

## Atlantic Ocean thermohaline circulation changes on orbital to suborbital timescales during the mid-Pleistocene

H. F. Kleiven,<sup>1</sup> E. Jansen,<sup>2,5</sup> W. B. Curry,<sup>3</sup> D. A. Hodell,<sup>4</sup> and K. Venz<sup>4</sup>

Received 8 February 2001; revised 15 August 2002; accepted 24 September 2002; published 19 February 2003.

[1] Mid-Pleistocene benthic  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  time series from the North Atlantic site 983 and Ceara Rise site 928 are compared to an array of existing isotopic records spanning the Atlantic basin and the geographic extremes of the North Atlantic Deep Water/Southern Ocean Water interface during both glacial and interglacial periods. This comparison allows the persistent millennial-scale intermediate depth North Atlantic ventilation changes recorded at site 983 to be placed within the context of the longer period water mass reorganizations taking place throughout the mid-Pleistocene. Our benthic  $\delta^{13}\text{C}$  results suggest that the intermediate depth North Atlantic experienced millennial-scale changes in ventilation throughout the mid-Pleistocene climate shift. The times of poorest ventilation (low benthic  $\delta^{13}\text{C}$ ) persisted for only a few millennia and were associated with rapid decreases in benthic  $\delta^{18}\text{O}$ , suggesting that ice sheet decay and melt water induced salinity changes were effective at throttling deep water production in the North Atlantic throughout the mid-Pleistocene. Similar but less pronounced decreases in the  $\delta^{13}\text{C}$  of the middepth waters also punctuated interglacials, suggesting that large ice sheet fluctuations do not explain all of the observed thermohaline circulation mode shifts in the North Atlantic. Meanwhile, on orbital timescales, glacial deep to intermediate water  $\delta^{13}\text{C}$  gradients evolved after  $\sim 0.95$  Ma. Taken together, these observations provide a number of new constraints for understanding the timing and evolution of deep water circulation changes across the mid-Pleistocene. *INDEX TERMS:* 4267 Oceanography: General: Paleoceanography; 4870 Oceanography: Biological and Chemical: Stable isotopes; 9325 Information Related to Geographic Region: Atlantic Ocean; *KEYWORDS:* mid-Pleistocene, deep water, North Atlantic, ODP, stable isotopes, millennial scale

**Citation:** Kleiven, H. F., E. Jansen, W. B. Curry, D. A. Hodell, and K. Venz, Atlantic Ocean thermohaline circulation changes on orbital to suborbital timescales during the mid-Pleistocene, *Paleoceanography*, 18(1), 1008, doi:10.1029/2001PA000629, 2003.

### 1. Introduction

[2] Understanding long-term history of North Atlantic intermediate to deep water circulation is important for assessing of the role of the thermohaline circulation (THC) in global climate change. Today, North Atlantic Deep Water (NADW) ventilates more than half of the volume of the deep oceans, affecting the physical and chemical properties of deep water globally. A growing body of geological and geochemical evidence demonstrates that at certain times in the past, the production of NADW, and with it the climate of the circum-Atlantic, changed at rates and with magnitudes that are of societal relevance. During the most recent glaciation, large reorganizations in the circulation of the North Atlantic Ocean and the Nordic Seas mirrored variations in air temperature over Greenland, suggesting that

ocean circulation was tightly linked to North Atlantic climate over both glacial-interglacial and shorter timescales [Boyle and Keigwin, 1987; Curry *et al.*, 1988; Curry and Oppo, 1997; Dokken and Jansen, 1999; Duplessy *et al.*, 1988; Fronval *et al.*, 1995; Keigwin *et al.*, 1994; Koc and Jansen, 1994; Oppo and Lehman, 1995]. During the coldest events, deep waters of a southern origin replaced NADW in the North Atlantic basin, and a nutricline developed between intermediate and deep waters. Concurrently, the ventilation by northern source waters shifted from deep to intermediate depths and was interrupted by numerous millennial-scale events during which ventilation was reduced at all depths in the north [Sarnthein *et al.*, 1994]. These brief episodes of poor ventilation are frequently associated with distinct layers of ice-rafted debris (IRD) that are believed to result from ice sheet instabilities that triggered episodically surges of icebergs to the North Atlantic [Alley and MacAyeal, 1994; Bond *et al.*, 1992; Broecker, 1994; Broecker *et al.*, 1992]. Enhanced melt-water flux, associated with these surges may have led to reduced convective overturning that weakened or even terminated deep convection in the North Atlantic [Maslin *et al.*, 1995; Vidal *et al.*, 1997; Zahn *et al.*, 1997]. In comparison, the relative stability of THC during the interglacial periods has led to the hypothesis that either the presence of, or the conditions associated with, large Northern Hemisphere ice sheets may be important for causing large changes in THC [McManus *et al.*, 1999]. However,

<sup>1</sup>Department of Geology, University of Bergen, Bergen, Norway.

<sup>2</sup>Bjerknes Centre for Climate Research and Department of Geology, University of Bergen, Bergen, Norway.

<sup>3</sup>Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA.

<sup>4</sup>Department of Geology, University of Florida, Gainesville, Florida, USA.

<sup>5</sup>Also at Nansen Environmental and Remote Sensing Centre, Bergen, Norway.

**Table 1.** Core Locations

Site	Latitude	Longitude	Depth, m	Sedimentation Rate, cm/ka	Reference
983	60°23'N	23°38'W	1985	13.0	this study
982	57°31'N	15°52'W	1145	2.6	Venz et al. [1999], this study
607	41°0'N	32°58'W	3427	4.1	Raymo et al. [1990]
659	18°05'N	21°02'W	3070	4.3	Tiedemann et al. [1994]
928	5°27'N	43°44'W	4012	4	this study

significant changes in THC and high latitude climate are recorded during the last interglacial [Adkins et al., 1997; Cortijo et al., 1994; Fronval and Jansen, 1996; Fronval et al., 1998].

[3] Despite the ample evidence for changes in glacial ocean ventilation, a complete understanding of the cause and effects of THC variability requires records of intermediate and deep water variability across a broad spectrum of climate states with different internal and external boundary conditions. The brevity of many THC changes requires that records with centennial resolution are necessary to accurately assess the range of conditions under which THC is unstable. Yet, the sedimentation rates required for achieving such high-resolution records render conventional piston coring incapable of providing cores of sufficient length to extend through many glacial cycles. Recent drilling by ODP Leg 162 in the subpolar North Atlantic [Jansen et al., 1996] retrieved sequences that continue, at high-resolution, as far back as the earliest Pleistocene and thus enable us to extend the range of boundary conditions associated with high-frequency (millennial-scale) variability into periods when the response to orbital forcing was different from the late Pleistocene. For example, McManus et al. [1999] generated a continuous millennial-scale record from site 980 in the North Atlantic over the past 0.5 Ma, and found that thermohaline variability characterized nearly all observed climate states during the late Pleistocene. Furthermore, Raymo et al. [1998] found evidence (at site 983) for millennial-scale climate variations within a window of the early Pleistocene (1.4–1.2 Ma) with pacing indistinguishable from that of the last glacial cycle.

[4] In contrast, the presence and nature of millennial-scale climate variability during the mid-Pleistocene is not yet documented. Previous work spanning this interval has focused on the mid-Pleistocene climate transition at around 0.9 Ma that involves a change in the frequency of variation from a dominant 41 ka obliquity periodicity prior to 0.9 Ma to a dominant late Pleistocene 100 ka periodicity [Berger and Jansen, 1994]. The increasing amplitude of glaciations over this interval makes it well suited for examining the influence of ice sheet size and the intensity of climate extremes on the style and stability of the thermohaline circulation. The fundamental understanding of the ocean's role in rapid climate changes provided by such a test ultimately improves our ability to assess the stability of the THC under increased greenhouse gas forcing of the climate system.

[5] In this study, we present mid-Pleistocene (1.2–0.7 Ma) records from ODP sites drilled in the middepth subpolar North Atlantic and deep western equatorial Atlantic,

