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Did North Atlantic overturning halt 17,000 years ago?

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[1]   Models indicate that a complete shutdown of deep and intermediate water production is a possible consequence of extreme climate conditions in the northern North Atlantic, and the high ratio of ^{231}Pa to ^{230}Th on Bermuda Rise is evidence that this might have happened ∼17 ka during Heinrich event 1 (H1). However, new radiocarbon data from bivalves that lived at ∼4.6 km on the Bermuda Rise during H1 lead to a different conclusion. The bivalve data do indeed indicate ventilation of the deep western North Atlantic was suppressed during H1 but not as much as it was during the last glacial maximum. We propose that high diatom flux to the Bermuda Rise during H1 is at least in part responsible for increased ^{231}Pa/^{230}Th at that time. Although we cannot say for sure why opal production was so high in a gyre center location at that time, increased leakage of silica rich waters from the Southern Ocean to the North Atlantic is one possibility.

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1.   Introduction

[2]   Paleoceanographic data have been interpreted as evidence that the Atlantic meridional overturning circulation (MOC), and by inference the North Atlantic heat flux, were reduced abruptly during late Quaternary times of cold climate as reflected in Greenland ice cores. However, for many years there has been speculation about a complete halt of overturning during the harshest climate extremes. The massive discharge of icebergs and fresh water that occurred about 17 ka, known as Heinrich event 1 (H1), has been associated with high Cd content in the deep Atlantic Ocean, and such low ratios of stable carbon isotopes that would (if taken at face value) indicate the complete replacement of North Atlantic Deep Water by water of Antarctic or even of North Pacific origin [*Boyle and Keigwin*, 1987] (Figure 1). However, there is also evidence that very low δ^{13}C sometimes can be an artifact of high carbon rain rate to the seafloor, where it has been suggested that a layer of organic fluff could cause anomalously low ratios when oxidized [*Mackensen et al.*, 1993]. Also, in fairness neither Cd/Ca, δ^{13}C nor any other paleoproxy can be certified as completely artifact-free. Hence we seek multiple proxy evidence to strengthen our conclusions. Four series of proxy data from the western North Atlantic, with emphasis on the Bermuda Rise (∼33.5°N, 57.5°W, 4.6 km), are in clear agreement that events such as the Last Glacial Maximum (LGM), H1, and the Younger Dryas were marked by reduced MOC compared to today (Figure 1).

2.   The ^{231}Pa/^{230}Th as a Tracer for Ventilation

[3]   Recently, *McManus et al.* [2004] measured the protactinium/thorium ratio (^{231}Pa/^{230}Th) in Sargasso Sea sediments as a proxy for the export of water from the North Atlantic basin since the LGM. This method was first developed by *Yu et al.* [1996] based on the spatial patterns of ^{231}Pa/^{230}Th in LGM sediments of the Atlantic and Southern Ocean, and its limitations as a proxy for MOC change were explored by *Marchal et al.* [2000]. Because the *McManus et al.* [2004] site lies in very deep water (∼4.6 km) on the Bermuda Rise, the ^{231}Pa/^{230}Th signal integrates a large part of the western North Atlantic water column. They reported that the MOC was ''nearly or completely eliminated'' during H1, whereas moderate overturning did occur during the last glacial maximum and during the Younger Dryas (YD) cold episode. One surprise in their results is that the suppression of the MOC lingered until ∼15 ka, more than a thousand years after the end of H1. A similar ^{231}Pa/^{230}Th history was reported from a core off Portugal [*Gherardi et al.*, 2005], and a proxy for magnetic mineral grain size suggests weak flow south of Greenland at ∼1.9 km during H1 [*Stanford et al.*, 2006]. The timing of the grain size changes south of Greenland and the shape of that curve are remarkably similar to the ^{231}Pa/^{230}Th result from the Bermuda Rise. In contrast, ^{231}Pa/^{230}Th from a site off Ireland at ∼1.7 km water depth indicates that intermediate depths were ventilated during H1 [*Hall et al.*, 2006].

