Glacial water mass geometry and the distribution of δ^{13}C of ΣCO$_2$ in the western Atlantic Ocean

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[1] Oxygen and carbon isotopic data were produced on the benthic foraminiferal taxa *Cibicidoides* and *Planulina* from 25 new piston cores, gravity cores, and multicores from the Brazil margin. The cores span water depths from about 400 to 3000 m and intersect the major water masses in this region. These new data fill a critical gap in the South Atlantic Ocean and provide the motivation for updating the classic glacial western Atlantic δ^{13}C transect of Duplessy et al. (1988). The distribution of δ^{13}C of ΣCO$_2$ requires the presence of three distinct water masses in the glacial Atlantic Ocean: a shallow ($\sim$1000 m), southern source water mass with an end-member δ^{13}C value of about 0.3–0.5‰ VPDB, a middepth ($\sim$1500 m), northern source water mass with an end-member value of about 1.5‰, and a deep (>2000 m), southern source water with an end-member value of less than -0.2‰, and perhaps as low as the -0.9‰ values observed in the South Atlantic sector of the Southern Ocean (Ninnemann and Charles, 2002). The origins of the water masses are supported by the meridional gradients in benthic foraminiferal δ^{18}O. A revised glacial section of deep water δ^{13}C documents the positions and gradients among these end-member intermediate and deep water masses. The large property gradients in the presence of strong vertical mixing can only be maintained by a vigorous overturning circulation.

1. Introduction

[2] Since the late 1980s, it has been known that the glacial distribution of δ^{13}C of ΣCO$_2$ in the deep Atlantic was significantly different from the modern distribution. The first comprehensive summaries of the glacial distribution of deep water δ^{13}C of ΣCO$_2$ documented that the North Atlantic Ocean was filled in its deepest locations with a water mass very low in δ^{13}C of ΣCO$_2$ [*Boyle and Keigwin*, 1982; *Curry and Lohmann*, 1982, 1983], while above 2000 m, it was occupied by a shallow water mass with very high δ^{13}C of ΣCO$_2$ [*Boyle and Keigwin*, 1987; *Oppo and Fairbanks*, 1987; *Duplessy et al.*, 1988; *Curry et al.*, 1988]. *Duplessy et al.* [1988] summarized much of what was known at the time about glacial δ^{13}C of ΣCO$_2$ in a classic figure depicting its distribution along a bathymetric section of the Atlantic Ocean from about 70°N to 45°S. The interpretation of this distribution of δ^{13}C of ΣCO$_2$ was that deep water production in the North Atlantic occurred by a different process than today and resulted in shallower overturning. The low δ^{13}C values in the deepest parts of the North Atlantic resulted from greater input of water with a low δ^{13}C value originating in the Southern Ocean.

[3] The *Duplessy et al.* [1988] δ^{13}C section ended in the South Atlantic just to the north of some cores with extremely low δ^{13}C values [*Charles and Fairbanks*, 1992], whose reliability as recorders of deep water

chemistry have been called into question [*Mackensen et al.*, 1993]. Recent work by *Ninnemann and Charles* [2002] has shown that the very low δ^{13}C of ΣCO$_2$ values are likely to be reliable and that there is evidence for vertical stratification of δ^{13}C of ΣCO$_2$ and two water masses in the South Atlantic sector of the Southern Ocean. Subsequent work has refined the original view of the glacial Atlantic Ocean by *Duplessy et al.* [1988] especially at shallower water depths. *Oppo and Lehman* [1993] produced a depth transect in the North Atlantic showing that the transition from the high to low δ^{13}C water mass at $\sim$2000 m was sharper than envisioned by *Duplessy et al.* [1988], with δ^{13}C decreasing by 1‰ across a $\sim$500 m depth interval. *Slowey and Curry* [1995] produced a depth transect in the Bahamas which showed that waters with very high δ^{13}C of ΣCO$_2$ spanned the shallow depths of 400 to 1500 m. These contributions together demonstrated that δ^{13}C values in the upper 2000 m were much higher than originally thought, reaching 1.5‰ (VPDB), more than 2‰ greater than the disputed Southern Ocean values. More recent revisions of δ^{13}C sections of the Atlantic Ocean have been produced [e.g., *Sarnthein et al.*, 1994], but few of the cores come from western basin locations, the principal flow path of the major deep water masses today and during the glacial period. Since synoptic differences in glacial δ^{13}C between eastern and western basin locations at similar water depths and densities were larger than today [*Curry et al.*, 1999], perhaps caused by higher productivity along the eastern basin or longer deep water residence times within the basins, a western basin section

is needed to determine principal glacial water mass characteristics, geometries and chemistries.

[4] Despite many advances since 1988, a paucity of data from the southwestern Atlantic gives rise to a very large gap in our understanding of the glacial deep water $\delta^{13}C$ distribution and deep water $\delta^{13}C$ gradients between the South Atlantic sector of the Southern Ocean and the North Atlantic. Although some early work had been accomplished in this region [e.g., *Curry and Lohmann*, 1982; *Boyle*, 1984], the cores suffered from very low sedimentation rates (1 cm kyr^{-1} or lower) and the records were poorly resolved. Very few cores have been measured in this geographic region and almost none from shallow (<2000 m) water depths. A few measurements from the Brazil margin suggested that the glacial, northern source water mass penetrated into the western South Atlantic, sandwiched between northward flowing shallow and deep southern source waters [*Oppo and Horowitz*, 2000]. However, the occurrence of each water mass in the South Atlantic was defined by measurements from a single core. Furthermore, these scant data did not permit an evaluation of the bathymetric or latitudinal extent of the water masses.

[5] In this paper we present benthic foraminiferal isotopic data from a suite of new cores from the western South Atlantic Ocean along the Brazil margin which provides new insight into the depth distribution (400 to 3000 m) and meridional gradients in $\delta^{13}C$ of ΣCO_2 that characterized the glacial South Atlantic Ocean. The bathymetric distribution of $\delta^{13}C$ requires the existence of three Atlantic Ocean water masses (two from the Southern Ocean and one from the north) and delineates their geometry and the gradients among them. By combining the data with previously published work and concentrating on the observations in the western basins, we update the *Duplessy et al.* [1988] $\delta^{13}C$ section for the glacial Atlantic Ocean.

2. Strategy

[6] In this paper we will call on several geochemical tracers of deep water properties to delineate the water mass geometry, origin and flow path during the glacial period. The primary evidence will come from $\delta^{13}C$ of the *Cibicidoides* taxonomic group of benthic foraminifera, which are known to be reliable recorders of deep water properties [*Belanger et al.*, 1981; *Graham et al.*, 1981]. Outside of areas with very high productivity, these fossils record with a high fidelity the $\delta^{13}C$ of the overlying water mass. Deep water $\delta^{13}C$ of ΣCO_2 is characteristic of its formation and since deep water $\Sigma^{13}C$ of ΣCO_2 can be altered only by mixing with water masses of another $\delta^{13}C$ composition, or by the addition of low $\delta^{13}C$ from oxidizing organic carbon along the water mass flow path flow or "aging" [*Curry and Lohmann*, 1982; *Mix and Fairbanks*, 1985; *Curry et al.*, 1988], geographic or bathymetric gradients of this tracer are extremely useful for delineating water mass geometry and geochemical characteristics. The tracer can be affected locally in areas of very high productivity [*Mackensen et al.*, 1993] but the magnitude of this effect is small [*McCorkle and Holder*, 2001] and limited in areal extent.