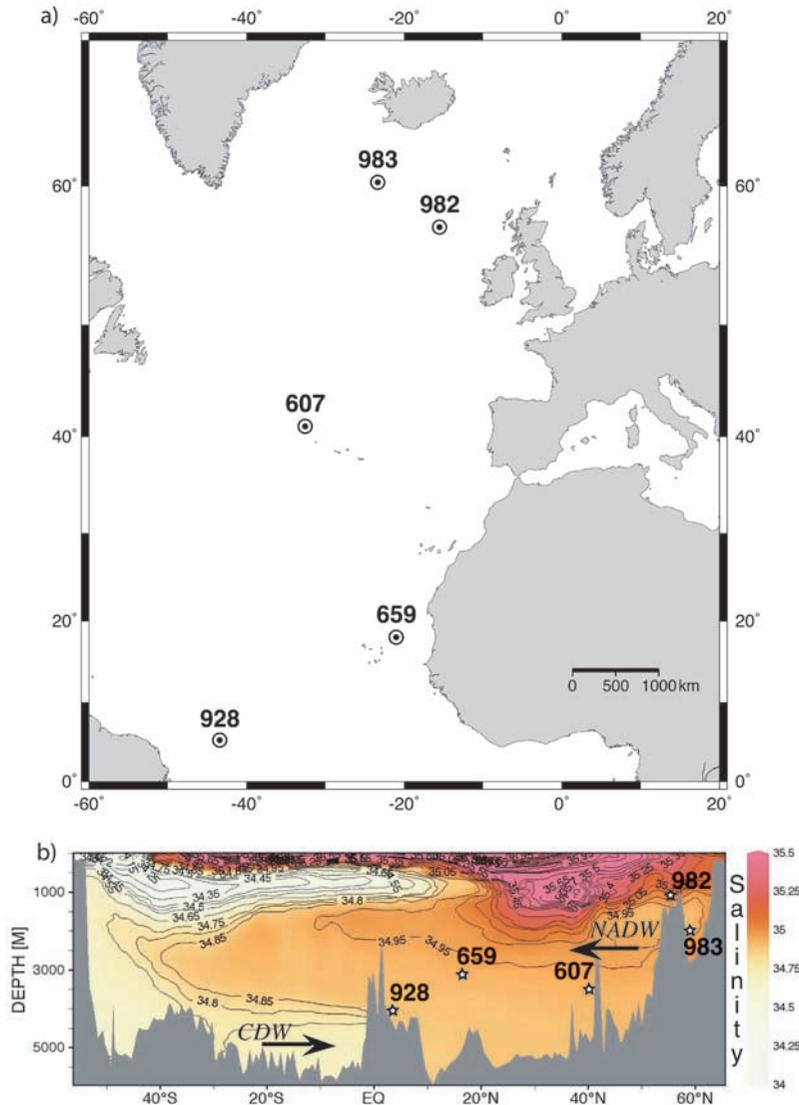
well positioned to reconstruct changes in properties and distribution of Atlantic deep water masses on both orbital and suborbital timescales. Benthic foraminiferal  $\delta^{18}\text{O}$  is used to reconstruct variations in ice volume and bottom water temperature, and benthic foraminiferal  $\delta^{13}\text{C}$  to monitor the regional ventilation changes. We compare our results to a depth transect of cores (Table 1, Figure 1) to document how gradients in benthic foraminiferal  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  have varied through the mid-Pleistocene. This allows us to place the deep water records from one region into the perspective of intermediate to deep water geometry in the entire North Atlantic. The timing and geometry of Atlantic deep water circulation changes documented with this array of sites allows us to evaluate the relative role of ice sheets in forcing THC instability.

## 2. Material and Methods

### 2.1. Core Selection

[6] To monitor long-term variations in the intermediate water masses in the North Atlantic during the mid-Pleistocene, we use benthic foraminiferal isotope records from site 982, located on the Rockall Plateau at 1145 m water depth (Table 1, Figure 1). Water masses at this location are in the flow path of the upper layer of the North Atlantic Deep Water (UNADW) (<2500 m) [Kawase and Sarmiento, 1986], and receive a small contribution from the deep water formed in the Norwegian Sea [Saunders, 1990]. During the last glaciation, water masses at the Rockall Plateau were strongly stratified: nutrient-depleted glacial North Atlantic intermediate water (GNAIW) filled the North Atlantic above 2000 m, whereas lower NADW (>2500 m) was replaced by nutrient rich Southern Ocean Water (SOW) [Bertram et al., 1995; Oppo and Lehman, 1993]. In a recent study Venz et al. [1999] suggested that distinct reductions in intermediate water ventilation at site 982 occurred during most glacial terminations over the past 1.0 Ma, comparable to glacial suppression of NADW inferred from deep water cores further south [Raymo et al., 1990]. Additional benthic foraminiferal carbon and oxygen isotopic measurements extending the site 982 record back to 1.2 Ma and are included in this paper (see Venz et al. [1999] for description of material and methods).

[7] New data is also presented from site 983, located on the Gardar Drift on the eastern flank of the Reykjanes Ridge, at 1985 m water depth (Figure 1). This places the site near the approximate boundary of GNAIW and SOW during the last glacial maximum [Oppo et al., 1997; Oppo and Lehman, 1995], and obtaining a long-term history of this GNAIW is one of the primary objectives of this study. In addition, this site should prove very sensitive to Nordic



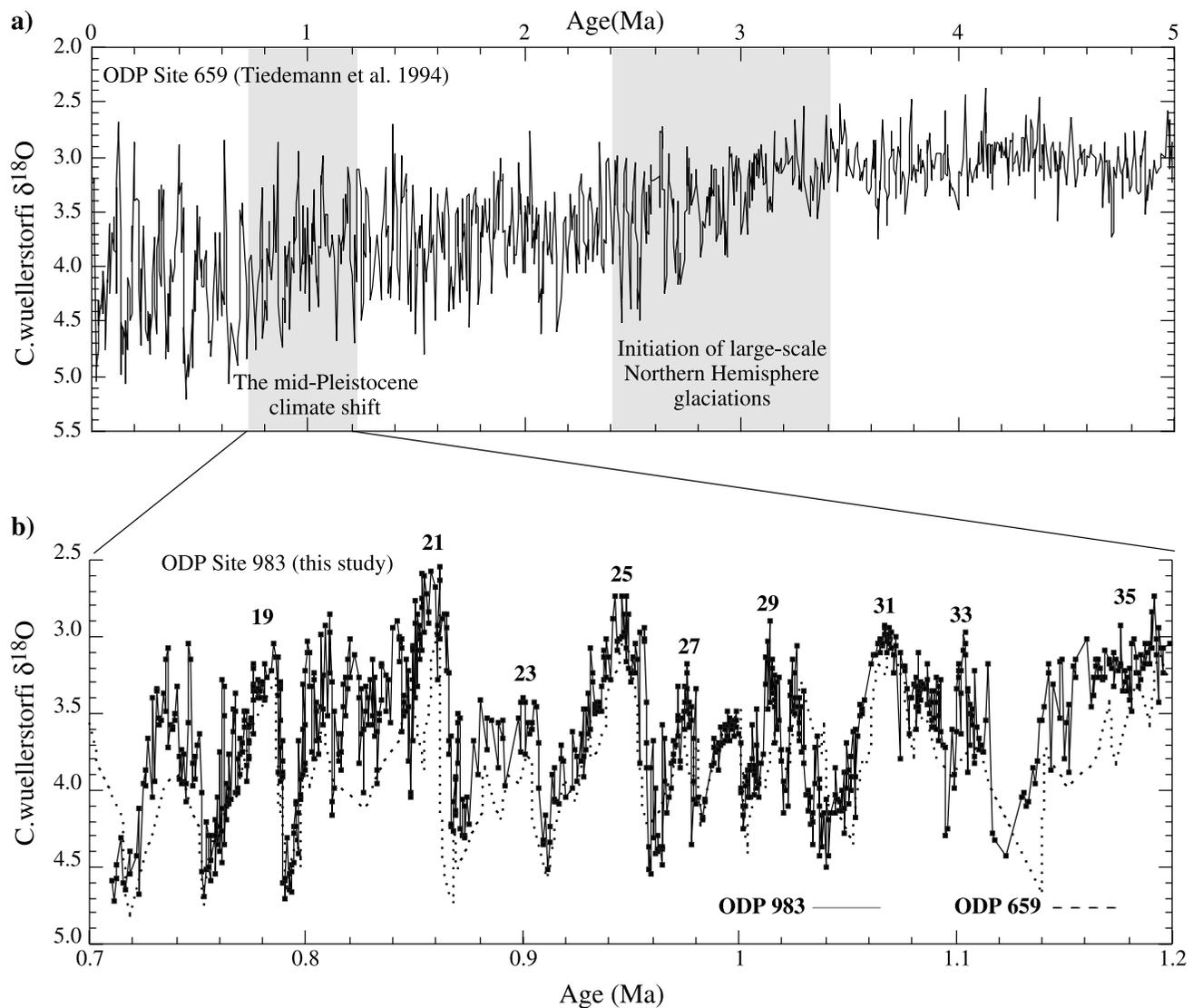
**Figure 1.** (a) Map showing the locations of the cores investigated and discussed in this study. Site locations and depths are described in Table 1. (b) The location of the core sites projected onto the north-south Atlantic WOCE A16 salinity profile.

Sea overflows from the Greenland-Scotland ridge, as this site lies directly downstream of overflows from the Iceland-Faroe ridge. Together with site 982 to the east, the site forms a depth transect spanning the interval between 1 and 2 km water depth in the North Atlantic. The sedimentation rates at site 982 averaged 2.6 cm/ka, whereas sedimentation rates at 983 are enhanced (15 cm/ka) owing to the interaction of bottom currents with the sea bed topography. Thus comparison of  $\delta^{13}\text{C}$  gradients between these sites should enable us to unravel the vertical extent of North Atlantic Intermediate Water (NAIW) formation in the Nordic Seas and the subpolar North Atlantic on orbital and suborbital timescales through the mid-Pleistocene.

[8] Also shown in this study is a comparison with published records from sites 659 (3070 m) off northwest Africa and 607 (3427 m) on the western flank of the Mid-Atlantic Ridge. These sites lie in water that is predominantly

NADW today, but  $\delta^{13}\text{C}$  values in both locations are sensitive to past changes in the relative contribution of high- $\delta^{13}\text{C}$  NADW and low- $\delta^{13}\text{C}$  SOW, and to changes in the location of the mixing zone between these two water masses [Bickert *et al.*, 1997; Oppo *et al.*, 1995; Raymo *et al.*, 1990; Tiedemann *et al.*, 1994].