[4]   As with δ^{13}C, ^{231}Pa/^{230}Th has an Achilles heel, because ^{231}Pa is scavenged more readily than ^{230}Th by biogenic silica [*Chase et al.*, 2002], and models clearly show the effect of particle flux [*Siddall et al.*, 2007]. Thus high production of opal by diatoms during H1 could account for the high ratio of ^{231}Pa/^{230}Th at that time. This effect is clearly demonstrated in the eastern equatorial Pacific by *Bradtmiller et al.* [2006] and by *Hall et al.* [2006] to the north. In the latter study, the production ratio of ^{231}Pa/^{230}Th was only achieved in Holocene sediments when diatom flux was at a maximum. Such high produc-

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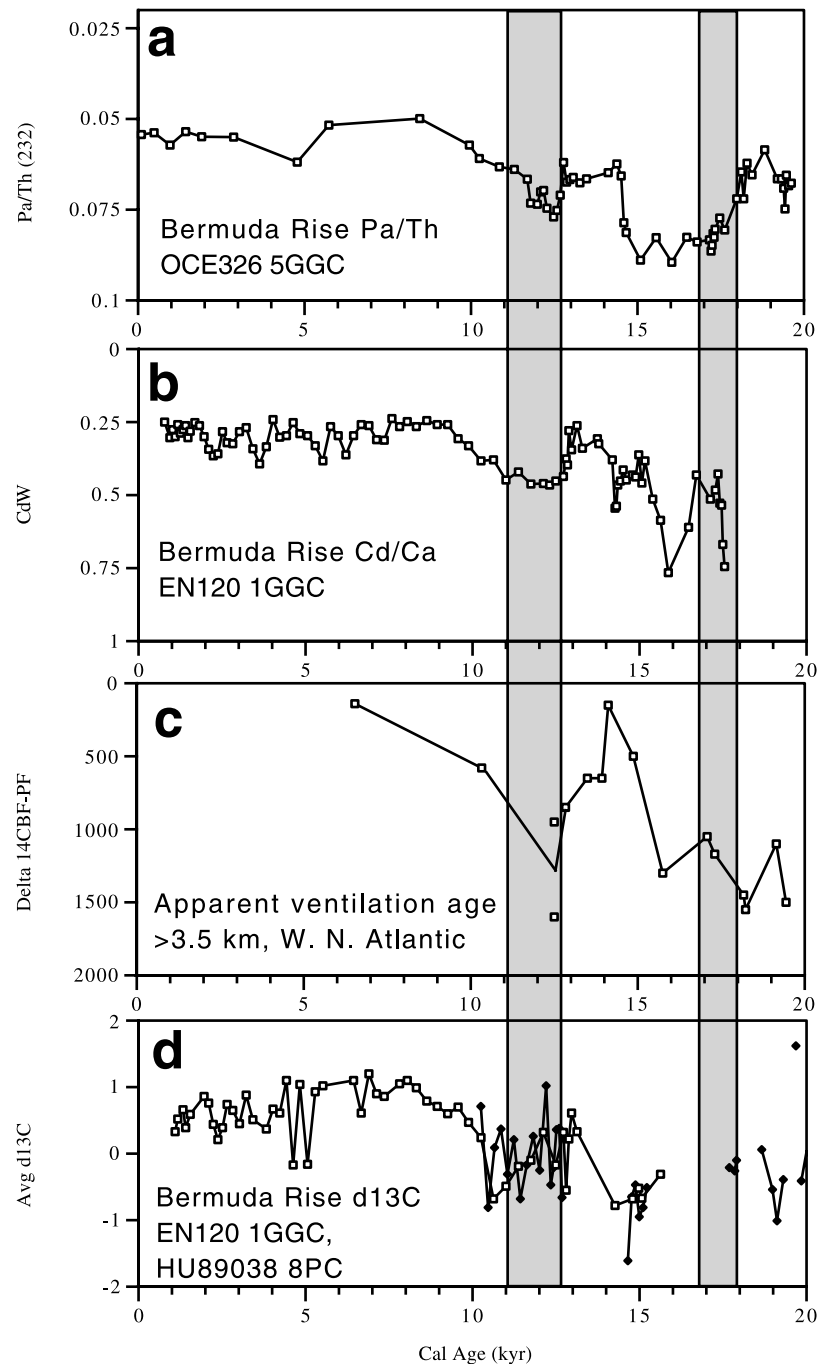
Figure 1. Four series of MOC proxy data from Bermuda Rise cores and cores elsewhere in the western North Atlantic: (a) $^{231}Pa/^{230}Th$ results from *McManus et al.* [2004], (b) Cd/Ca results on benthic foraminifera [*Boyle and Keigwin*, 1987], (c) stack of apparent ventilation ages (difference between conventional ^{14}C ages on benthic and planktonic foraminiferal pairs) from the western North Atlantic >3.5 km water depth [*Keigwin*, 2004; *Robinson et al.*, 2005], (d) $\delta^{13}C$ on the benthic foraminifer *Cibicidoides* spp. from *Boyle and Keigwin* [1987] (EN120 1GGC) and this paper (HU89038 8PC). In making the stack of radiocarbon ventilation data (Figure 1c), we assume that the difference in $\Delta^{14}C$ between sites is less than the changes through time. The shaded bars illustrate the duration of the Younger Dryas and H1 in the western North Atlantic region. Note that although there are differences in detail, the proxy data all agree that MOC was reduced compared to today during the Younger Dryas and H1.