[7] The $\delta^{18}O$ value of benthic foraminiferal fossils is also a useful tracer of water mass properties because the $\delta^{18}O$ is controlled by temperature and $\delta^{18}O$ of sea water ($\delta^{18}O_{sw}$), which generally covaries with sea water salinity because $\delta^{18}O_{sw}$ and salinity are controlled by evaporation and precipitation at the ocean surface. Thus the $\delta^{18}O$ value of benthic foraminiferal fossils is strongly related to sea water density [*Lynch-Stieglitz et al.*, 1999]. Unfortunately the $\delta^{18}O$ gradients within the deep ocean are very small and laboratory intercalibration issues [*Ostermann and Curry*, 2000] make it difficult to compare benthic foraminiferal $\delta^{18}O$ with great confidence. The calcitic $\delta^{18}O$ gradient between the North and South Atlantic is small today, because the effects of temperature and salinity tend to cancel each other out: the South Atlantic is colder and fresher while the North Atlantic is warmer and saltier. However, these effects do not quite cancel, and the equilibrium calcite $\delta^{18}O$ values of water masses originating in the South Atlantic are generally higher at every water depth and density than water masses originating in the North Atlantic because the large difference in temperature dominates the equilibrium $\delta^{18}O$ values. Thus the $\delta^{18}O$ gradients between cores at similar depths can confirm the origin of the glacial water masses.

[8] Trace metal evidence from published work will also help to identify the origin of the glacial water masses. Cd/Ca values in the South Atlantic have already been used by *Oppo and Horowitz* [2000] to show that three water masses were needed to explain the Cd/Ca values in three cores from this region. In a similar manner, *Marchitto et al.* [2000, 2002] measured benthic foraminiferal Zn/Ca to demonstrate that the deepest waters penetrating into the glacial North Atlantic had very high Zn/Ca values and must have originated in the Southern Ocean.

3. Methods

[9] Twenty five new piston, gravity and multicores were collected from the slopes of the Brazil Margin between 25° and 28°S, spanning the depth range of 400 to 3000 m (Table 1). The cores sample the major water masses in the region: (1) South Atlantic water above about 600 m; (2) Antarctic Intermediate Water (AAIW) between 600 and 1000 m; (3) Upper Circumpolar Deep Water (upper CPDW) between about 1000 and 2000 m; and (4) North Atlantic Deep Water NADW) below 2000 m. Cores were collected from water depths down to 4000 m, which would intersect Lower Circumpolar Deep Water (lower CPDW) and Antarctic Bottom Water (AABW) in this area, but fossil preservation was too low to produce reliable stratigraphies and geochemical data.

[10] *Cibicidoides* and *Planulina* species, including *C. wuellerstorfi*, *C. kullenbergi*, *C. pachyderma*, *C. floridanus*, and *P. ariminensis*, are abundant in these cores. Individual specimens (>150 microns) were picked from the samples and analyzed on a Finnigan MAT252 mass spectrometer with an integrated automated carbonate device using standard procedures [*Ostermann and Curry*, 2000]. During the course of this laboratory analysis, the external precision of the laboratory standards was $\delta^{13}C = 0.06‰$ and $\delta^{18}O = 0.09‰$. The isotopic data were converted to VPDB using

Table 1. Locations, Water Depths, and Benthic Foraminiferal Stable Isotopic Data for Brazil Margin Cores[a]

Core	Latitude	Longitude	Depth	Holocene ^{13}C	Holocene ^{18}O	Glacial ^{13}C	Glacial ^{18}O	Stratigraphy
KNR159-99GGC	27.37 S	46.84 W	790	1.54	2.18	0.94	3.48	oxygen isotope stratigraphy
CAM-61PC	22.52 S	39.90 W	1890	1.23	2.43	0.90	4.45	this paper
KNR159-MC130A	27.77 S	46.43 W	1796	1.23	2.55	no data	no data	multicore top
KNR159-MC15D	27.70 S	46.50 W	1604	1.10	2.48	no data	no data	stained benthic
KNR159-MC32H	27.56 S	46.18 W	2096	1.23	2.57	no data	no data	stained benthic
KNR159-MC35E	27.25 S	46.47 W	1253	1.13	2.46	no data	no data	multicore top
KNR159-MC75EF	27.49 S	46.34 W	1823	1.03	2.48	no data	no data	multicore top
RC16-119	27.7 S	46.47 W	1507	1.04	2.43	0.91	4.20	*Oppo and Horowitz* [2000]
RC16-83	26.7 S	43.33 W	2438	1.35	2.54	0.57	4.44	*Oppo and Horowitz* [2000]
V29-253	26.95 S	44.68 W	2069	1.27	2.47	0.62	4.42	*Oppo and Horowitz* [2000]
KNR159-105JPC	27.35 S	46.63 W	1108	1.11	2.34	0.38	4.28	14C/oxygen isotope stratigraphy
KNR159-10GGC	26.48 S	45.93 W	630	1.56	1.90	1.02	3.62	oxygen isotope stratigraphy
KNR159-112GGC	28.87 S	45.70 W	2843	1.27	2.74	0.15	4.68	oxygen isotope stratigraphy
KNR159-136GGC	26.69 S	46.34 W	462	1.59	1.47	1.26	3.27	oxygen isotope stratigraphy
KNR159-17JPC	27.70 S	46.49 W	1627	0.91	2.84	0.98	4.19	oxygen isotope stratigraphy
KNR159-20JPC	28.64 S	45.54 W	2951	1.10	2.66	0.21	4.63	oxygen isotope stratigraphy
KNR159-36GGC	27.27 S	46.47 W	1268	1.18	2.53	0.54	4.20	14C/oxygen isotope stratigraphy
KNR159-73GGC	27.89 S	46.04 W	1128	1.28	2.63	0.46	4.52	oxygen isotope stratigraphy
KNR159-90GGC	27.35 S	46.63 W	1105	1.27	2.50	0.56	4.37	oxygen isotope stratigraphy
KNR159-14GGC	26.68 S	46.50 W	441	1.41	1.37	1.16	3.19	14C/oxygen isotope stratigraphy
KNR159-113JPC	28.87 S	45.68 W	2837	1.01	3.11	−0.15	4.62	oxygen isotope stratigraphy
KNR159-115GGC	28.74 S	45.53 W	3021	1.20	2.78	0.16	4.67	oxygen isotope stratigraphy
KNR159-137JPC	26.69 S	46.34 W	462	no data	no data	1.29	3.36	oxygen isotope stratigraphy
KNR159-33GGC	27.56 S	46.19 W	2082	1.11	2.37	0.76	4.49	oxygen isotope stratigraphy
KNR159-34JPC	27.56 S	46.19 W	2082	1.16	2.50	0.71	4.45	oxygen isotope stratigraphy
KNR159-37GGC	27.25 S	46.63 W	938	1.39	2.48	0.84	3.84	oxygen isotope stratigraphy
KNR159-38JPC	27.27 S	46.63 W	936	1.36	2.30	0.66	3.93	oxygen isotope stratigraphy
KNR159-42JPC	27.76 S	46.63 W	2296	1.28	2.54	0.54	4.61	oxygen isotope stratigraphy
KNR159-153JPC	26.39 S	45.69 W	898	no data	no data	0.62	4.19	oxygen isotope stratigraphy

[a]Latitude and longitude are presented in degrees. Water depth is presented in meters. Isotopic values are presented in permil with respect to VPDB. The stratigraphy column denotes the method used to identify the Holocene and glacial sections within the cores.

the NBS-19 standard using the conversion $\delta^{13}C = 1.95‰$ VPDB and $\delta^{13}C = -2.20‰$ VPDB.

[11] Stratigraphic control is based on the oxygen isotope stratigraphy of the benthic foraminifera, the oxygen isotope stratigraphy of the planktonic foraminiferal species *Globigerinoides ruber* (white, 212–250 microns), and a number of ^{14}C AMS dates on *G. ruber* (Table 1). Sedimentation rates in the cores vary from 5 to 15 cm kyr^{-1}. For the reconstructions, Holocene values were based on core top values for multicores and on the youngest samples in piston and gravity cores with discernible Holocene sections. Glacial maximum sections were identified by their highest δ^{18}O values (either from the planktonic or benthic stratigraphy) or from radiocarbon dates. We used a broad definition of the glacial maximum (18 to 21 ka) and we focused on the stratigraphic levels where individual benthic isotopic measurements were most stable, trying to avoid levels in the core where bioturbation may have mixed together samples of different age. The full Brazil margin data set and the levels of our glacial and Holocene picks are available as supplemental data from the NOAA Paleoclimate Data Center and as auxiliary material.[1]

[12] For the discussion of the Brazil margin results, we compare the isotopic data to published results from a variety of western basin Atlantic cores and cores from the South Atlantic sector of the Southern Ocean (Table 2). We restricted the sample set to cores which are in locations that are unaffected by the sills of the eastern basin of the

Atlantic: cores located in the Atlantic Ocean to the west of the mid-Atlantic Ridge, cores from above the sill depth along the ridge, and cores from the Southern Ocean south of the Walvis Ridge. Cores within the eastern basins below the sill depths are affected by greater aging of the deep water and consequently have lower δ^{13}C values [*Curry and Lohmann*, 1983; *Curry et al.*, 1988]. The core locations and water depths are presented in Figure 1.