[9] To these four records, we add a new record from site 928 drilled at the Ceara Rise at 4012 m water depth. In contrast to 983 which lies at the interface of northern and southern source waters during the last glacial period, 928 lies in the mixing zone between southward flowing NADW (2–4 km) and northward flowing CDW (>4 km) today. Several studies from the last glacial cycle have demonstrated the potential of the Ceara Rise in documenting NADW variability on both orbital and millennial timescales at these water depths [Bickert *et al.*, 1997; Curry *et al.*, 1988; Curry and Oppo, 1997; Oppo and Fairbanks, 1990]. Thus, site



**Figure 2.** (a) The benthic  $\delta^{18}\text{O}$  record of *Tiedemann et al.* [1994] from ODP site 659 in the eastern equatorial Atlantic; a proxy for paleoclimate and sea level fluctuations for the past 5 Ma. The Pliocene and Pleistocene climate transitions are highlighted by shading, and (b) The new high-resolution benthic  $\delta^{18}\text{O}$  record from ODP site 983 (solid line) plotted versus the benthic  $\delta^{18}\text{O}$  record from site 659 (dashed line) for comparison across the mid-Pleistocene (0.7–1.2 Ma). Interglacial stages are labeled.

928, which is our deepest and southernmost end-member, is in a very sensitive location for monitoring even small deviations in the flux or vertical extent of NADW through the mid-Pleistocene.

## 2.2. Data Analyses

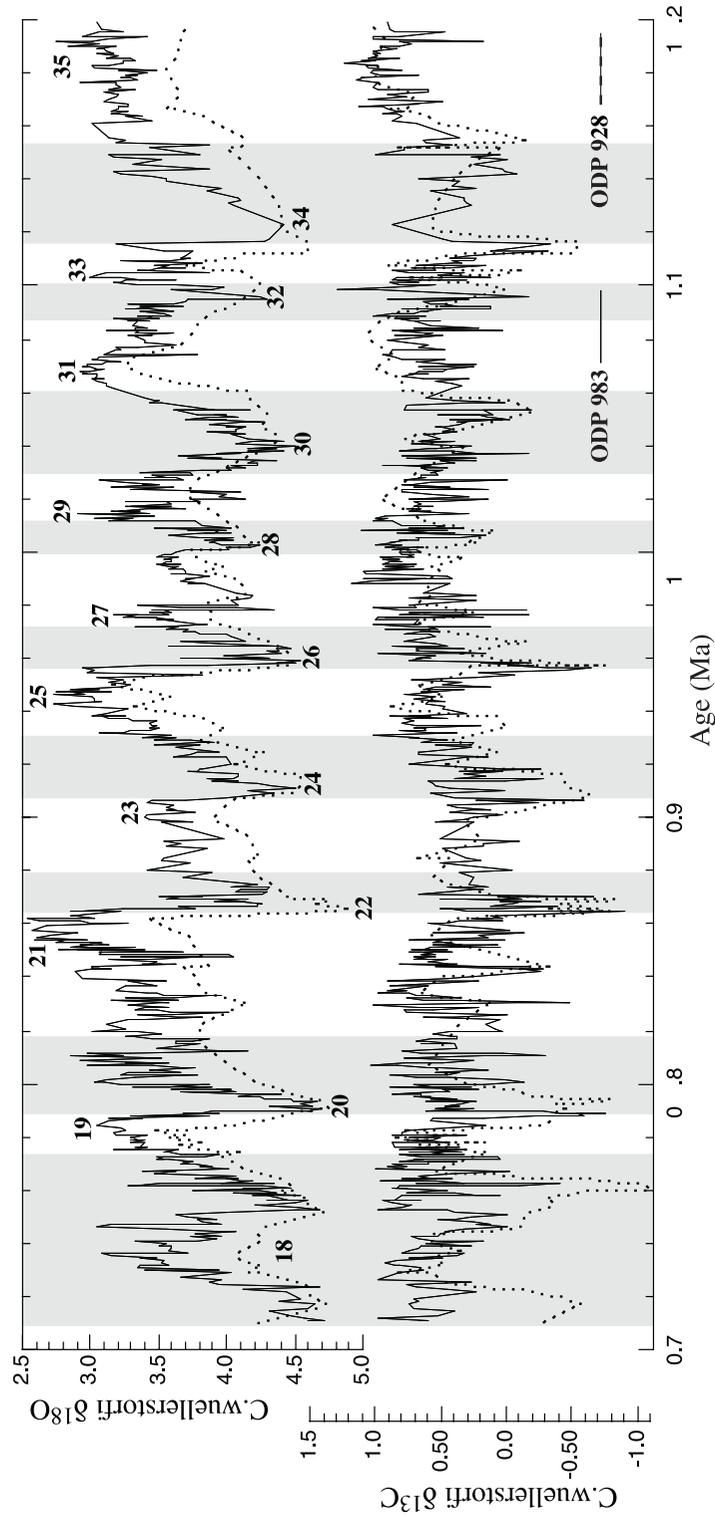
[10] Benthic foraminiferal isotopes at site 983 were generated in several laboratories. The bulk of the data were analyzed at University of Florida (UF) using a VG Prism mass spectrometer, whereas a smaller number of samples were analyzed at Cambridge University (CU) (VG Prism) and at Scripps Institution of Oceanography (SIO) (Finnigan Mat 252). The benthic foraminifera, *Cibicides wuellerstorfi* were selected for stable isotopic measurements. The foraminiferal abundance allowed us to generate the first high-resolution

(<500-yr.) benthic record spanning Marine Isotope Stages (MIS) 35 through 18 from the North Atlantic (Figure 2).

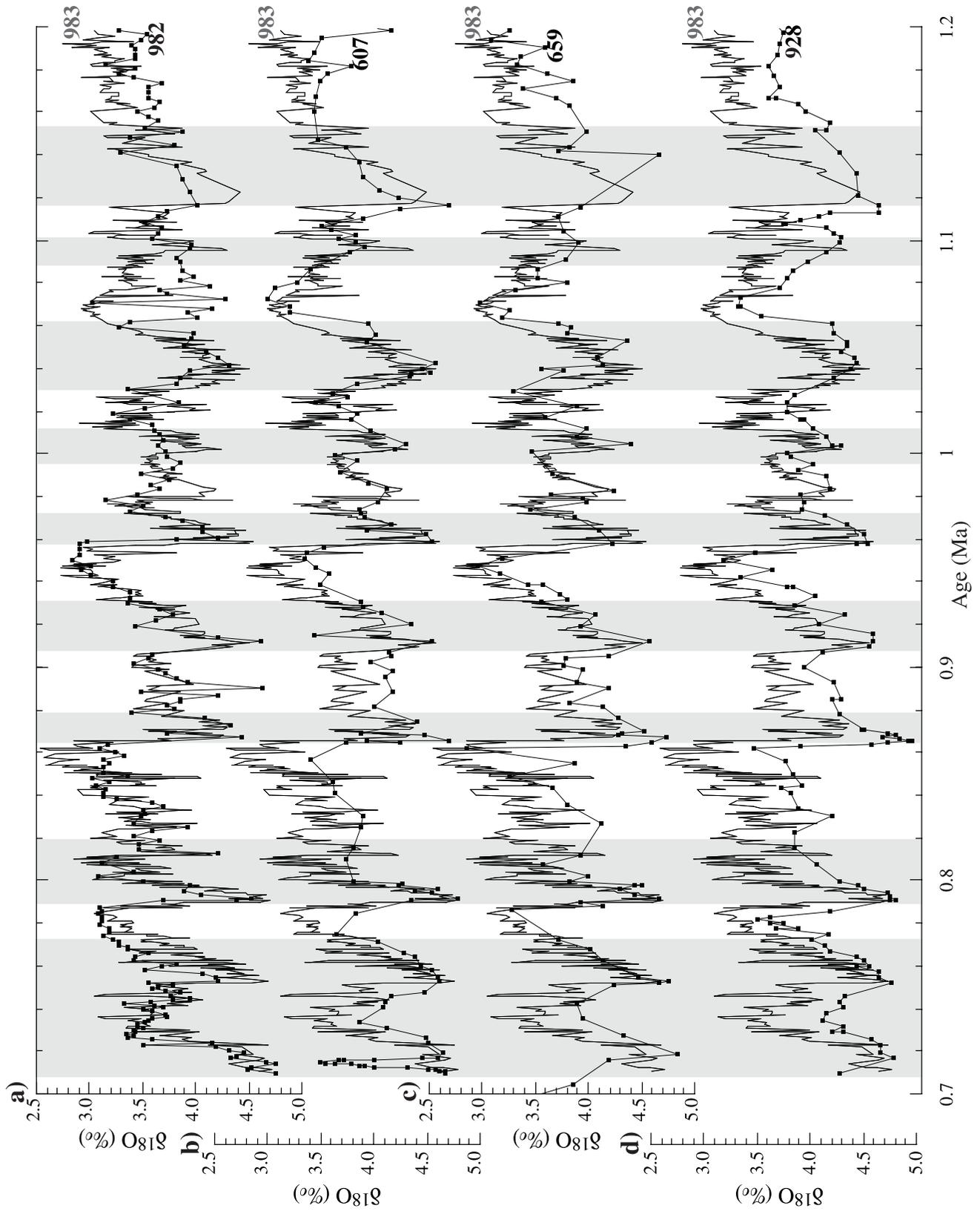
[11] Stable oxygen and carbon isotopic composition from site 928 were analyzed at the Woods Hole Oceanographic Institution (WHOI) using a Finnigan MAT 252 coupled with an automated carbonate preparation device. The measurements were predominately run on *Cibicides wuellerstorfi* and to a minor degree on *Cibicides kullenbergi*, and *Cibicides cicatricosus*. The new mid-Pleistocene benthic  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  records from sites 983 and 928 are both plotted to age in Figure 3.