Table 1. Paired Bivalve and Planktonic Foraminiferal Radiocarbon Dates From Two Bermuda Rise Cores

Species	Midpoint Depth, cm	Conventional ^{14}C Age, ka	Error, 1σ	Accession Number	Calibration Age, ka	Error, 1σ
		Core HU89038 8PC				
S. scheltemai	365	15,970	120	LLNL 126567		
G. inflata	365	14,800	60	OS-57569	17,280	220
T. cf equalis	575	18,200	160	LLNL 126568		
G. inflata	575	16,700	90	OS-57570	19,443	90
		Core OCE326 GGC5				
S. scheltemai	221	15,800	90	OS-42495		
G. inflata[a]	221	14,750	65	OS-33903	17,077	248

[a]This sample reported on previously by *McManus et al.* [2004].

tivity normally would be unexpected for an oligotrophic location such as the northeast Bermuda Rise, but diatom accumulation rates were indeed much higher during the LGM and termination than during the Holocene under eastern Atlantic upwelling systems [*Abrantes*, 2000]. Barium as a tracer also indicates higher productivity over the Iberian margin during the last three terminations [*Thomson et al.*, 2000]. *McManus et al.* [2004] checked for the opal effect by measuring the ratio of Si to Al, which they found to be the same in H1 sediments as in continental rocks (~3.0 to 3.5). On that basis, they discounted the role of diatom production in the ^{231}Pa/^{230}Th of bulk sediments from the Bermuda Rise. However, the amount of opal that survived to be buried in the geological record may well be less important than the flux of opal that reached the seafloor in the first place. Because opal is unsaturated everywhere in the ocean, it is possible that there might have been a high opal flux during H1 in the northern Sargasso Sea, but much of the opal dissolved away on the seafloor before burial.

3. Δ^{14}C as a Tracer for Ventilation

[5] Yet another proxy has been brought to bear on problems of western North Atlantic MOC. *Robinson et al.* [2005] created a depth profile of change in seawater Δ^{14}C for the past 20,000 years by compiling ^{14}C data on corals, foraminifera, and molluscs. In general, their results are concordant with those of *McManus et al.* [2004], strengthening the conclusion that the MOC was reduced during the last glacial maximum, H1 and the YD. In detail, however, there are some important differences, and these could be caused by uncertainties in using ^{14}C as a tracer for the MOC. For example, we do not know the "preformed" radiocarbon content of high-latitude surface waters, ^{14}C doesn't tell us about the mixing history of a water parcel, and past changes in the surface ocean "reservoir effect" are usually unconstrained. Nevertheless, in contrast to ^{231}Pa/^{230}Th, the ^{14}C data indicate that the extent of overturning in the western North Atlantic increased from the LGM to H1 to the YD. The critical ^{14}C data for H1 came from a single bivalve from the same Bermuda Rise core as the ^{231}Pa/^{230}Th data (Table 1). That species, *Spinula scheltemai* (Figure 2), is endemic to the deep South Atlantic [*Allen and Sanders*, 1996] and provides biogeographic evidence for transport from the south. *S. scheltemai* produces few, but large eggs, so the larvae probably traveled northward with prevailing deep currents during H1. The

radiocarbon age of *S. scheltemai* is only about 1000 years greater than coeval planktonic foraminifera (Figure 3 and Table 1), whereas elsewhere in the deep western North Atlantic the age difference (the apparent ventilation age) can be as much as 1450 years during the LGM [*Keigwin*, 2004]. The modern difference is several hundred years. If the reservoir age of the Sargasso Sea surface was much greater during H1 than the present 400 years, this could create an anomalously low apparent ventilation age, but probably not as much as observed.