4. Data/Results

4.1. Glacial-Interglacial Differences at the Brazil Margin

[13] Holocene bathymetric profiles of foraminiferal δ^{18}O and δ^{13}C reflect the modern water masses intersecting the Brazil margin (Figure 2). The midwater δ^{13}C maximum and δ^{18}O minimum between 2 and 3 km are caused by the presence of NADW penetrating far into the South Atlantic and bisecting upper CPDW above and lower CPDW below those depths. The δ^{13}C minimum associated with the upper CPDW is well resolved; it is also a mid-water maximum in benthic foraminiferal δ^{18}O. Below NADW (>2700 m), δ^{18}O values increase and δ^{13}C values decrease as the hydrographic properties of lower CPDW are recorded in the benthic foraminiferal shell chemistry.

[14] The oxygen isotopic data for the Holocene and glacial profiles show similar shapes: a steep depth gradient from the low surface δ^{18}O values (based on the δ^{18}O values of the planktonic foraminifer *G. ruber*) rapidly increasing over the upper 1000 m to much greater δ^{18}O values (for the *Cibicidoides* taxa) characteristic of colder deep water

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[1]Auxiliary material is available at ftp://ftp.agu.org/apend/pa/ 2004PA001021.

Table 2. Locations, Water Depths, and Benthic Foraminiferal Stable Isotopic Data for Published Western Atlantic and Southern Ocean Cores[a]

Core	Latitude	Longitude	Depth	Holocene ^{13}C	Holocene ^{18}O	Glacial ^{13}C	Glacial ^{18}O	Reference
CH75-04	10.01 N	56.01 W	3820	0.9	2.8	−0.2	4.6	*Curry et al.* [1988]
CH75-03	10.05 N	57.53 W	3410	0.9	2.9	0.1	4.7	*Curry et al.* [1988]
CH74-227	35.27 N	29.25 W	3225	no core top	no core top	0.1	4.4	*Curry et al.* [1988]
V25-59	1.37 N	33.48 W	3824	1.0	2.7	0.1	4.3	*Curry et al.* [1988]
V29-202	60.383 N	20.967 W	2658	0.8	2.9	0.5	4.4	*Oppo et al.* [1997]
V29-204	61.18 N	23.02 W	1869	1.3	2.8	1.4	4.5	*Curry et al.* [1999]
EW9302-14JPC	61.42 N	24.106 W	1653	no core top	no core top	1.5	4.5	*Oppo et al.* [1997]
V29-198	58.733 N	15.567 W	1139	1.1	2.3	1.4	4.0	*Oppo and Lehmann* [1993]
V28-14	64.783 N	29.567 W	1855	0.9	2.5	1.4	4.5	*Curry et al.* [1988]
V26-176	36.05 N	72.383 W	3942	1.1	2.5	0.2	4.1	*Curry et al.* [1988]
V28-73	57.183 N	20.867 W	2063	1.2	2.8	1.2	4.1	*Oppo and Lehmann* [1993]
EN120-1GGC	33.67 N	57.62 W	4450	0.3	2.4	−0.3	4.0	*Boyle and Keigwin* [1987]
CHN82-4	41.708 N	33.85 W	3427	1.3	2.6	0.5	4.4	*Boyle and Keigwin* [1985/1986]
CHN82-20	43.498 N	29.867 W	3020	1.3	2.5	0.7	4.3	*Boyle and Keigwin* [1985/1986]
CHN82-15	43.372 N	28.232 W	2151	1.1	2.6	1.2	4.0	*Boyle and Keigwin* [1987]
KNR64-5	16.52 N	74.81 W	3047 (1750)[b]	1.0	2.4	1.2	3.5	*Boyle and Keigwin* [1987]
V28-122	11.93 N	78.68 W	3623 (1750)[b]	0.8	2.3	1.2	3.9	*Oppo and Fairbanks* [1987]
V28-127	11.65 N	80.13 W	3237 (1750)[b]	0.9	2.4	1.3	4.1	*Oppo and Fairbanks* [1987]
EW9209-1JPC	5.91 N	44.20 W	4056	0.5	2.6	0.0	4.5	*Curry* [1996]
EW9209-2JPC	5.64 N	44.47 W	3528	1.4	2.5	0.1	4.5	*Curry* [1996]
EW9209-3JPC	5.31 N	44.26 W	3288	0.9	2.6	0.3	4.4	*Curry* [1996]
ODP925	4.21 N	43.49 W	3041	1.4	2.6	0.3	4.3	*Bickert et al.* [1997]
ODP926	3.72 N	42.71 W	3598	1.2	2.7	0.2	4.3	*Bickert et al.* [1997]
ODP927	5.46 N	44.48 W	3315	0.5	2.6	0.3	4.4	this paper
ODP928	5.46 N	43.75 W	4012	1.2	2.7	0.1	4.3	this paper
ODP929	5.98 N	43.74 W	4358	0.2	2.8	0.1	4.3	*Bickert et al.* [1997]
OCE205-149JPC	26.26 N	77.67 W	423	1.7	0.5	2.3	2.1	*Slowey and Curry* [1995]
OCE205-106GGC	25.977 N	78.181 W	654	1.3	1.3	1.9	2.9	*Slowey and Curry* [1995]
OCE205-108GGC	25.984 N	78.180 W	743	1.2	1.6	1.8	3.3	*Slowey and Curry* [1995]
OCE205-33GGC	26.221 N	77.671 W	783	1.2	1.6	1.7	3.3	*Slowey and Curry* [1995]
OCE205-103GGC	26.07 N	78.070 W	965	1.3	2.2	1.5	3.9	*Slowey and Curry* [1995]
OCE205-100GGC	26.061 N	78.028 W	1057	1.5	2.4	1.5	3.9	*Slowey and Curry* [1995]
OCE205-97JPC	26.937 N	77.854 W	1183	1.3	2.4	1.5	4.1	*Slowey and Curry* [1995]
OCE205-7JPC	26.137 N	77.735 W	1320	1.3	2.8	1.5	3.8	*Slowey and Curry* [1995]
OCE205-117JPC	26.034 N	77.878 W	1535	1.4	2.4	1.5	4.4	*Slowey and Curry* [1995]
DSDP 552	56.05 N	23.23 W	2311	no core top	no core top	0.9	4.1	*Sarnthein et al.* [1994]
M17049	55.26 N	26.73 W	3331	0.7	2.6	0.6	4.5	*Sarnthein et al.* [1994]
M17051	56.16 N	31.99 W	2295	1.0	2.6	0.8	4.5	*Sarnthein et al.* [1994]
M17050	55.47 N	27.89 W	2795	0.5	2.6	0.5	4.4	*Sarnthein et al.* [1994]
KNR140-68GGC	32.943 N	76.552 W	775	0.7	2.1	no data	no data	*Keigwin* [2004]
KNR140-61GGC	32.998 N	76.356 W	1005	1.2	2.7	no data	no data	*Keigwin* [2004]
KNR140-59GGC	32.977 N	76.316 W	1205	1.2	2.6	no data	no data	*Keigwin* [2004]
KNR140-63JPC	32.988 N	76.407 W	900	1.0	2.2	1.5	3.8	*Keigwin* [2004]
KNR140-56GGC	32.939 N	76.296 W	1400	0.8	2.6	1.3	4.1	*Keigwin* [2004]
KNR140-54GGC	32.934 N	76.276 W	1495	0.8	2.3	no data	no data	*Keigwin* [2004]
KNR140-53GGC	32.932 N	76.246 W	1605	1.1	2.6	no data	no data	*Keigwin* [2004]
KNR140-51GGC	32.784 N	76.12 W	1790	0.9	2.5	1.2	4.1	*Keigwin* [2004]
KNR140-50GGC	32.753 N	76.236 W	1903	0.5	2.4	1.1	4.3	*Keigwin* [2004]
KNR140-64GGC	32.742 N	76.127 W	2101	no core top	no core top	1.2	4.1	*Keigwin* [2004]
KNR140-67JPC	32.74 N	76.129 W	2102	no core top	no core top	1.5	4.1	*Keigwin* [2004]
KNR140-66GGC	32.502 N	76.294 W	2155	1.0	2.5	no data	no data	*Keigwin* [2004]
KNR140-1JPC	32.375 N	76.383 W	2243	1.0	2.2	no data	no data	*Keigwin* [2004]
KNR140-2JPC	32.226 N	76.29 W	2394	no core top	no core top	0.4	4.2	*Keigwin* [2004]
KNR140-43GGC	32.017 N	76.067 W	2590	1.1	2.6	0.9	4.5	*Keigwin* [2004]
KNR140-37JPC	31.69 N	75.43 W	2972	0.9	2.8	0.4	4.5	*Keigwin and Schlegel* [2002]
KNR140-39GGC	31.669 N	75.415 W	2975	1.4	2.7	0.3	4.4	*Keigwin and Schlegel* [2002]
KNR140-36JPC	31.359 N	75.062 W	3007	1.1	2.7	no data	no data	*Keigwin* [2004]
KNR140-30GGC	30.734 N	74.468 W	3433	0.5	2.4	no data	no data	*Keigwin* [2004]
KNR140-32GGC	30.801 N	74.797 W	3615	0.3	2.5	no data	no data	*Keigwin* [2004]
KNR140-26GGC	29.7 N	73.401 W	3845	no core top	no core top	−0.2	4.3	*Keigwin* [2004]
KNR140-29GGC	30.018 N	73.604 W	3978	1.0	2.4	no data	no data	*Keigwin* [2004]
KNR140-28GGC	30.098 N	73.837 W	4211	0.4	2.4	−0.5	4.4	*Keigwin* [2004]
KNR140-12JPC	29.075 N	72.898 W	4250	no core top	no core top	−0.5	4.5	*Keigwin* [2004]
KNR140-22JPC	28.025 N	74.407 W	4712	1.2	2.7	−0.3	4.5	*Keigwin* [2004]
RC11-83	41.60 S	9.80 E	4718	0.2	2.3	−0.9	4.1	*Charles and Fairbanks* [1992]
TN057-20	42 S	1 E	1335	0.6	2.4	0.4	3.8	*Ninnemann and Charles* [2002]
RC15-93	46.1 S	13.22 W	2714	0.3	2.5	−1.0	4.0	*Ninnemann and Charles* [2002]
TN057-15	51.90 S	4.52 E	3744	0.0	2.8	−0.8	4.2	*Ninnemann and Charles* [2002]
RC15-94	42.98 S	20.85 W	3762	−0.2	2.4	−0.8	4.1	*Ninnemann and Charles* [2002]