## 2.3. Age Model

[12] The age model for site 983 was developed using the *Imbrie and Imbrie* [1980] ice-volume simulation model as



**Figure 3.** The new mid-Pleistocene benthic  $\delta^{18}O$  and  $\delta^{13}C$  time series from ODP sites 983 (solid lines) and 928 (dashed lines) plotted against age. Glacial and interglacial stages are shaded and labeled.



our tuning target. This model assumes that the rate of climatic response is proportional to the magnitude of the summer insolation forcing at 65°N. We calculated this target curve with the equations and time constants for waxing and waning of ice sheets given by *Imbrie and Imbrie* [1980], and the monthly insolation series for July at 65°N from *Berger and Loutre* [1991]. The benthic  $\delta^{18}\text{O}$  record from site 983 was then aligned to features in the target curve, using linear interpolation between tie points. This age model was further refined through tuning of the extracted precession components from the benthic  $\delta^{18}\text{O}$  record to the precession component of the ice volume model (see *Channell and Kleiven* [2000] for a review of methods). For correlation purposes, we generated new timescales for 982, 607, 659, and 928 by matching their benthic oxygen isotope records to the ice volume model. The  $\delta^{18}\text{O}$  records from sites 982, 607, 659, and 928 are all plotted versus age in Figure 4, using the new age-depth relationships that were obtained in this study. The site 983 record is plotted on each panel to illustrate the resulting correlation between the sites.

### 3. Results

#### 3.1. Oxygen Isotopes

[13] The structure of the benthic  $\delta^{18}\text{O}$  records reflects variations in global ice-volume and changes in deep water temperature. The fractionation of oxygen isotopes leaves the ocean enriched in  $\delta^{18}\text{O}$  when ice sheets are formed on land, whereas the attendant cooling of bottom waters formed at high latitudes affects the ratio of  $^{18}\text{O}/^{16}\text{O}$  incorporated into foraminiferal tests during calcification. Here we compare benthic  $\delta^{18}\text{O}$  gradients between our sites, to examine how the magnitude of  $\delta^{18}\text{O}$  variability (e.g., ice volume/deep ocean temperature changes) was recorded at various depths and latitudes in the North Atlantic throughout the mid-Pleistocene. Because of variable sampling density and sedimentation rates at each site, we will primarily focus on apparent long-term  $\delta^{18}\text{O}$  trends in the data. At site 983, where sampling resolution is much higher, details of both orbital and suborbital variability in  $\delta^{18}\text{O}$  are discussed.

[14] The detailed comparison between the benthic oxygen isotope records from sites 983, 982, 607, 659 and 928 (Figure 4) show that distinct  $\delta^{18}\text{O}$  gradients existed between the intermediate depth cores (983 and 982) and the deeper cores (607, 659 and 928) between 1.2 and 0.7 Ma. A noticeable feature of Figure 4a is the similarity of the sites 983 and 982  $\delta^{18}\text{O}$  records throughout both glacial and interglacial intervals. The amplitude modulation of the  $\delta^{18}\text{O}$  records is in close agreement, and many of the well-documented isotope events at site 983 are represented at site 982, despite the disparity in the sedimentation rate between the two sites. The persistence of nearly identical  $\delta^{18}\text{O}$  values at sites 982 and 983 through the entire mid-Pleistocene, except in MIS 31 where 982 is different than

any of the study cores, suggests that no measurable temperature or salinity gradients developed between 1000 and 2000 m depth in the subpolar North Atlantic for nearly 0.5 Ma, regardless of the background climate state.

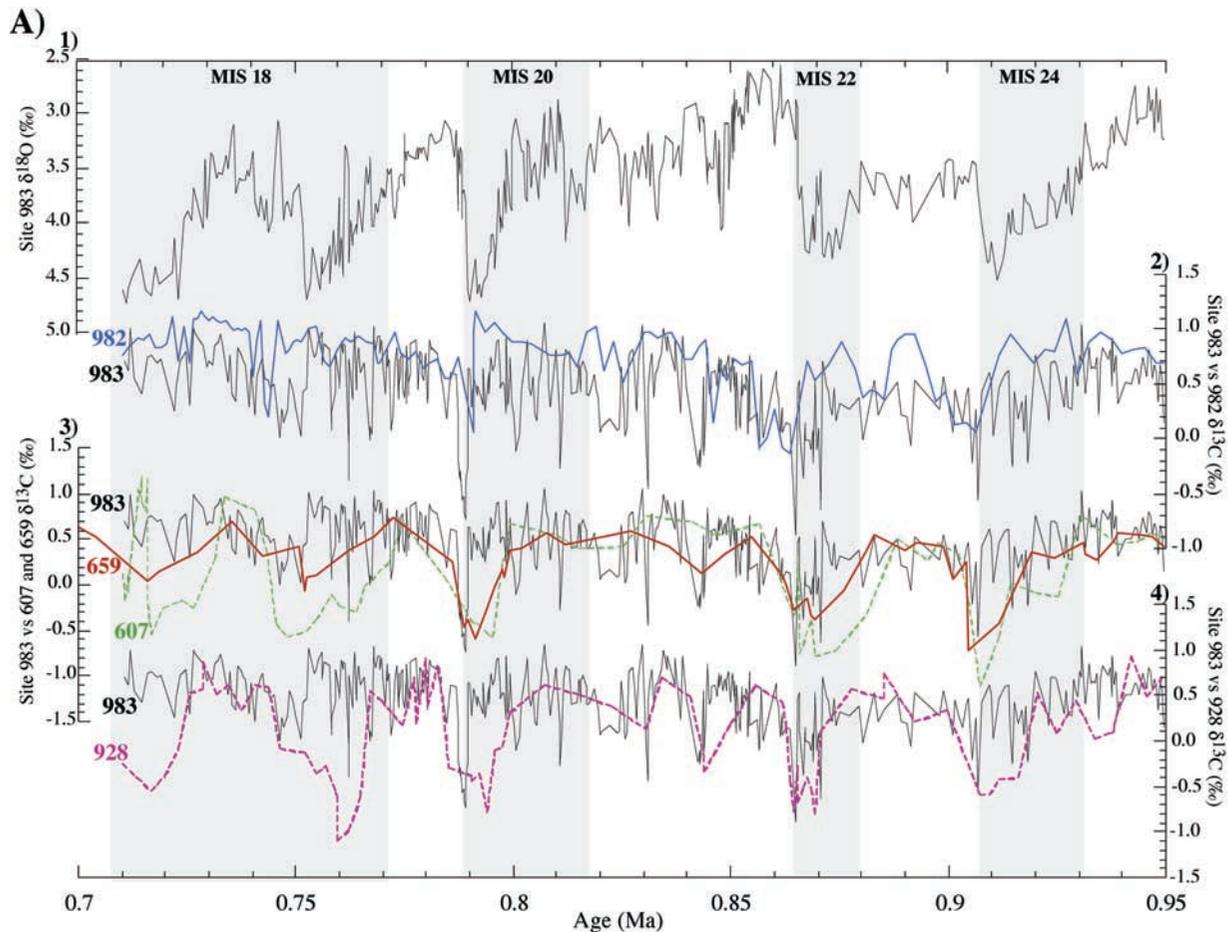
[15] In contrast, the foraminiferal  $\delta^{18}\text{O}$  values at site 928 are higher than those at site 983 throughout most of the mid-Pleistocene (Figure 4d), due to the different water mass properties at each site. Located at opposite ends of the NADW spectrum, the 983/982  $\delta^{18}\text{O}$  records reflects warmer intermediate source waters and are influenced by overflows from the Nordic Seas, whereas site 928, at the distal interface between NADW and CPDW, is bathed by deeper and denser water masses. Hence the  $\delta^{18}\text{O}$  offset between 983 and 928 primarily reflects the colder bottom waters at site 928. This  $\delta^{18}\text{O}$  difference is only reduced during some extreme  $\delta^{18}\text{O}$  maxima when all records display similar  $\delta^{18}\text{O}$  values. The  $\delta^{18}\text{O}$  values at sites 607 and 659 approach those at sites 982 and 983 during most glacial intervals, confirming the lack of glacial  $\delta^{18}\text{O}$  gradients in the deep North Atlantic basin. In contrast, many of the mid-Pleistocene interglacial  $\delta^{18}\text{O}$  values are offset by  $>0.4\text{‰}$  between the deeper (607/659) and more intermediate (983/982) sites, implying that mid-Pleistocene interglacial North Atlantic intermediate to deep temperature gradients were comparable to the 1.8°C gradient between lower NADW (2.0°C) and upper NADW (3.8°C) observed today. Although interglacial differences in the  $\delta^{18}\text{O}$  values between the intermediate and deeper water records are apparent throughout the mid-Pleistocene, they are generally greater after  $\sim 1$  Ma.

