Dryas. Maximum Cd_W values were reached at both these sites during the Younger Dryas, suggesting a dramatic reduction in southward penetration of both deep and intermediate northern source waters. Cd_W data from the intermediate depth North Atlantic site are consistent with this interpretation. However, lower Cd_W values in the North Atlantic than in the South Atlantic indicate that NAIW continued to form, although it was less influential at the southern site. The early reduction in NAIW may indicate that intermediate waters are more sensitive to surface perturbation than deep waters, which appear closely linked with the rapid Younger Dryas temperature decreases over Greenland.

[20] The reduction in both NAIW and NADW during the Younger Dryas suggests a stronger decrease in northward heat transport than would a reduction in NADW alone. Although the deep North Atlantic core did not penetrate glacial sediments, data from IOS82 PC SO1 (42.38°N, 23.52°W; 3540 m) [*Boyle*, 1992] can be used to estimate glacial values (Figure 3, blue bars). For the deep North Atlantic, glacial Cd_W values are similar to Younger Dryas values. At both intermediate depth sites, Cd_W values are

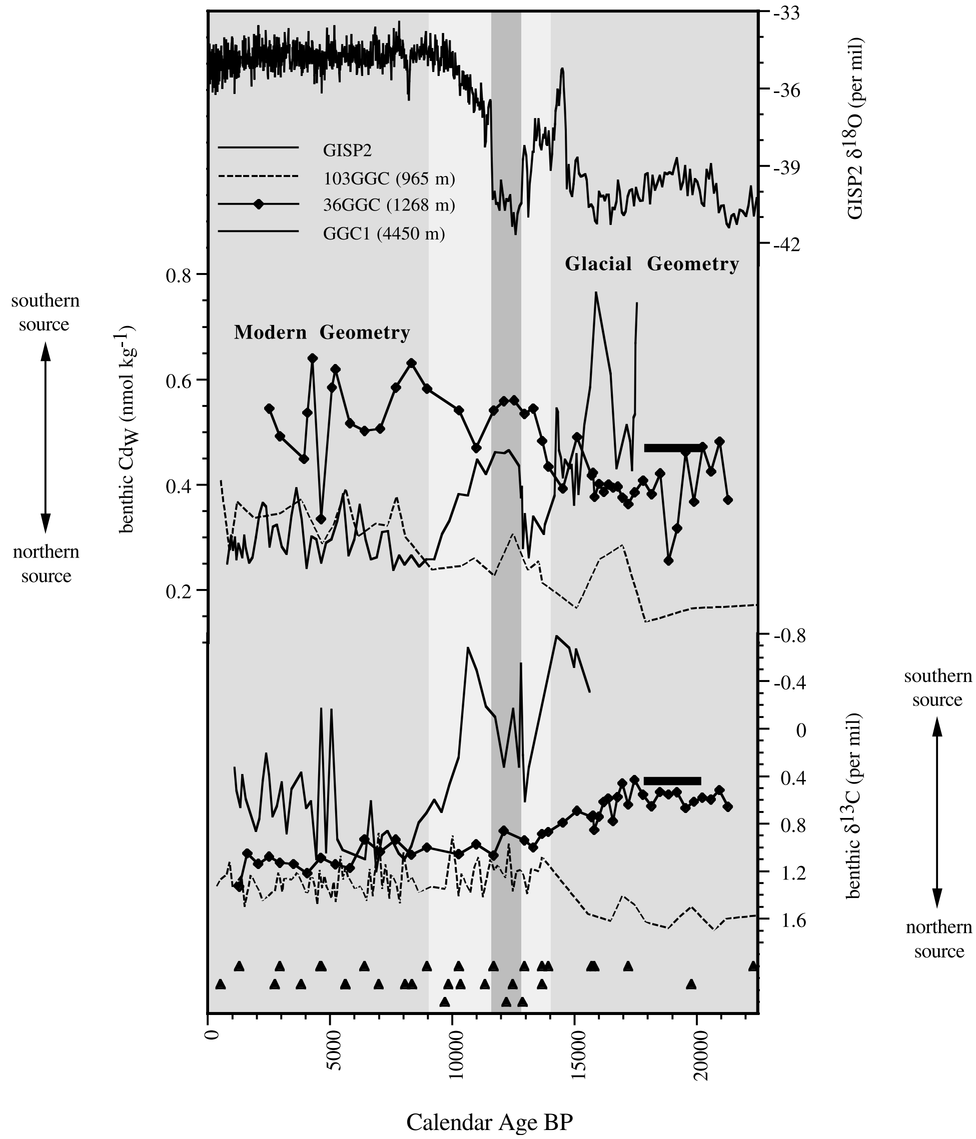

Figure 3. Cd$_W$ and δ^{13}C data. Data shown are (1) GISP2 δ^{18}O (pink) [*Grootes et al.*, 1993]; (2) mean Cd$_W$ from KNR159-5-36GGC (27°31′S, 46°28′W; 1268 m; red), OC205-2-103GGC (26°04′N, 78°03′W; 965 m; green) [*Marchitto et al.*, 1998], and EN120-GGC1 (33°40′N, 57°37′W; 4450 m; blue) [*Boyle and Keigwin*, 1987]; (3) mean δ^{13}C 36GGC (red) [*Oppo and Horowitz*, 2000], 103GGC (green) [*Slowey and Curry*, 1995; *Marchitto et al.*, 1998; *Curry et al.*, 1999], and EN120-GGC1 (blue) [*Boyle and Keigwin*, 1987]. Glacial Cd$_W$ and δ^{13}C estimates for the deep North Atlantic (blue bars) are based on data from IOS82 PC SO1 (42.38°N, 23.52°W; 3540 m) [*Boyle*, 1992]. Accelerator mass spectrometer (AMS) radiocarbon dates for 103GGC were obtained in this study and previously [*Marchitto et al.*, 1998; *Curry et al.*, 1999; J. F. McManus, unpublished data, 2003]. The age models for 103GGC and 36GGC are based on AMS radiocarbon dates converted to calendar age (green triangles for 103GGC and red triangles for 36GGC) and linear interpolation between points. The age model for GGC1 is based on cross correlation with features that have been radiocarbon dated in nearby cores [*Boyle and Keigwin*, 1987]. Newly obtained ages for GGC1 (blue triangles) support the model of *Boyle and Keigwin* [1987]. Yellow shading indicates the Younger Dryas interval. See color version of this figure at back of this issue.