Table 2. (continued)

Core	Latitude	Longitude	Depth	Holocene ^{13}C	Holocene ^{18}O	Glacial ^{13}C	Glacial ^{18}O	Reference
V22-108	43.18 S	3.25 W	4171	0.1	2.4	−0.8	4.2	*Ninnemann and Charles* [2002]
TN057-21	41.13 S	7.82 E	4981	0.3	2.6	−0.8	4.3	*Ninnemann and Charles* [2002]

[a]Latitude and longitude are presented in degrees. Water depth is presented in meters. Isotopic values are presented in permil with respect to VPDB. The reference identifies the source of the data.

[b]Effective sill depth for the Caribbean Sea cores. The data for these cores are plotted at the sill depth in all figures.

temperatures and lower salinities below about 1000 m. Today and during the glacial period the bathymetric gradient of δ^{18}O above 1000 m is most likely the result of the steep temperature gradient within the thermocline. In general the glacial-interglacial differences in δ^{18}O are larger below 2000 m ($\Delta\delta^{18}$O = ~1.9‰) than above 2000 m ($\Delta\delta^{18}$O = ~1.7‰), despite the deeper cores in general having lower sedimentation rates. Thus these differences in glacial-interglacial amplitude are unlikely to result from bioturbation.

[15] Glacial-interglacial δ^{13}C changes ($\Delta\delta^{13}$C) exhibit much greater variability with water depth. *Cibicidoides* $\Delta\delta^{13}$C decreases from ~−0.4‰ at about 400 m to a mid-water minimum at 1000 m of $\Delta\delta^{13}$C = −0.8‰. The glacial-interglacial difference then increases to $\Delta\delta^{13}$C = −0.1‰ at about 1500–1600 m. $\Delta\delta^{13}$C then decreases again below 1600 m reaching minimum values of $\Delta\delta^{13}$C = −1.0‰ at about 3000 m, the deepest cores in the data set. The bathymetric pattern for the glacial δ^{13}C profile requires the presence of three water masses: a small intermediate-depth water mass with low δ^{13}C centered at 1000 m, a middepth deep water mass with higher δ^{13}C located from about 1200 to 2000 m, and a water mass below 2000 m with steeply decreasing glacial δ^{13}C values. A middepth maximum in benthic foraminiferal δ^{13}C, which occurs at ~2500 m during the Holocene, shoaled to ~1500 m during the glacial period.

4.2. Brazil Margin Glacial Profiles Compared With the North Atlantic

[16] In Figure 3 we compare the glacial bathymetric distributions of δ^{13}C and δ^{18}O from the Brazil margin and from cores in the western North Atlantic basins. The North Atlantic cores are a composite of a number of previously published and some unpublished data (Table 2). Many of the records were produced by the authors using the same mass spectrometer system as the new Brazil margin data set.

[17] The δ^{13}C profiles reveal several important gradients and patterns that are indicative of large-scale mixing between water masses. In the glacial North Atlantic, a water mass with homogenous δ^{13}C values of about 1.5‰ occupied the depths between 1000 and 1800 m. At this water depth there was a strong latitudinal gradient in δ^{13}C (up to 1‰) between cores from the western North Atlantic and cores from the western South Atlantic. Above 1000 m the δ^{13}C values in the North Atlantic were consistently about 1‰ higher than in the South Atlantic. The δ^{13}C values of the South Atlantic cores at about 1000 m were very similar to the values observed by *Ninnemann and Charles* [2002] in their shallowest core from the nearby Southern Ocean. Below about 2000 m, the North Atlantic was higher in δ^{13}C than the South Atlantic by a smaller amount, about 0.4‰; the same meridional gradient persisted down to about 3000 m despite strong bathymetric gradients in each basin. The bathymetric

δ^{13}C gradients below 2000 m were nearly the same in the North and South Atlantic: approximately −0.7 to −1‰ δ^{13}C per 1000 m increase in water depth. At and below 3000 m, the δ^{13}C values in the North Atlantic approach the very low δ^{13}C values observed by *Ninnemann and Charles* [2002] in the deepest cores from the South Atlantic sector of the Southern Ocean. The bathymetric gradient of δ^{13}C in the South Atlantic extrapolates toward the low Southern Ocean δ^{13}C values, but poor preservation of calcite below 3000 m precludes observations of the lowest δ^{13}C values.

[18] The glacial δ^{18}O bathymetric profiles from the North and South Atlantic are less distinctly different (Figure 3), but important gradients are still evident. At nearly every depth in the water column, the average glacial δ^{18}O values tend to be higher in the South Atlantic than in the North Atlantic. Above 1000 m, the South Atlantic δ^{18}O values were about 0.5‰ greater during the glacial period, similar to the gradient observed today between the North and South Atlantic subtropical gyres. Below 2000 m, the δ^{18}O values in the South Atlantic cores were about 0.25‰ higher than the North Atlantic. At about 1500 m, the δ^{18}O gradient falls to near zero. Significantly, this is the depth level of the high-δ^{13}C water mass in the North Atlantic and the depth level of the same high-δ^{13}C water mass as it penetrated into the South Atlantic.