[16] When examined in detail, it is clear that the mean offset between the interglacial  $\delta^{18}\text{O}$  values at site 983 and the deeper sites is due to the frequent millennial-scale low  $\delta^{18}\text{O}$  excursions which are only resolved at site 983. The interglacial millennial-scale variability in benthic  $\delta^{18}\text{O}$  often exceeds 0.5‰ in amplitude with the highest  $\delta^{18}\text{O}$  values similar to, and the lowest values well below, those found in the deeper water sites. These millennial oscillations comprise several data points and are not limited to interglacial periods but, with the exception of MIS 34 where the scarcity of *Cibicides* made high-resolution oxygen isotope analyses impossible, span the entire 1.2–0.7 Ma interval considered in this study.

#### 3.2. Carbon Isotopes

[17] The  $\delta^{13}\text{C}$  signal recorded in benthic foraminiferal shells can be used to record changes in the production and circulation of deep ocean waters. Benthic foraminiferal  $\delta^{13}\text{C}$  is influenced both by changes in the mean ocean value of  $\delta^{13}\text{C}$  of  $\delta\text{CO}_2$ , and by changes in local deep water chemistry. Here we examine the new mid-Pleistocene benthic  $\delta^{13}\text{C}$  records from site 983 and 928 to reconstruct the mode and stability of North Atlantic intermediate and deep water ventilation over a variety of global climate configurations.

**Figure 4.** (opposite) The mid-Pleistocene benthic  $\delta^{18}\text{O}$  time series from sites (a) 982, (b) 607, (c) 659 and, (d) 928 (solid dotted black lines) plotted against age. The benthic  $\delta^{18}\text{O}$  record from site 983 (gray solid line) is plotted on each panel to illustrate the resulting correlation between the sites.



**Figure 5.** (a) The 0.7–0.95 Ma interval, and (b) The 0.95–1.2 Ma interval. Comparison of benthic  $\delta^{13}\text{C}$  trends from site 983 (black line), with the records from site 982 (blue line) in panel 2, site 607 (green line) and 659 (red line) in panel 3, and site 928 (pink line) in panel 4. The upper panel (1) is the benthic  $\delta^{18}\text{O}$  record from site 983. Glacial stages between 0.7–1.2 Ma are shaded and labeled.

[18] The  $\delta^{13}\text{C}$  records from sites 983 and 928 are plotted versus age in Figure 3, together with their respective benthic oxygen isotope records. To first order, the benthic  $\delta^{13}\text{C}$  time series at site 983 reflects variations in North Atlantic intermediate water circulation, whereas  $\delta^{13}\text{C}$  changes at site 928 record variations in the composition and relative mixture of northern and southern source deep water masses. The  $\delta^{13}\text{C}$  time series at site 928 is characterized by strong glacial-interglacial variability, similar to the orbital-scale trends in the benthic oxygen isotopes. Significant  $\delta^{13}\text{C}$  reductions occur at times of ice maxima whereas high  $\delta^{13}\text{C}$  values mark interglacial periods. This pattern of low benthic  $\delta^{13}\text{C}$  values during glaciations is typical of Late Pleistocene deep water records (>3000 m depth) throughout the Atlantic and is attributed to the northward expansion and shoaling of low  $\delta^{13}\text{C}$  Southern Ocean water as the flux of lower NADW wanes during glaciations [Raymo *et al.*, 1990]. In contrast, during interglacial periods, the benthic  $\delta^{13}\text{C}$  values at site 928 are comparable to those found at intermediate depths of the North Atlantic (site 983), implying that a common low nutrient water mass bathes both

locations. However, unlike the deepwater  $\delta^{13}\text{C}$  pattern at site 928, the intermediate depth benthic  $\delta^{13}\text{C}$  record from site 983 shows no significant low frequency changes in mean values over glacial cycles (the mean glacial value is similar to that in the interglacial periods). The contrast between the increasing magnitude and duration of glacial  $\delta^{13}\text{C}$  minima in the deeper water sites (e.g. 928), and the orbital-scale stability in 983  $\delta^{13}\text{C}$  values across the mid-Pleistocene, results in greater glacial intermediate to deep water  $\delta^{13}\text{C}$  gradients in the North Atlantic after 0.95 Ma (Figure 3).

[19] Relative to the orbital-scale quietude, the suborbital changes in benthic  $\delta^{13}\text{C}$  values at site 983 are striking. Most of the variance in the benthic  $\delta^{13}\text{C}$  record from site 983 occurs as abrupt minima that last up to a few millennia and punctuate both glacial and interglacial states. Although the largest  $\delta^{13}\text{C}$  reductions at site 983 are associated with glacial terminations, and often approach values found in deeper water sites (e.g. 928), smaller  $\delta^{13}\text{C}$  perturbations (on the order of 0.5–1.0‰) occur throughout the record. This persistent suborbital  $\delta^{13}\text{C}$  variability at site 983 implies that rapid changes in the

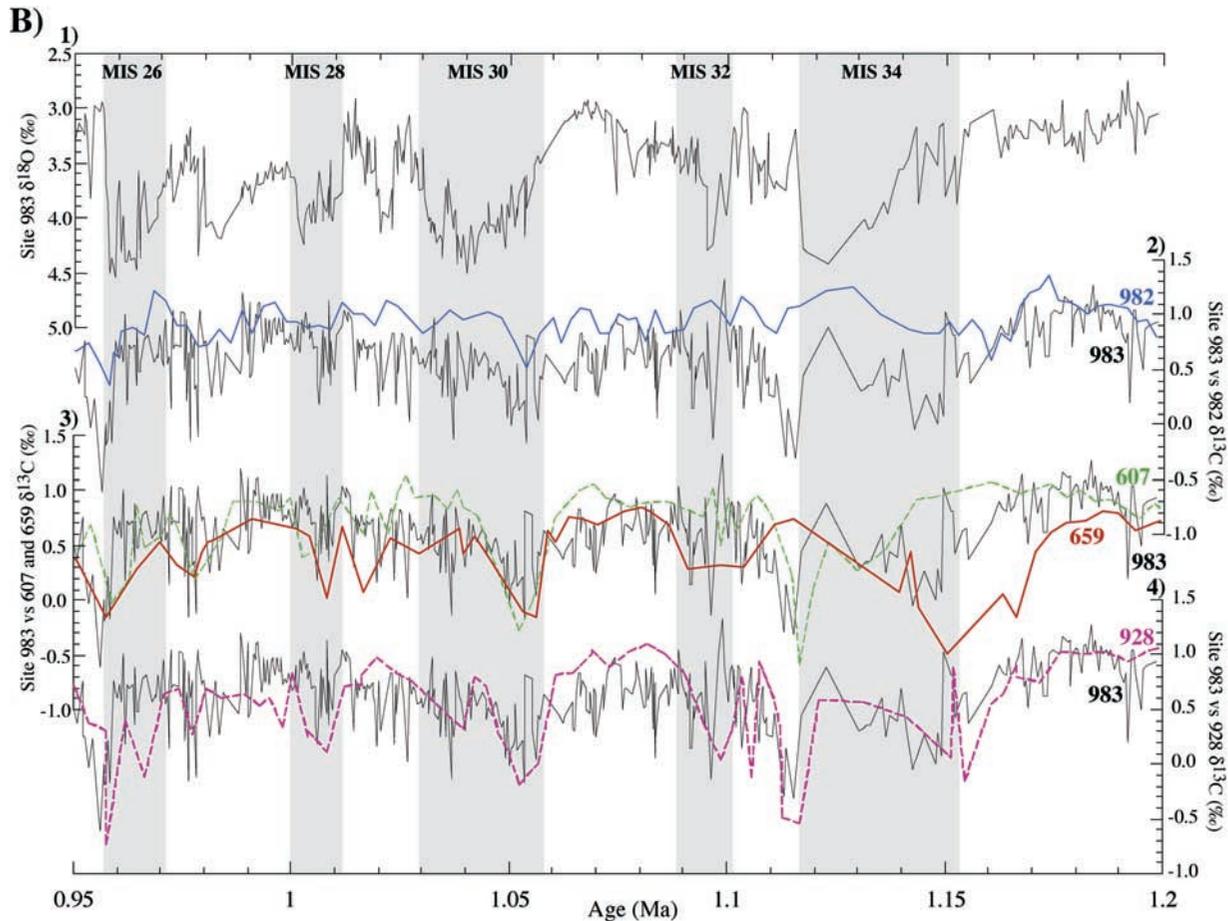


Figure 5. (continued)

ventilation of the intermediate depth North Atlantic occurred throughout the interval from 0.7 to 1.2 Ma regardless of the background climate and ice sheet conditions.

#### 4. Discussion

[20] The addition of new isotopic records from the subpolar and equatorial North Atlantic spanning a variety of climatic states provides new insight into the nature and modes of North Atlantic deep and intermediate water circulation through the mid-Pleistocene. The variability expressed in our new carbon isotopic records suggests that suborbital reorganizations in the circulation and ventilation of Atlantic intermediate waters were common throughout the period from 1.2–0.7 Ma. Meanwhile, on orbital timescales, glacial deep to intermediate water  $\delta^{13}\text{C}$  gradients evolved after  $\sim 0.95$  Ma. Taken together, these observations provide a number of new constraints for understanding the timing and evolution of deep water circulation changes across the mid-Pleistocene.