higher during the Younger Dryas than during the glacial. These results suggest a weaker overall North Atlantic MOC during the Younger Dryas than during the last glacial, which may imply less northward heat transport during the Younger Dryas than during the Last Glacial Maximum.

[21] At the end of the Younger Dryas cold period, one low Cd$_W$ value at the Brazilian margin site suggests a possible increase in the influence of nutrient-depleted northern source water. By 9 ka, Cd$_W$ values at all sites reached Holocene levels, suggesting that the modern deepwater

configuration was finally established at this time. The GISP2 $\delta^{18}O$ record suggests that Holocene warmth was also reached at ~9 ka, providing further evidence for a close link between the MOC, heat transport, and North Atlantic temperatures.

[22] Glacial-interglacial circulation changes suggested by the $\delta^{13}C$ trends from EN120-GGC1 [*Boyle and Keigwin*, 1987], OC205-2-103GGC [*Slowey and Curry*, 1995; *Marchitto et al.*, 1998; *Curry et al.*, 1999], and KNR159-5-36GGC [*Oppo and Horowitz*, 2000] are similar to those suggested by the Cd_W data (Figure 3). For the last glacial the $\delta^{13}C$ data suggest that the deep North Atlantic was the most nutrient rich of the three sites and the intermediate depth North Atlantic was the most nutrient depleted, in agreement with the Cd_W data. Similarly, the overall glacial-interglacial trends of decreasing nutrients in the deep North Atlantic and increasing nutrients in the intermediate depth North Atlantic also agree with the Cd_W data. However, the intermediate depth South Atlantic $\delta^{13}C$ data obtained by *Oppo and Horowitz* [2000] exhibit an overall trend of increasing $\delta^{13}C$ since the last glacial. As discussed above, the trend of increasing Cd_W values at the South Atlantic site indicates increasing nutrients on glacial-interglacial timescales. Therefore the glacial-interglacial $\delta^{13}C$ trend was not driven by decreasing nutrients. Rather, increasing $\delta^{13}C$ in parallel with the Cd_W increase suggests that the $\delta^{13}C_{AS}$ signature changed on glacial-interglacial timescales.