5. Discussion
5.1. Glacial Section of Deep Water δ^{13}C of ΣCO$_2$

[19] Figure 4 shows the modern distribution of δ^{13}C of ΣCO$_2$ measured by *Kroopnick* [1985] and glacial distribution of δ^{13}C of ΣCO$_2$ inferred from the latitude-depth distribution of benthic foraminiferal δ^{13}C within the western basin of the Atlantic. Note that there is a much larger range of δ^{13}C values during the glacial maximum than in the modern ocean. Highest glacial δ^{13}C values occurred in surface waters of the North Atlantic subtropical gyre. Lowest δ^{13}C values occurred in the deepest parts of the South Atlantic sector of the Southern Ocean. Within the basins, large bathymetric and meridional gradients in δ^{13}C occurred. In the North Atlantic, the major bathymetric transition occurred at about 2000 m, with a 1‰ decrease in δ^{13}C over a 500 m depth range, a water mass boundary already well known from previous studies [e.g., *Oppo and Lehman*, 1993]. Below this depth level, a gradual decrease in δ^{13}C continued and reached δ^{13}C values <0‰ VPDB. Zn/Ca values of benthic foraminifera in the deep North Atlantic, from several of the same cores used here, confirm the long-held view that deep water at the deepest levels of the North Atlantic originated in the Southern Ocean [*Marchitto et al.*, 2002]. The δ^{13}C variations above this deep water represent gradational mixtures of the deep Southern Ocean water mass and the shallower water mass
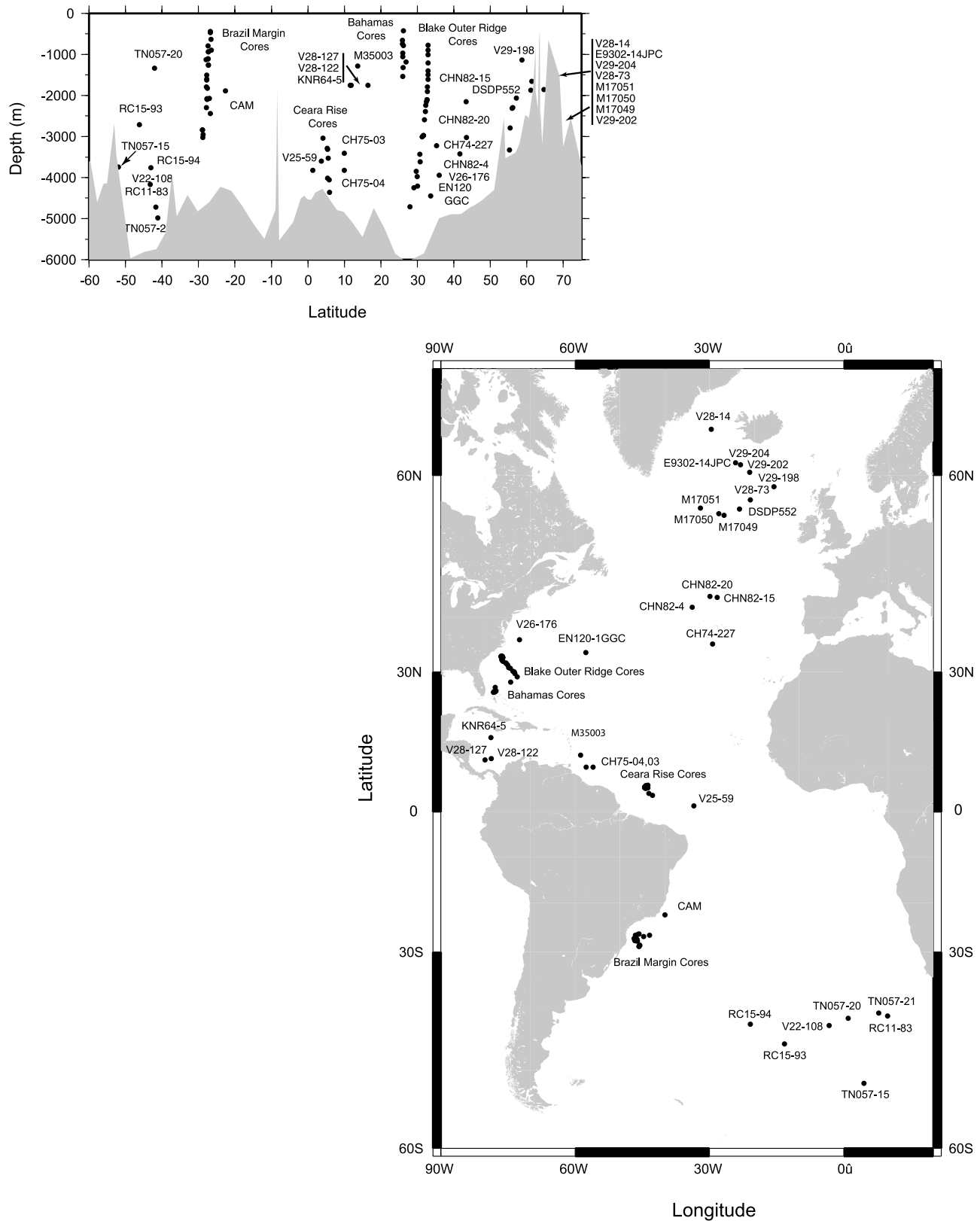
Western Atlantic Core Locations

Figure 1. Core locations and water depths.
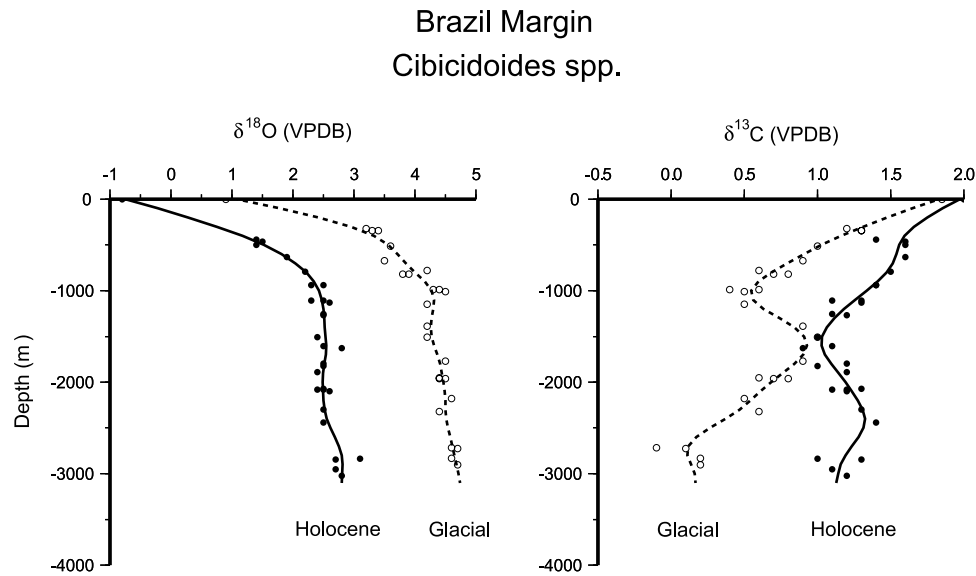
Brazil Margin
Cibicidoides spp.