##### 4.1. Glacial Intermediate to Deep Water Circulation

[21] Taken at face value, the low glacial benthic  $\delta^{13}\text{C}$  values found at all of the sites below 2000m (site 607, 659 and 928) suggests that a common high nutrient water mass

filled the deep North Atlantic during mid-Pleistocene glaciations (Figures 5a and 5b). At the same time, high  $\delta^{13}\text{C}$  source waters ventilated the mid depth North Atlantic resulting in a middepth nutricline ( $\delta^{13}\text{C}$  gradient) similar to that observed in last glacial maximum (LGM)  $\delta^{13}\text{C}$  reconstructions from the subpolar North Atlantic [Boyle and Keigwin, 1982; Marchitto et al., 1998; Oppo et al., 1997; Oppo and Lehman, 1993]. This LGM mode of deep water formation produced nutrient-depleted lower density water, which only ventilated the upper 2000 meters of the water column, whereas the deep North Atlantic was bathed with nutrient-rich southern source waters. Our new North Atlantic isotopic records suggest that this two-component deep water geometry extend through the mid-Pleistocene: the shallow to middepth sites 982 and 983 often exhibit enhanced glacial values (high- $\delta^{13}\text{C}$ ), documenting increased production of nutrient-depleted intermediate depth water in the shallow subpolar North Atlantic. Increased  $\delta^{13}\text{C}$  values are also observed at the Rockall Plateau and Gardar Drift during the last glacial maximum (LGM) and are interpreted to result from a shift in the convection cell from the Nordic Seas to the subpolar North Atlantic [Oppo and Lehman, 1993]. For the LGM, Oppo and Lehman [1993] found that the core of nutrient depleted GNAIW, with  $\delta^{13}\text{C}$  values of  $\sim 1.5\text{‰}$  was located near a depth of 1000 m in the subpolar northeastern

Atlantic. Thus the high-latitude location and the relatively high  $\delta^{13}\text{C}$  values at site 982 (1145 m depth) indicate that this site likely is in or near the core of GNAIW.

[22] The millennial-scale variability that characterizes the two-component mode of ventilation during the LGM [Chapman and Shackleton, 1998; Oppo and Lehman, 1995; Vidal *et al.*, 1997] and late Pleistocene glaciations [McManus *et al.*, 1999] is also evident in the mid-Pleistocene. The relatively high glacial  $\delta^{13}\text{C}$  values at site 983 are interrupted by rapid incursions of high nutrient (low  $\delta^{13}\text{C}$ ) water. The  $\delta^{13}\text{C}$  oscillations at site 983 (1985 m) vary between values close to those of site 982 (1145 m) and site 928 (4112 m) suggesting that the interface between low nutrient content, well ventilated northern intermediate waters and high nutrient content southern ocean deep waters varied rapidly. For example, Figures 5a and 5b shows that, during the glacial terminations, the  $\delta^{13}\text{C}$  values at site 983 converge with those observed at site 928, suggesting that the low  $\delta^{13}\text{C}$  SOW bathing site 928 may expand and fill the subpolar North Atlantic to at least 1985 m. In contrast, the  $\delta^{13}\text{C}$  values at site 982 only decrease slightly during terminations, suggesting less influence of SOW at 1145 m. In a recent paper, Curry *et al.* [1999] demonstrated active ventilation down to about 965 m water depth in the MIS 3 record of the North Atlantic. Low  $\delta^{13}\text{C}$  and high Cd/Ca are absent at these depths, even when cores at 1865 m show very low  $\delta^{13}\text{C}$  values. Thus, although small increases in the volume of SOW bathing site 983 during deglaciations would lower the  $\delta^{13}\text{C}$  of bottom waters significantly, the persistence of a nutricline ( $\delta^{13}\text{C}$  gradient) between 982 and 983 argues against a complete cessation of northern source ventilation. A shallow overturning cell may still have been actively maintaining the observed mid depth nutricline between 982 and 983.

[23] A variety of mechanisms could cause the observed shoaling of the interface between low nutrient, northern source water, and the denser, higher nutrient, water underlying it. For example, either an increased volume of southern source water or a decrease in the volume or density of the northern source water produced would result in a nutricline shoaling. Venz *et al.* [1999] showed that between 0–1.0 Ma the severity of  $\delta^{13}\text{C}$  minima at site 982 were strongly related to the influx of IRD, such that the largest  $\delta^{13}\text{C}$  minima are associated with the largest peaks of IRD. This relationship suggests that during periods of major deglacial iceberg melting, the reduction in North Atlantic surface water salinity may have led to a further reduction in the amount or density of North Atlantic deep water production. Yet, massive melt water events cannot be the only cause of THC reorganizations since millennial-scale changes in ocean ventilation changes also occur during mid-Pleistocene interglacial periods.

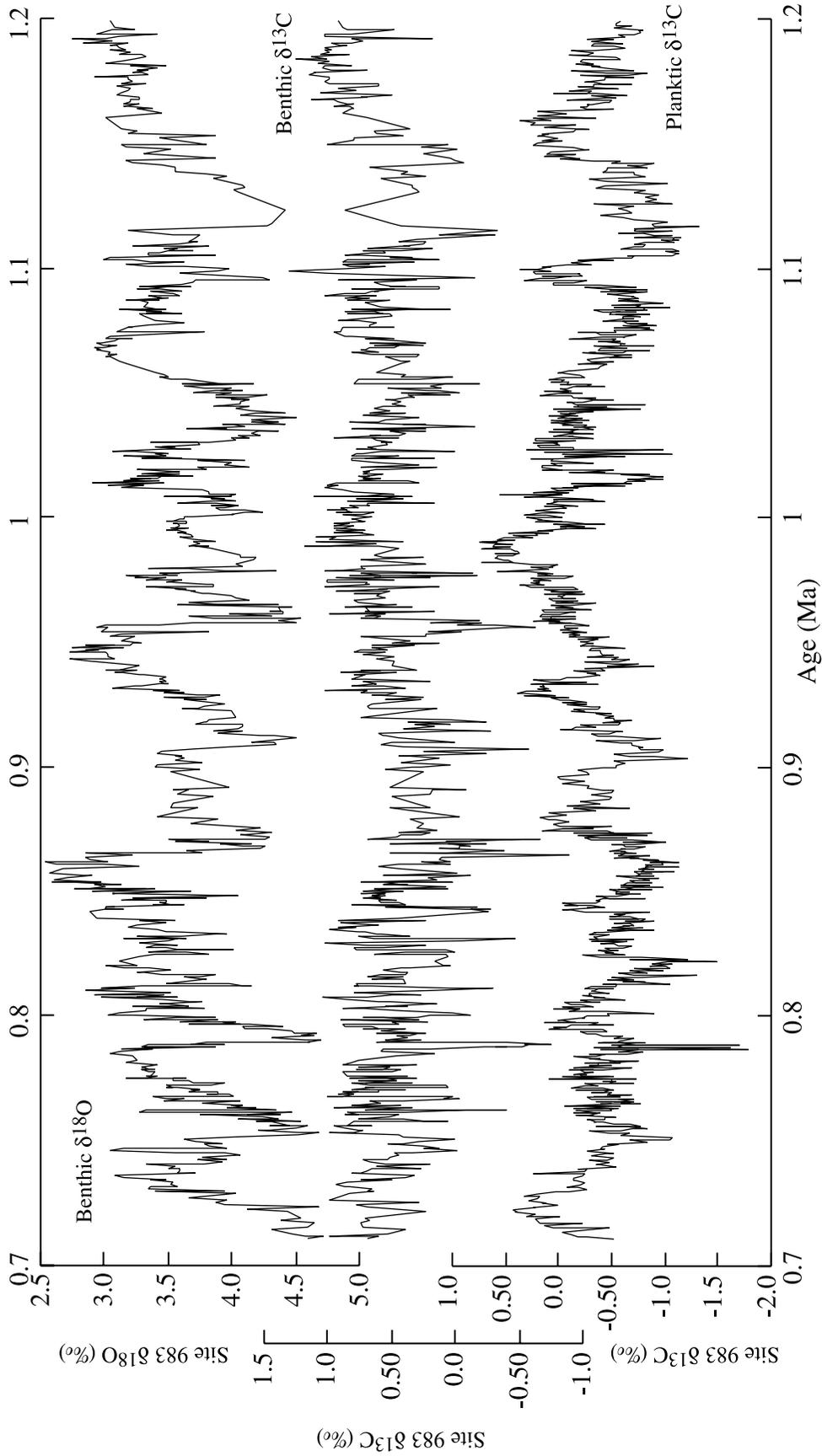
#### 4.2. Interglacial Intermediate to Deep Water Circulation

[24] The high-resolution record of interglacial variability recorded in benthic  $\delta^{13}\text{C}$  from site 983 provides a natural test of the importance of large ice sheets on the overall stability of convective overturning in the North Atlantic. Despite strong evidence during glacial periods and termi-

nations for rapid shoaling of the mixing interface between northern and southern source waters, it is unlikely that rapid reductions of NADW allowing greater northward penetration of SOW can account for all of the benthic  $\delta^{13}\text{C}$  variability observed at site 983, especially during peak interglacial periods when NADW production is vigorous and the interface between northern and southern source waters is located much deeper and further south near site 928. Yet, despite the general vigor of NADW production, there is still significant millennial-scale benthic  $\delta^{13}\text{C}$  variability at site 983 (Figures 5a and 5b) during mid-Pleistocene interglaciations. The most likely source of these rapid  $\delta^{13}\text{C}$  fluctuations is changes in the isotopic composition and/or relative mixture of overflow waters bathing site 983.