[6] To verify this one observation of apparent ventilation age during H1, we reproduced it using *S. scheltemai* and other bivalves in Bermuda Rise core HU89038 PC-008 (Figure 3). One individual *S. scheltemai* (both valves) was found in the H1 interval. It has a conventional ^{14}C age of 15,970 ± 120 years, and planktonic foraminifera (*G. inflata*) from the same sample are 14,800 ± 60 conventional ^{14}C years old (Table 1). With an apparent ventilation age of 1170 years, the agreement of results between this core and the bivalve date on the *McManus et al.* [2004] core is
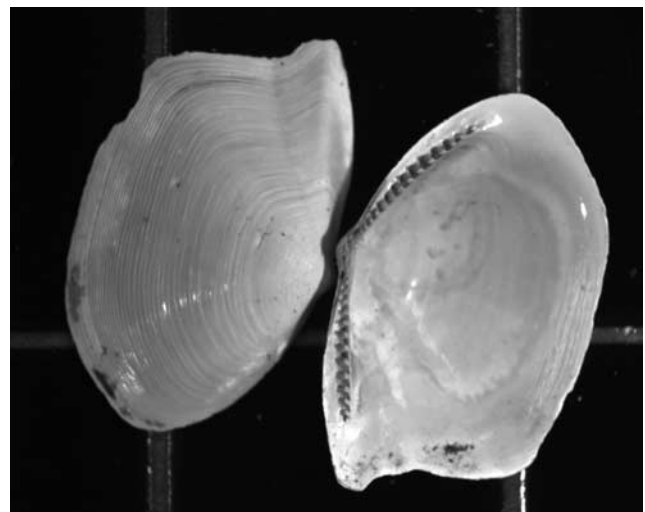

Figure 2. Photograph of *Spinula scheltemai* from OCE326 5GGC on a 1 cm^2 grid. These two valves were articulated prior to the photography. The long axis of the shell is about 1 cm, close to the maximum size of this species [*Allen and Sanders*, 1982]. The lustrous nacreous layer and shreds of the outer organic lining (periostracum) illustrate the excellent preservation of this specimen.

excellent. Deeper in HU89038 PC-008, at a level dated to 16,700 conventional ^{14}C years (approximately LGM), we found a specimen of *Thyasira cf equalis*, a bivalve that is common in the western North Atlantic today (J. A. Allen, personal communication, 2006). *T. cf equalis* has a conventional ^{14}C age of 18,200 ± 160 years, giving an apparent ventilation age of 1500 years. This is concordant with the oldest western North Atlantic ventilation ages based on benthic foraminifera, and it implies that ventilation during the LGM may have been more suppressed than it was during H1 on the Bermuda Rise.

[7] H1 in HU89038 PC-008, as in other cold intervals from Bermuda Rise cores, contains significant biogenic silica in the sand fraction (>63 μm). Radiolaria are preserved in Bermuda Rise sediments in significant numbers until about 14.5 ka [*Keigwin et al.*, 1991], and the abundance of diatoms in some samples from core PC-008 made picking foraminifera so difficult that we used a settling method to separate the opal from the remaining sand fraction (mostly foraminifera and pyrite). This was necessary only in the interval 16.5 to 18.6 calibrated ka (330 to 490 cm), which brackets H1 according to δ^{18}O stratigraphy (Figure 3). Within that interval, the mass of opal is 63 ± 10% of the sand fraction. Although it is notoriously difficult to measure the opal content of marine sediments that are as clay rich as the Bermuda Rise, X-ray diffraction results from ODP Site 1063 indicate an average opal content of ~20% in bulk sediment from the stadial event between interstadials 19 and 20 (stage 5/4 boundary) [*Dunbar*, 2001]. Si/Al is about 3.8 in those samples.