Figure 2. Holocene (solid line, solid symbols) and glacial (dashed line, open symbols) profiles of *Cibicidoides* and *Planulina* stable isotopic compositions. Surface values are provided by stable isotope measurements on *G. ruber*. Lines fit through the data produced with a spline function. Several features of the Holocene and glacial water masses are depicted in the figures. In the $\delta^{18}O$ bathymetric profiles the steep gradient in the upper water column is controlled by the thermocline. A small midwater minimum in $\delta^{18}O$ at 2000–2500 m in the Holocene profile shows the effects of NADW on this South Atlantic location. During the glacial period, this same $\delta^{18}O$ minimum occurred at 1500 m. The $\delta^{13}C$ profiles document changes in water mass position and characteristics. The high $\delta^{13}C$ values associated with northern source waters shoaled during the glacial period to about 1500 m. A very steep bathymetric gradient in $\delta^{13}C$ below 1500 m was caused by gradational mixing between the northern source and southern source water masses at this location.

often referred to as Glacial North Atlantic Intermediate Water (GNAIW; *Boyle and Keigwin* [1987]).

5.2. Water Mass End-Members and Mixing

[20] To maintain large gradients in deep water properties in the presence of strong vertical mixing requires a vigorous deep ocean circulation. Vertical mixing within the deep oceans occurs, in particular, near rough bottom topography [*Polzin et al.*, 1997; *Ledwell et al.*, 2000; *Mauritzen et al.*, 2002]. Today vertical mixing along the Mid-Atlantic Ridge is estimated to be several orders of magnitude stronger than above the smooth bottoms of the abyssal plains and continental slopes [*Polzin et al.*, 1997]. This mixing produces weak but observable gradients in water mass properties today [*Mauritzen et al.*, 2002]. The gradients are weak because the range of hydrographic properties is small, presumably because NADW dominates the North Atlantic basins. (NADW mixing mostly with itself cannot produce large gradients in water mass properties.) The mixing process reduces the density and raises the buoyancy of deep water, providing necessary upward vertical motion of deep water needed to counterbalance the downward flow of cold, dense deep water formed at high latitudes. *Wunsch* [2003] points out that mixing rates in the deep ocean were likely to have been stronger during the glacial than today because of increased wind stress and greater tidal mixing in deep basins rather than on the continental shelves,

which were exposed during times of lower sea level. The occurrence of enhanced tidal dissipation in the deep sea during low sea level has been confirmed in simulations with a tidal model [*Egbert et al.*, 2004].

[21] During the glacial maximum, the large differences in water mass properties of GNAIW and Southern Ocean deep water, and the greater penetration of the southern ocean deep water into the North Atlantic provide the elements needed to produce large vertical gradients in water mass properties. Thus we observe a steep decrease in $\delta^{13}C$, beginning at about 2000 m in the water column, between the very high $\delta^{13}C$ values of GNAIW (end-member value of 1.5‰) and the very low values of the deep Southern Ocean water mass (end-member value of −0.2‰ to perhaps as low as −0.9‰). Following this line of reasoning, the upper boundary of this mixing zone is controlled by the shallowest bathymetry of the Mid-Atlantic Ridge.

[22] The presence of strong gradients and high levels of deep ocean mixing seems to imply that circulation remained vigorous for much of the glacial maximum period. To maintain large gradients in hydrographic properties requires active advection (production) of the water masses and large differences in their end-member hydrographic properties. The change in water mass geometry (NADW shoaling to become GNAIW) may have had an effect on the heat transport within the North Atlantic, but overall mass transports in the Atlantic may not have changed very much

North and South Atlantic Glacial Profiles
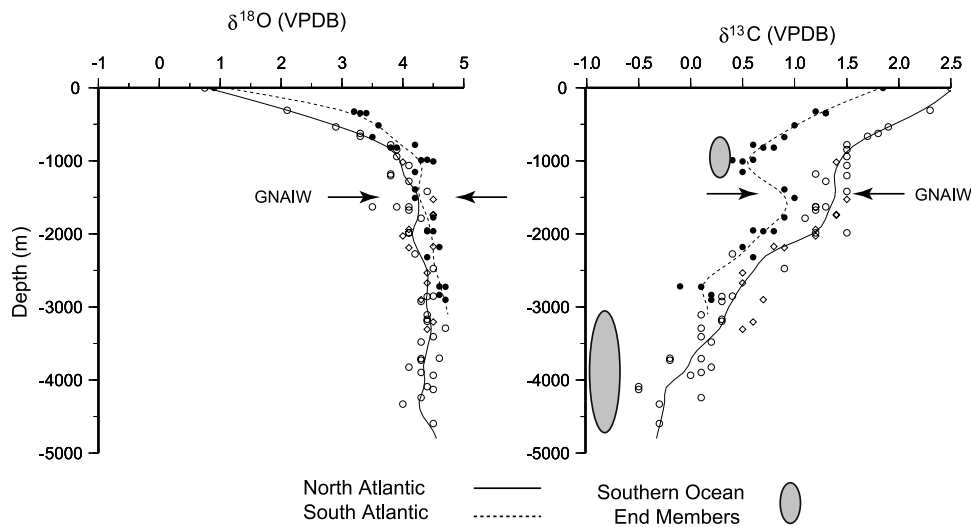
Cibicidoides spp.

Figure 3. Comparison of bathymetric gradients of $\delta^{18}O$ and $\delta^{13}C$ in the North Atlantic (solid line, open symbols: diamonds from north of 40°N, circles from south of 40°N) and South Atlantic (dashed line, closed circles) during the glacial period. Lines fit through the data produced with a spline function. The shaded ellipses show the approximate water depths and $\delta^{13}C$ values for the water masses observed in the Southern Ocean by *Ninnemann and Charles* [2002]. The arrows mark the depth level for Glacial North Atlantic Intermediate Water penetration into the South Atlantic The meridional gradients in $\delta^{13}C$ are large above 1500 m, suggesting that there was a mixing zone between water masses of northern and southern origin. Below about 2000 m, there was a steep bathymetric gradient in each ocean basin. At all depths the South Atlantic was lower in $\delta^{13}C$ than the North Atlantic. The deep bathymetric gradients appear to point toward the very low $\delta^{13}C$ values observed by *Ninnemann and Charles* [2002] for the Southern Ocean, implying that mixing between this water mass and Glacial North Atlantic Intermediate Water caused the observed gradients.

[*Wunsch*, 2003]. *McManus et al.* [2004] suggest that export of deep water from the North Atlantic during the glacial maximum was no more than 30–40% reduced, but only during Heinrich event 1 and the Younger Dryas is there evidence that North Atlantic overturning was significantly lower than today. As suggested by *Wunsch* [2003], reduced overturning in the North Atlantic may have been compensated by increased production of Southern Ocean deep water, so that the overall rate of deep ocean circulation may have been as strong as, perhaps stronger than today.

[23] South Atlantic $\delta^{13}C$ values were much lower than North Atlantic values at nearly every water depth. Above 2000 m, the bathymetric $\delta^{13}C$ gradients in the South Atlantic require the presence of two water masses: one centered at about 1000 m, with a $\delta^{13}C$ value of about 0.5‰VPDB and another centered at 1500 m with a $\delta^{13}C$ value >0.8‰. Our updated glacial western Atlantic cross section (Figure 4), which includes a data point from the shallow Southern Ocean (42°S, *Ninnemann and Charles* [2002]), indicates that the Southern Ocean was the most likely source of the shallower (1000 m), intermediate water mass, whereas the middepth water mass was derived from the north. The other water mass centered at 1500 m, which is the southern expression of GNAIW, originated in the

North Atlantic with a $\delta^{13}C$ value of about 1.5‰ VPDB. Its much lower $\delta^{13}C$ value in the South Atlantic implies that it had undergone significant aging along its flow path or its $\delta^{13}C$ value resulted from mixing with a water mass of lower $\delta^{13}C$. Very low values of $\delta^{13}C$ in the North and South Atlantic came from the third water mass, flowing from the deep Southern Ocean and originating with an end-member $\delta^{13}C$ value of <-0.2‰ and maybe as low as -0.9‰.