[25] Interestingly, the same benthic  $\delta^{18}\text{O}/\delta^{13}\text{C}$  covariance characteristic of glacial and deglacial millennial-scale THC events, also occurs during interglacials. This could be due to several factors. The light oxygen isotopic values could be due to higher bottom water temperatures, or to the influence of isotopically light water from small melting episodes of the remaining ice sheets in the Nordic Seas area. The isotopic signal may be further enhanced by direct entrainment of these light isotopes into sinking deep waters [Lehman *et al.*, 1993]. Likewise, the lighter carbon isotopes could be due to changes in the ventilation rate, preformed chemistry, or temperature driven changes in air-sea carbon isotopic fractionation of NADW [Broecker and Maier-Reimer, 1992; Charles *et al.*, 1993]. Eventually detailed surface and deepwater records from Nordic sea convection sites may help to delineate which mechanisms upset the delicate balance between atmospheric forcing, ocean currents and heat transport, and freshwater forcing that allows the modern style of NADW production. Until then, the 983 planktic  $\delta^{13}\text{C}$  record may at least provide some constraints on the influence of preformed changes in the isotopic composition of North Atlantic surface waters (upstream from the convection regions) on the  $\delta^{13}\text{C}$  of NADW. For example, if changes in the benthic  $\delta^{13}\text{C}$  of site 983 in the flow path of NADW mirrored those of the planktic  $\delta^{13}\text{C}$  then the deep water isotopic variability could be explained entirely by changes in the chemistry of the source waters. However, at least at site 983 there is little similarity between the planktic and benthic  $\delta^{13}\text{C}$  records on either orbital or suborbital timescales (Figure 6) suggesting preformed changes in surface water  $\delta^{13}\text{C}$  are not the dominant influence on Atlantic middepth  $\delta^{13}\text{C}$  changes.

[26] Although NADW typically dominates the ventilation of the North Atlantic during interglacial periods, exceptions do occur. For example, MIS 21, is marked by rapid reductions in benthic  $\delta^{13}\text{C}$  at site 983 to values similar to those observed during other terminations, which we interpreted previously as SOW incursions. However, MIS 21 is hardly a typical interglacial period, broken into 3 orbitally paced isotopic substages there is evidence that significant ice growth may have occurred during this time. Each significant  $\delta^{13}\text{C}$  minimum is associated with a termination with the  $\delta^{18}\text{O}$  returning to typical interglacial values. Thus the changing ice volume during MIS 21 may allow convective changes similar to those more typical of deglaciations. Further evidence that these  $\delta^{13}\text{C}$  changes are not driven by variations in the isotopic



**Figure 6.** Time series of (a) benthic  $\delta^{18}\text{O}$ , (b) benthic  $\delta^{13}\text{C}$ , and (c) planktic  $\delta^{13}\text{C}$  spanning the 0.7–1.2 Ma interval from site 983.

values of northern source waters comes from the shallower site 982, which is bathed by the same overflow waters. The distinct benthic  $\delta^{13}\text{C}$  increases at 982 imply that while ventilation decreased below 2000 m, above this the upper water column was better ventilated.

[27] Rapid shifts in the style or intensity of deep water convection characterize even the most stable interglacial periods at 983 implying that internal mechanisms within the ocean-atmospheric system may also generate THC instabilities. The large interglacial ventilation changes imply that massive freshwater fluxes from armadas of melting icebergs are not a prerequisite for convective instability, although they may be important for triggering the near total convective shutdowns that occur during deglaciations. Instead, more localized forcing at the sites of convection may play an important role. In this sense the inference that even small melt events can affect interglacial THC mode switches is consistent with model results that show even small freshwater perturbations can trigger convective reorganizations [Paillard and Labeyrie, 1994; Rahmstorf, 1995; Weaver and Hughes, 1994]. However, the observations that  $\delta^{13}\text{C}$  reductions in the North Atlantic often occur prior to IRD events [Oppo et al., 1997; Zahn et al., 1997] implies that the thermohaline circulation changes are forced by mechanisms other than freshwater forcing by melting icebergs. Detailed studies of interhemispheric couplings, tropical to high latitude couplings, as well as changes in atmospheric or surface-ocean forcing at critical regions of the high latitudes are needed to assess further the release mechanisms for the observed millennial-scale variability.

### 4.3. Evolution of Deep Water Circulation

[28] There is a clear trend in our records toward an increase in the Atlantic deep intermediate water  $\delta^{13}\text{C}$  gradients

across the mid-Pleistocene climate shift, suggesting a fundamental change in the mode of ocean circulation. Preshift and postshift time differ in that the glacial  $\delta^{13}\text{C}$  gradient between 1000–2000 m (site 982–983) decrease after 0.95 Ma (Figures 5a and 5b), and at the same time the glacial  $\delta^{13}\text{C}$  gradient between 2000–4000 m (site 983–928) increase from MIS 24 and onward. The establishment and intensification of this North Atlantic intermediate to deep chemical gradient coincides with a number of changes in the chemistry of deep waters globally. Atlantic and Pacific deep water  $\delta^{13}\text{C}$  values converge more strongly during glacial periods after MIS 24 suggesting that glacial suppression of NADW increased into the Late Pleistocene [Raymo et al., 1990]. Likewise, intermediate to deep water  $\delta^{13}\text{C}$  gradients in the Southern Ocean increase significantly since 1.1 Ma [Hodell et al., 2003]. Such dramatic changes in ocean ventilation and vertical nutrient distributions have long been implicated in Late glacial to interglacial atmospheric  $\text{CO}_2$  changes [e.g., Boyle, 1988]. The fact that this glacial mode of ocean circulation developed during the mid Pleistocene climate shift forces us to at least consider the possibility that mechanisms other than the development of large ice sheets cause the 100 kyr cycle [Shackleton, 2000].

[29] **Acknowledgments.** We thank D. I. Blindheim, R. Sørensen, and O. Hansen for helping to generate the data and figures presented here. Thanks also to N. J. Shackleton for running some of this data in his lab. We also thank U. S. Ninnemann, N. J. Shackleton, and R. Schneider for useful discussions. Suggestions and careful reviews by C. D. Charles and two anonymous reviewers resulted in significant improvements to this manuscript. This research used samples provided by ODP. The ODP is sponsored by the U.S. National Science Foundation (NSF) and participating countries under management of Joint Oceanographic Institution (JOI), Inc. Funding for this research was provided by the Norwegian Science Foundation (HFK and EJ) and JOI/USSSP (WBC and DAH).

## References

- Adkins, J. F., E. A. Boyle, L. Keigwin, and E. Cortijo, Variability of the North Atlantic thermohaline circulation during the last interglacial period, *Nature*, **390**, 154–156, 1997.
- Alley, R. B., and D. R. MacAyeal, Ice-rafted debris associated with binge/purge oscillations of the Laurentide Ice Sheet, *Paleoceanography*, **9**(4), 503–511, 1994.
- Berger, W. H., and E. Jansen, Mid-Pleistocene climate shift—The Nansen connection, in *The Polar Oceans and Their Role in Shaping the Global Environment*, *Geophys. Monogr. Ser.*, vol. 85, edited by O. M. Johannessen et al., pp. 295–311, AGU, Washington, D. C., 1994.
- Berger, A., and M. F. Loutre, Insolation values for the climate of the last 10 million years, *Quat. Sci. Rev.*, **10**, 297–317, 1991.
- Bertram, C. J., H. Elderfield, N. J. Shackleton, and J. A. MacDonal, Cadmium/calcium and carbon isotope reconstructions of the glacial northeast Atlantic Ocean, *Paleoceanography*, **10**, 563–578, 1995.
- Bickert, T., W. B. Curry, and G. Wefer, Late Pliocene to Holocene (2.6–0 Ma) western equatorial Atlantic deep-water circulation: Inferences from benthic stable isotopes, in *Proceedings of the Ocean Drilling Program, Scientific Results*, edited by N. J. Shackleton et al., pp. 239–252, Ocean Drill. Prog., College Station, Tex., 1997.
- Bond, G., et al., Evidence for massive discharges of icebergs into the North Atlantic during the last glacial period, *Nature*, **360**, 245–249, 1992.
- Boyle, E. A., The role of vertical chemical fractionation in controlling late Quaternary atmospheric carbon dioxide, *J. Geophys. Res.*, **93**(C12), 15,701–15,714, 1988.
- Boyle, E. A., and L. D. Keigwin, Deep circulation of the North Atlantic over the last 200,000 years: Geochemical evidence, *Science*, **218**, 784–787, 1982.
- Boyle, E. A., and L. D. Keigwin, North Atlantic thermohaline circulation during the past 20,000 years linked to high-latitude surface temperature, *Nature*, **330**(6134), 35–40, 1987.
- Broecker, W. S., Massive iceberg discharges as triggers for global climate change, *Nature*, **372**, 421–424, 1994.
- Broecker, W. S., and E. Maier-Reimer, The Influence of air and sea exchange on the carbon isotope distribution in the sea, *Global Biogeochem. Cycles*, **6**, 315–320, 1992.
- Broecker, W. S., G. Bond, J. McManus, M. Klas, and E. Clark, Origin of the Northern Atlantic's Heinrich events, *Clim. Dyn.*, **6**, 265–273, 1992.
- Channell, J. E. T., and H. F. Kleiven, Geomagnetic paleointensity and astrochronological ages for the Matuyama-Brunhes boundary and the boundaries of the Jaramillo Subchron: Palaeomagnetic and oxygen isotope records from ODP site 983, *Philos. Trans. R. Soc. London*, **358**, 1027–1047, 2000.
- Chapman, M. R., and N. J. Shackleton, Millennial-scale fluctuations in North Atlantic heat flux during the last 150,000 years, *Earth Planet. Sci. Lett.*, **159**, 57–70, 1998.
- Charles, C. D., J. D. Wright, and R. G. Fairbanks, Thermodynamic influences on the marine carbon isotope record, *Paleoceanography*, **6**(6), 697–728, 1993.
- Cortijo, E., et al., Eemian cooling in the Norwegian Sea and North Atlantic ocean preceding continental ice-sheet growth, *Nature*, **372**, 446–449, 1994.
- Curry, W. B., and D. W. Oppo, Synchronous, high-frequency oscillations in tropical sea surface temperatures and North Atlantic Deep Water production during the last glacial cycle, *Paleoceanography*, **12**(1), 1–14, 1997.
- Curry, W. B., J.-C. Duplessy, L. D. Labeyrie, and N. J. Shackleton, Changes in the distribution of  $\delta^{13}\text{C}$  of deep water  $\Sigma\text{CO}_2$  between the last glaciation and the Holocene, *Paleoceanography*, **3**, 317–341, 1988.
- Curry, W. B., T. M. Marchitto, J. F. McManus, D. W. Oppo, and K. L. Laarkamp, Millennial-scale changes in ventilation of the thermocline, intermediate, and deep waters of the glacial North Atlantic, in *Chapman Conference on*