4. Conclusion

[8] We do not know why so much opal was occasionally produced in the northern Sargasso Sea, nor do we know why it may have been selectively preserved. *Brzezinski et al.* [2002] and *Matsumoto et al.* [2002] have suggested that during the LGM, an enhanced Fe supply to the Southern Ocean led to NO_3^- depletion and diminished $Si(OH)_4$ use (as suggested by the experiment of *Hutchins and Bruland* [1998]). They further suggested that this high-Si surface water was transported northward into the subtropics and lead to more diatom production at the expense of coccolithophorids. This scenario has received support from *Bradtmiller et al.* [2007], who found that peak opal fluxes and maximum ^{231}Pa/^{230}Th are coincident on deglaciation in the equatorial Atlantic sediments. However, until we understand the transport of $Si(OH)_4$ to the Sargasso Sea and its preservation as opal, it is premature to conclude that export of all deep and intermediate waters from the North Atlantic was suspended during H1. Although in theory a complete shutdown of North Atlantic ventilation is possible [*Manabe and Stouffer*, 1988; *Schiller et al.*, 1997], we need concordant multiproxy data at many locations before concluding
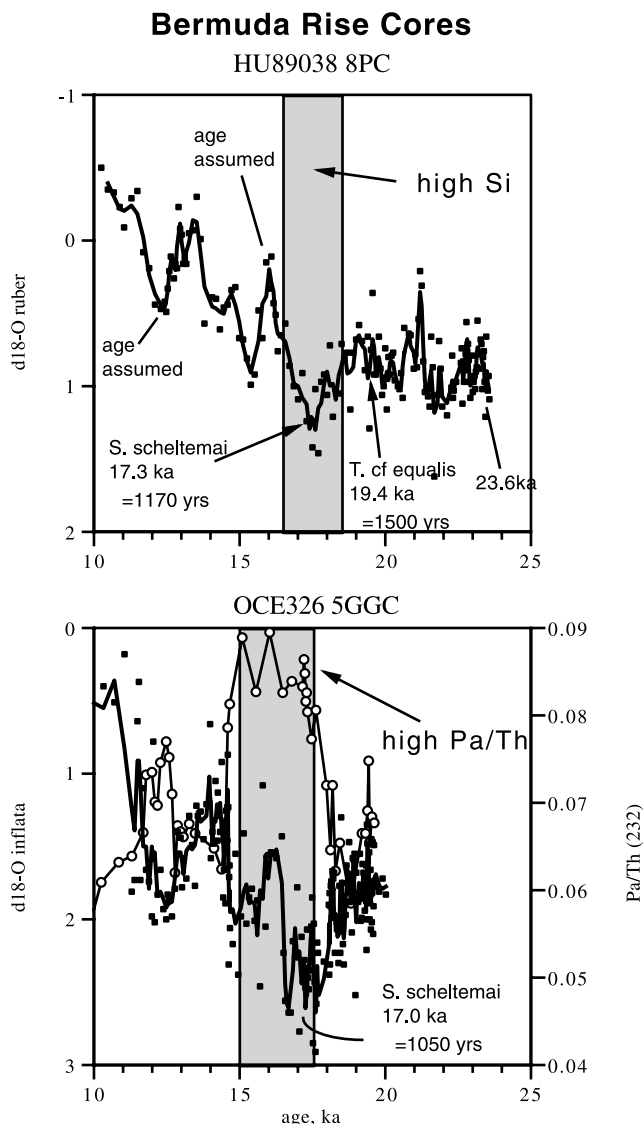

Bermuda Rise Cores

HU89038 8PC

OCE326 5GGC

Figure 3. Oxygen isotope stratigraphies on two cores from the northeast Bermuda Rise at about 4.6 km water depth (approximately 33°41.4′N, 57°34.5′W). Results and age model in core 5GGC are after *McManus et al.* [2004]. The age model in core 8PC is based on the ^{14}C dates on planktonic foraminifera (shown) as well as correlation of the deglacial oscillations to earlier work [*Keigwin et al.*, 1991]. The offset in δ^{18}O between the two sites most likely reflects the seasonality of the two species. *Globigerinoides ruber* lives year-round in surface waters, whereas *Globorotalia inflata* lives deep within the late winter surface mixed layer [*Deuser*, 1987]. The shaded interval in the 8PC plot marks the presence of relatively high opal (diatom) content in the sand fraction and in 5GGC plot marks the high ratio of ^{231}Pa/^{230}Th (shown as circles and based on ^{232}Th correction [*McManus et al.*, 2004]). Radiocarbon results on the bivalve *S. scheltemai* (Table 1) and planktonic foraminifera from Heinrich event 1 (shaded interval) in each core show that we have sampled the same event and that the apparent ventilation age (Δ) was about 1100 years. In contrast, the apparent ventilation age during the LGM (~19 ka) in 8PC was about 1500 years in agreement with measurements on benthic foraminifera elsewhere in the western North Atlantic [*Keigwin*, 2004].

that it actually happened. In other words, the burden of proof when interpreting ^{231}Pa/^{230}Th as a proxy for MOC is to show that opal flux to the seafloor is not a concern.

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