[24] The three water masses described above were first identified in the South Atlantic based on their Cd/Ca values [*Oppo and Horowitz*, 2000]. The deepest water mass had very high Cd/Ca values grading between $Cd_w = \sim 0.7$ nmol kg^{-1} at 4000 m to $Cd_w = 0.4$ nmol kg^{-1} at 2000 m. Unfortunately, few of these deeper cores had usable $\delta^{13}C$ measurements [*Oppo and Horowitz*, 2000], but almost certainly the $\delta^{13}C$ values would have been very low. At about 1600 m, *Oppo and Horowitz* [2000] observed a minimum in Cd/Ca values ($Cd_w = 0.3$ nmol kg^{-1}) associated with a local maximum in benthic foraminiferal $\delta^{13}C$. At 1200 m, another water mass was identified based on its higher Ca/Ca values ($Cd_w = 0.4$ nmol kg^{-1}) and lower $\delta^{13}C$ values. *Oppo and Horowitz* [2000] identified this water mass as similar to Antarctic Intermediate Water but without the high $\delta^{13}C$ value caused by air-sea exchange.

Western Atlantic GEOSECS δ^{13}C (PDB)

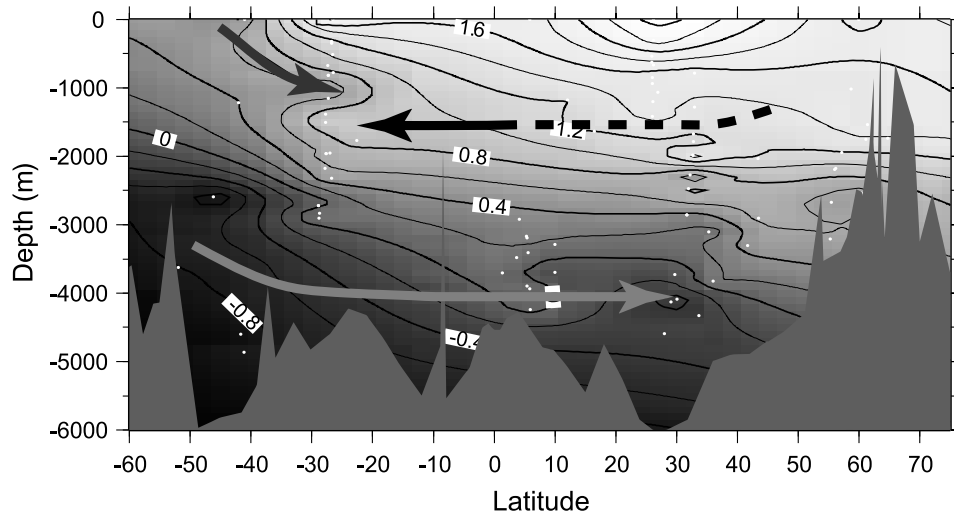## Western Atlantic Glacial δ^{13}C (PDB)

Figure 4. The distribution of δ^{13}C of ΣCO_2 in the modern western Atlantic [*Kroopnick*, 1985] and a revised and updated glacial transect of δ^{13}C of ΣCO_2 for the western Atlantic Ocean basins. A relatively simple three-component model is proposed to explain the water mass distribution and gradients. The patterns in the South Atlantic imply that the northern source water at 1500 m penetrated as far as 30°S latitude. The penetration of the deep Southern Ocean water mass can be observed as far as 60°N. The shallow, southern source water mass did not penetrate to 25°N, but there are too few data at intermediate water depths between about 25°S and 25°N in the western Atlantic to constrain its northward extent. See color version of this figure at back of this issue.

Oppo and Horowitz [2000] concluded that the low nutrient, high δ^{13}C water mass at 1600 m must have originated in the North Atlantic and that the steep bathymetric gradient in Cd_w below 2000 m was a mixing gradient between the northern and southern water masses.

[25] The section in Figure 4 shows the latitudinal extent of these three water masses, the gradients between the end-members, and evidence for some aging along flow paths. The meridional and bathymetric gradients require two water masses flowing from the Southern Ocean, bisected by the southward flowing GNAIW. *Ninnemann and Charles* [2002] document that the stratification in the Southern Ocean was strong during the glacial period, implying that two water masses were present, a shallow water mass with

relative high $\delta^{13}C$ overlying a water mass with very low $\delta^{13}C$. While our results do not confirm that the very low $\delta^{13}C$ values in the deepest sites accurately reflect the overlying bottom water, the bathymetric and meridional gradients in $\delta^{13}C$ require mixing with a water mass with very low $\delta^{13}C$. In the North and South Atlantic, the bathymetric gradients point toward $\delta^{13}C$ values as low as observed by *Ninnemann and Charles* [2002].

[26] Combined Cd/Ca and $\delta^{13}C$ measurements constrain the effects of mixing between water masses and aging along the flow path [*Lynch-Stieglitz et al.*, 1996]. A $\delta^{13}C$ gradient of -0.5% at about 1500 m from the North Atlantic to the South Atlantic (Figure 4) is accompanied by a Cd_w increase of <0.1 nmol kg^{-1} [*Marchitto et al.*, 1998; *Oppo and Horowitz*, 2000]. The Cd_w increase is smaller than predicted by the $\delta^{13}C$ decrease if aging alone produced the $\delta^{13}C$ gradients, so some of the $\delta^{13}C$ gradient may be the result of mixing between water masses. At about 1000 m, the meridional gradient in $\delta^{13}C$ is very large ($\sim-1\%$) and is accompanied by a Cd_w increase of 0.2 nmol kg^{-1}. Although these gradients are in the right direction for the "aging effect" if the water mass was flowing from north to south at these depths, this is an unlikely possibility based on the bathymetric gradients of $\delta^{13}C$ in Figure 3 and the water mass geometry shown in Figure 4. It is much more likely that intermediate water at 1000 m was flowing from south to north. Although this water mass exhibits a distinct low in $\delta^{13}C$ in the South Atlantic, the northward penetration of this water mass is poorly constrained in Figure 4. There is Cd/Ca and $\delta^{13}C$ evidence for a 50:50 north:south water mass mixture at 13°N [*Zahn and Stuber*, 2002], but unfortunately there are no cores between 25°S and 13°N at intermediate water depths, so it is difficult to determine the northward penetration of the Southern Ocean intermediate water mass. (Core coverage of Holocene samples also precludes observing the prominent geochemical signature of modern Antarctic Intermediate Water/upper Circumpolar Deep Water using core top samples (see supplemental Figure S1).

5.3. Oxygen Isotope Gradients and Glacial Water Masses

[27] The horizontal gradients in benthic foraminiferal $\delta^{18}O$ provide support for the distribution and source regions of the three components we identify (Figure 3). In today's ocean the only depths where the North and South Atlantic have the same equilibrium $\delta^{18}O_{calcite}$ values are the depths where NADW penetrates far into the South Atlantic. During the glacial period, benthic foraminiferal $\delta^{18}O$ values from North and South Atlantic locations converge only at 1500 m; above and below this water depth, glacial South Atlantic benthic foraminifera are consistently higher in $\delta^{18}O$ than glacial North Atlantic benthic foraminiferal $\delta^{18}O$. This pattern is consistent with our inference from $\delta^{13}C$ that this is the depth level where the northern source, high $\delta^{18}O$ water mass penetrated farthest into the South Atlantic.

[28] Below 2000 m, glacial benthic foraminifera in the South Atlantic are $\sim 0.25\%$ higher in $\delta^{18}O$ than in North Atlantic because of a north-south gradient in hydrographic properties caused by water mass differences. Today South Atlantic and North Atlantic benthic foraminifera have the same $\delta^{18}O$ because NADW dominates both ocean basins. A greater proportion of Southern Ocean deep water during the glacial periods set up differences in hydrographic properties between the basins. The difference in glacial benthic foraminiferal $\delta^{18}O$ between the North and South Atlantic below 2000 m is about the same as the measured difference in sea water $\delta^{18}O$ ($\delta^{18}O_{sw}$) observed by *Adkins et al.* [2002] from profiles of pore water $\delta^{18}O$. For the samples below 2000 m, the differences in mean calcitic $\delta^{18}O$ are significant at the 95% confidence level. Higher benthic foraminiferal $\delta^{18}O$ values would imply the presence of more Southern Ocean deep water. Thus the $\delta^{18}O$ gradients tend to support a southern origin for the deepest water mass, which was already suggested by *Marchitto et al.* [2002] based on Zn/Ca measurements in the North Atlantic, and a higher proportion of this water mass in the South Atlantic than in the North Atlantic. The $\delta^{18}O$ gradients also suggest a southern origin for the intermediate water mass centered at 1000 m, supporting the conclusion of *Oppo and Horowitz* [2000]. The gradients in benthic foraminiferal $\delta^{18}O$ are small compared to the possible errors caused by bioturbation, disequilibrium fractionation, and laboratory intercalibration, so a large number of measurements will be needed to confirm the observation. Taken together with the other trace metal and $\delta^{13}C$ gradients, though, the $\delta^{18}O$ values tend to support the presence of three water masses with different hydrographic properties and their northern and southern sources.