- Mechanisms of Millennial-Scale Global Climate Change*, *Geophys. Monogr. Ser.*, vol. 112, edited by P. U. Clark, R. S. Webb, and L. D. Keigwin, pp. 59–76, AGU, Washington, D. C., 1999.
- Dokken, T. M., and E. Jansen, Rapid changes in the mechanism of ocean convection during the last glacial period, *Nature*, 401, 458–461, 1999.
- Duplessy, J. C., et al., Deepwater source variations during the last climatic cycle and their impact on the global deepwater circulation, *Paleoceanography*, 3, 343–360, 1988.
- Fronval, T., and E. Jansen, Rapid changes in ocean circulation and heat flux in the Nordic seas during the last interglacial period, *Nature*, 383, 806–810, 1996.
- Fronval, T., E. Jansen, J. Bloemendal, and S. Johnsen, Oceanic evidence for coherent fluctuations in Fennoscandian and Laurentide ice sheets on millennium time scales, *Nature*, 374, 443–446, 1995.
- Fronval, T., E. Jansen, H. Hafliðason, and H. P. Sejrup, Variability in surface and deep water conditions in the Nordic Seas during the last interglacial period, *Quat. Sci. Rev.*, 17, 963–985, 1998.
- Hodell, D. A., K. Venz, C. D. Chales, and U. S. Ninnemann, Pleistocene vertical carbon isotope and carbonate gradients in the South Atlantic sector of the Southern Ocean, *Geochem. Geophys. Geosyst.*, 5, doi:10.1029/2002GC000367, in press, 2003.
- Imbrie, J., and J. Z. Imbrie, Modelling the climatic response to orbital variations, *Science*, 207, 943–953, 1980.
- Jansen, E., et al., (Eds.), *Proceedings of the Ocean Drilling Program, Initial Report 162*, Ocean Drill. Prog., College Station, Tex., 1996.
- Kawase, M., and J. L. Sarmiento, Circulation and nutrients in middepth Atlantic waters, *J. Geophys. Res.*, 91, 9748–9770, 1986.
- Keigwin, L. D., W. B. Curry, S. J. Lehman, and S. Johnsen, The role of the deep ocean in North Atlantic climate change between 70 and 130 kyr ago, *Nature*, 371, 323–326, 1994.
- Koc, N., and E. Jansen, Response of the high-latitude Northern Hemisphere to orbital climate forcing: Evidence from the Nordic seas, *Geology*, 22, 523–526, 1994.
- Lehman, S. J., D. G. Wright, and T. F. Stocker, *Ice in the Climate System*, *NATO ASI Ser. I*, vol. 12, edited by W. R. Pelstier, pp. 187–209, Springer-Verlag, New York, 1993.
- Marchitto, T. M. J., W. B. Curry, and D. W. Oppo, Millennial-scale changes in North Atlantic circulation since the last glaciation, *Nature*, 393, 557–561, 1998.
- Maslin, M. A., N. J. Shackleton, and U. Pflaumann, Surface water temperature, salinity and density changes in the northeast Atlantic during the last 45,000 years: Heinrich events, deep water formation, and climatic rebounds, *Paleoceanography*, 10(3), 527–544, 1995.
- McManus, J. F., D. W. Oppo, and J. L. Cullen, A 0.5 Million-year record of millennial-scale climate variability in the North Atlantic, *Science*, 283, 971–974, 1999.
- Oppo, D. W., and R. G. Fairbanks, Atlantic ocean thermocline circulation of the last 150,000 years: Relationship to climate and atmosphere CO<sub>2</sub>, *Paleoceanography*, 5, 277–288, 1990.
- Oppo, D. W., and S. J. Lehman, Mid-depth circulation of the subpolar North Atlantic during the Last Glacial Maximum, *Science*, 259, 1148–1152, 1993.
- Oppo, D. W., and S. J. Lehman, Suborbital time-scale variability of North Atlantic deep water during the past 200,000 years, *Paleoceanography*, 10(5), 901–910, 1995.
- Oppo, D. W., et al., A  $\delta^{13}\text{C}$  record of upper North Atlantic Deep Water during the past 2.6 million years, *Paleoceanography*, 10(3), 373–394, 1995.
- Oppo, D. W., M. Horowitz, and S. J. Lehman, Marine core evidence for reduced deep water production during Termination II followed by a relatively stable substage 5e (Eemian), *Paleoceanography*, 12(1), 51–63, 1997.
- Paillard, D., and L. Labeyrie, Role of the thermohaline circulation in the abrupt warming after Heinrich events, *Nature*, 372, 162–164, 1994.
- Rahmstorf, S., Bifurcations of the Atlantic thermohaline circulation in response to changes in the hydrological cycle, *Nature*, 378, 145–149, 1995.
- Raymo, M. E., W. F. Ruddiman, N. J. Shackleton, and D. W. Oppo, Evolution of Atlantic-Pacific  $\delta^{13}\text{C}$  gradients over the last 2.5 m.y., *Earth Planet. Sci. Lett.*, 97, 353–368, 1990.
- Raymo, M. E., K. Ganley, S. Carter, D. W. Oppo, and J. McManus, Millennial-scale climate instability during the early Pleistocene epoch, *Nature*, 392, 699–702, 1998.
- Sarnthein, M., et al., Changes in the east Atlantic deep water circulation over the last 30,000 years: Eight time slice reconstructions, *Paleoceanography*, 9, 209–267, 1994.
- Saunders, P. M., Cold outflow from the Faroe Bank Channel, *J. Phys. Oceanogr.*, 20, 29–43, 1990.
- Shackleton, N. J., The 100,000 year ice-age cycle identified and found to lag temperature, carbon dioxide, and orbital eccentricity, *Science*, 289, 1897–1902, 2000.
- Tiedemann, R., M. Sarnthein, and N. J. Shackleton, Astronomic timescale for the Pliocene Atlantic  $\delta^{18}\text{O}$  and dust flux records of Ocean Drilling Program site 659, *Paleoceanography*, 9(4), 619–638, 1994.
- Venz, K. A., D. A. Hodell, C. Stanton, and D. A. Warnke, A 1.0 Myr record of Glacial North Atlantic Intermediate Water variability from ODP site 982 in the northeast Atlantic, *Paleoceanography*, 14, 42–52, 1999.
- Vidal, L., et al., Evidence for changes in the North Atlantic Deep Water linked to meltwater surges during the Heinrich events, *Earth Planet. Sci. Lett.*, 146, 13–27, 1997.
- Weaver, A. J., and T. M. C. Hughes, Rapid interglacial climate fluctuations driven by North Atlantic Ocean circulation, *Nature*, 367, 447–450, 1994.
- Zahn, R., et al., Thermohaline instability in the North Atlantic during meltwater events: Stable isotope and ice-rafted detritus records from core SO75-26KL, Portuguese margin, *Paleoceanography*, 12(5), 696–710, 1997.

W. B. Curry, Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA. (curry@whoi.edu)

D. A. Hodell and K. Venz, Department of Geological Sciences, University of Florida, 241 Williamson Hall, PO Box 112120, Gainesville, FL 32611, USA. (dhodell@geology.ufl.edu; venz@ufl.edu)

E. Jansen, Bjerknes Centre for Climate Research and Department of Geology, University of Bergen, Allegaten 55, N-5007 Bergen, Norway. (eystein.jansen@geol.uib.no)

H. F. Kleiven, Department of Geology, University of Bergen, Allégaten 55, N-5077 Bergen, Norway. (kikki@geol.uib.no)