[23] During the last glacial, water at the Brazilian margin site had a low $\delta^{13}C_{AS}$ exchange signature of 0–0.3‰, while today it has a very high $\delta^{13}C_{AS}$ exchange signature of 0.5‰ [*Oppo and Horowitz*, 2000]. During the glacial the low-$\delta^{13}C_{AS}$ signature at the Brazilian margin site is similar to that of GNAIW, so waters at this site may be the result of GNAIW aging along its flow path from the North Atlantic to the South Atlantic. Today, the very high $\delta^{13}C_{AS}$ signature observed at this location could not result from aging of a low-$\delta^{13}C_{AS}$ exchange signature water mass like NAIW since the $\delta^{13}C_{AS}$ is a conservative property of a water mass. Instead, water at this location and depth is more influenced by AAIW, which has a very high $\delta^{13}C_{AS}$ signature [*Oppo and Horowitz*, 2000]. Thus the nearly constant north-south gradient in Cd_W between the intermediate depth North Atlantic and the intermediate depth South Atlantic could be viewed as simple aging of northern source waters during the glacial but not during the Holocene.

[24] The increase in glacial $\delta^{13}C$ values began at ~17 ka, but it is not possible to separate the contributions of the increase in the mean ocean $\delta^{13}C$ value that resulted from the increase in the size of the terrestrial biosphere from the increase because of the changes in the $\delta^{13}C_{AS}$ exchange signature. These complicating effects may also explain why the Younger Dryas is not clearly expressed in the $\delta^{13}C$ of the intermediate depth North Atlantic or the intermediate depth South Atlantic.

5. Conclusion

[25] New Cd_W data from an intermediate depth southwestern Atlantic core clarify the response of NAIW since the last glacial. During the last glacial, deep, nutrient-rich Southern Ocean water was overlain by nutrient-depleted NAIW [*Boyle and Keigwin*, 1987], and NAIW penetrated farther into the South Atlantic than it does today [*Oppo and Horowitz*, 2000]. The new data suggest a trend of decreasing southward penetration of NAIW that began with the gradual cooling leading to the Younger Dryas and culminating during the event. Lower Cd_W values in the intermediate depth North Atlantic [*Marchitto et al.*, 1998] than in the intermediate depth South Atlantic, however, indicate that NAIW continued to form. Data from a previous study suggest that a dramatic reduction in NADW contribution to the deep North Atlantic occurred later and more abruptly, synchronously with the rapid cooling that marked the beginning of the Younger Dryas [*Boyle and Keigwin*, 1987]. The similar timing of surface cooling in the North Atlantic region and changes in intermediate and deep circulation confirm a close link between the MOC and North Atlantic climate. This linkage is further bolstered by our observation that deepwater geometry reached its modern configuration at about the same time that deglacial warming of the North Atlantic was complete, ~9 kyr.