6. Conclusions

[29] 1. The glacial distribution of benthic foraminiferal $\delta^{13}C$ from the western South Atlantic Ocean requires the presence of three water masses below the subtropical gyre. At about 1000 m there was a southern source intermediate water mass. On the basis of $\delta^{13}C$ alone, there is little evidence for northward penetration of this water mass into the North Atlantic. A water mass centered at 1500 m represented the southward penetration of the North Atlantic water mass which has been called Glacial North Atlantic Intermediate Water. Below 2000 m, the strong bathymetric gradient in $\delta^{13}C$ marks the presence of the mixing zone between GNAIW and a deep, southern source water mass. This southern ocean water mass penetrated far into the deep North Atlantic with its effects evident as shallow as 2000 m as far north as 60°N. It was also probably the source for the very low $\delta^{13}C$ seen in many eastern basin North Atlantic cores during the glacial period.

[30] 2. The end-member compositions of the water masses were very different and the mixing among the water masses set up very strong meridional and bathymetric gradients in the western Atlantic. The northern source water mass had an end-member $\delta^{13}C$ composition of 1.5‰. The deep Southern Ocean water mass had an end-member $\delta^{13}C$ composition of less than $-0.2‰$ and perhaps as low as $-0.9‰$. The $\delta^{13}C$ bathymetric gradients in both the North

and South Atlantic each point toward the very low benthic foraminiferal $\delta^{13}C$ values identified by *Ninnemann and Charles* [2002] in the South Atlantic sector of the Southern Ocean. At intermediate water depths (1000 m), a southern source water mass occurred in the South Atlantic and had an end-member $\delta^{13}C$ composition of about 0.3–0.5‰, very much like $\delta^{13}C$ values seen at similar water depths in the glacial Southern Ocean [*Ninnemann and Charles*, 2002]. This intermediate water mass was perhaps similar to modern Antarctic Intermediate Water, but its $\delta^{13}C:Cd_w$ values imply that it was formed without the strong air-sea enrichment in ^{13}C occurring today in AAIW [*Oppo and Horowitz*, 2000].

[31]   3. The benthic foraminiferal $\delta^{18}O$ gradients in the glacial Atlantic show that at nearly every depth the South Atlantic benthic foraminifera were higher in $\delta^{18}O$ than North Atlantic benthic foraminifera. The one exception to this observation was at 1500 m, the depth of northern source GNAIW, where the $\delta^{18}O$ values in the North and South Atlantic were indistinguishable. The glacial $\delta^{18}O$ data

provide additional support for the northern origin of the high-$\delta^{13}C$ water mass found at 1500 m in the South Atlantic.

[32]   4. The presence of large, sustained bathymetric gradients in deep water properties indicates that horizontal advection remained strong relative to vertical mixing throughout much of the glacial period, and that circulation in the deep ocean remained vigorous for much of that period.

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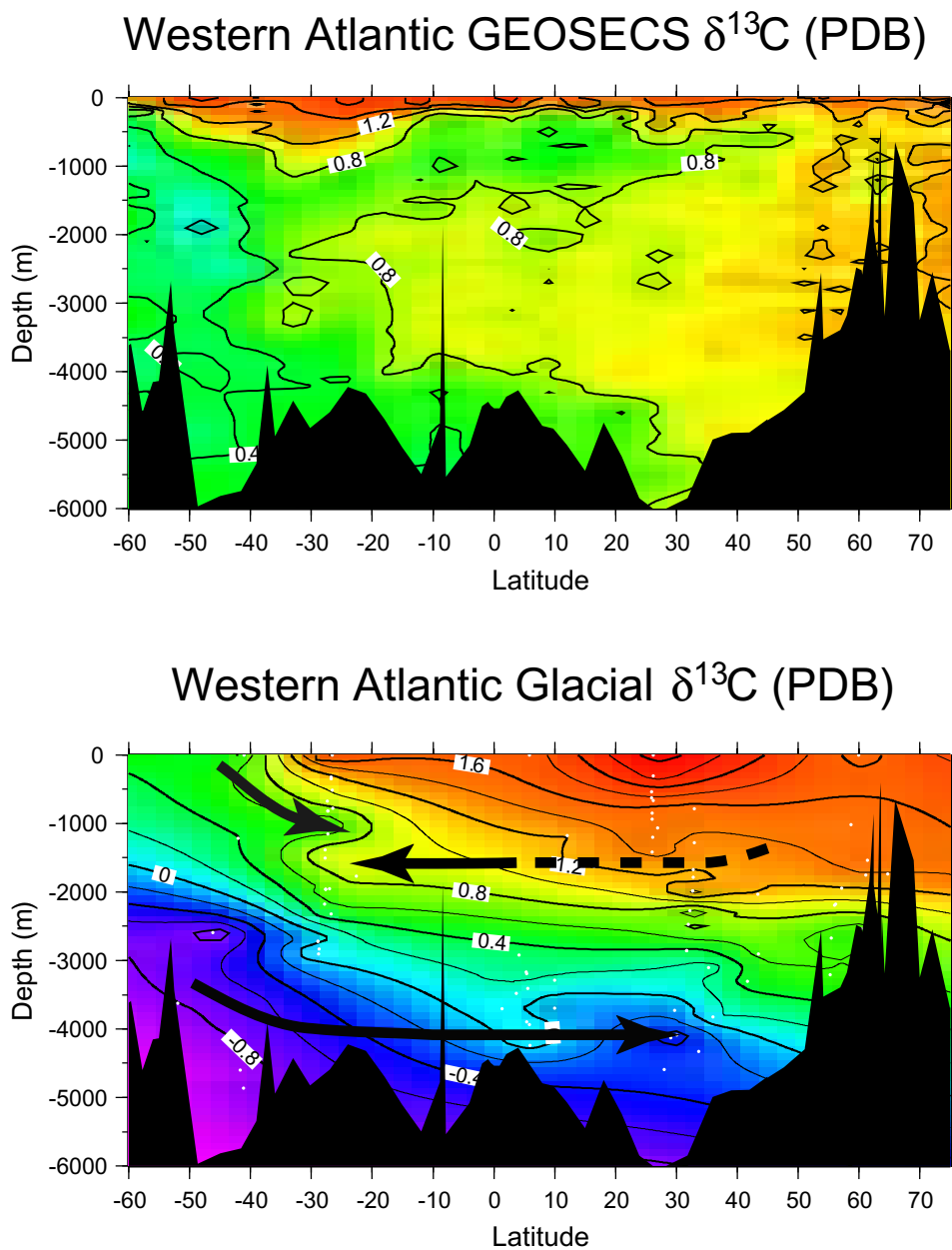
Western Atlantic GEOSECS δ¹³C (PDB)

Western Atlantic Glacial δ¹³C (PDB)

Figure 4. The distribution of $\delta^{13}C$ of ΣCO_2 in the modern western Atlantic [*Kroopnick*, 1985] and a revised and updated glacial transect of $\delta^{13}C$ of ΣCO_2 for the western Atlantic Ocean basins. A relatively simple three-component model is proposed to explain the water mass distribution and gradients. The patterns in the South Atlantic imply that the northern source water at 1500 m penetrated as far as 30°S latitude. The penetration of the deep Southern Ocean water mass can be observed as far as 60°N. The shallow, southern source water mass did not penetrate to 25°N, but there are too few data at intermediate water depths between about 25°S and 25°N in the western Atlantic to constrain its northward extent.