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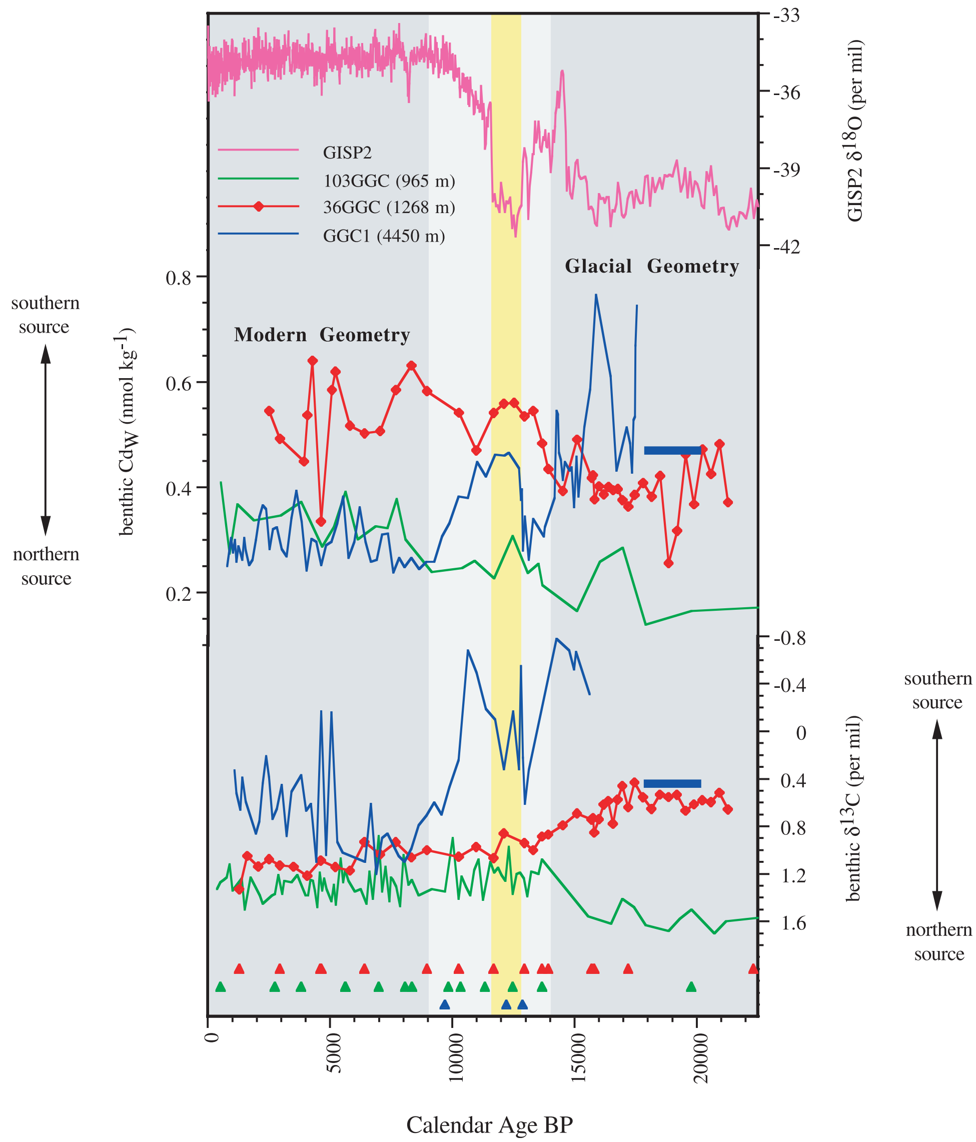

Figure 3. Cd$_W$ and δ^{13}C data. Data shown are (1) GISP2 δ^{18}O (pink) [*Grootes et al.*, 1993]; (2) mean Cd$_W$ from KNR159-5-36GGC (27°31′S, 46°28′W; 1268 m; red), OC205-2-103GGC (26°04′N, 78°03′W; 965 m; green) [*Marchitto et al.*, 1998], and EN120-GGC1 (33°40′N, 57°37′W; 4450 m; blue) [*Boyle and Keigwin*, 1987]; (3) mean δ^{13}C 36GGC (red) [*Oppo and Horowitz*, 2000], 103GGC (green) [*Slowey and Curry*, 1995; *Marchitto et al.*, 1998; *Curry et al.*, 1999], and EN120-GGC1 (blue) [*Boyle and Keigwin*, 1987]. Glacial Cd$_W$ and δ^{13}C estimates for the deep North Atlantic (blue bars) are based on data from IOS82 PC SO1 (42.38°N, 23.52°W; 3540 m) [*Boyle*, 1992]. Accelerator mass spectrometer (AMS) radiocarbon dates for 103GGC were obtained in this study and previously [*Marchitto et al.*, 1998; *Curry et al.*, 1999; J. F. McManus, unpublished data, 2003]. The age models for 103GGC and 36GGC are based on AMS radiocarbon dates converted to calendar age (green triangles for 103GGC and red triangles for 36GGC) and linear interpolation between points. The age model for GGC1 is based on cross correlation with features that have been radiocarbon dated in nearby cores [*Boyle and Keigwin*, 1987]. Newly obtained ages for GGC1 (blue triangles) support the model of *Boyle and Keigwin* [1987]. Yellow shading indicates the Younger Dryas interval.