Carbon isotope evidence for a northern source of deep water in the glacial western North Atlantic

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The prevailing view of western Atlantic hydrography during the Last Glacial Maximum (LGM) calls for transport and intermixing of deep southern and intermediate northern end members. However, $\delta^{13}C$ and $\Delta^{14}C$ results on foraminifera from a sediment core at 5.0 km in the northern subtropics show that there may have also been a northern source of relatively young, very dense, nutrient-depleted water during the LGM (18 ky to 21 ky ago). These results, when integrated with data from other western North Atlantic locations, indicate that the ocean was poorly ventilated at 4.2 km, with better ventilation above and below that depth. If this is a signal of water mass source and not nutrient storage, it would indicate that a previously unrecognized deep water end member originated along the western margin of the Labrador Sea, analogous to dense water formation today around Antarctica and in the Okhotsk Sea.

ocean ventilation | western North Atlantic | Last Glacial Maximum | carbon isotopes | oxygen isotopes

Over the past 30 y, paleoceanographers have learned that during the Last Glacial Maximum (LGM), North Atlantic Deep Water (NADW) shoaled and was replaced by Antarctic Bottom Water (AABW) that was transported from the south (1, 2). This reorganization affected climate through distribution of heat, salt, and CO_2. Carbon isotope results from a new sediment core at 5,010 m depth near Corner Rise (CR) Seamounts in the Sargasso Sea (Fig. 1) are the deepest paleo-data from the western North Atlantic, and they define a new mixing line between an LGM southern source of bottom water at 4.2 km and a young nutrient depleted northern source at 5.0 km.

Corner Rise Results

On R/V *Knorr* cruise 197/10, we surveyed the northern part of the CR region and cored the flank of an abyssal hill where 3.5-kHz sonar data show at least 50 m of sediment drape (Fig. 1*D*). Sediment collected from 5 km on CR by giant gravity core (GGC) 17 is very similar to the drift deposit at 4.4 km to 4.6 km on nearby Bermuda Rise (BR), but with more shells of the benthic foraminifer *Cibicidoides* (Fig. S1). Together with ice-rafted lithic particles, this genus reached peak abundance during the Heinrich Stadial 1 (HS1) interval on CR (Fig. 2*B*). Chronology of 17GGC is based on 11 accelerator mass spectrometer (AMS) ^{14}C dates on the planktonic foraminifer *Globorotalia inflata* (Dataset S2), and linear interpolation assuming zero age at the core top. Ages are calibrated years before present, with only the standard 400-y reservoir correction [CALIB calibration program 6.1 (3)]. In general, sediment accumulated at 5 $cm \cdot ky^{-1}$ to 10 $cm \cdot ky^{-1}$, with higher sedimentation rates during a brief interval at the beginning of the Younger Dryas (YD; 40 $cm \cdot ky^{-1}$) and during the 3,000 y preceding the LGM (23 $cm \cdot ky^{-1}$) (Fig. 2*C*). The high sedimentation rate intervals may simply coincide with higher fluxes of glacial sediment to the deep ocean before events of cold climate, but we cannot exclude possible changes to the deep, southern recirculating gyre associated with the Gulf Stream (4). Absence of a sedimentation rate peak associated with the extreme cooling of HS1 may reflect remoteness of the site from the sources of Heinrich icebergs, but it is also consistent with minimal production of northern-source deep waters (2) and reduced sediment transport at that time.

The oxygen isotope history of 17GGC exhibits variability that is typical of the past 25 ky (Fig. 2*A*). The $\delta^{18}O$ of *Cibicidoides* has a glacial–interglacial range of ∼2‰, about double the estimated ice volume effect (5), indicating local temperature and $\delta^{18}O$ of water (or salinity) influences. *Cibicidoides* $\delta^{18}O$ increased slightly into the LGM (∼18–21 ka), with mean LGM values of 4.34 ± 0.06‰ ($n = 9$). The $\delta^{18}O$ decrease began between the sample dated to 17.0 ka and the next underlying sample interpolated to be 17.3 ka, and continued to the Holocene in steps centered on about 12 and 15 ka. These are the familiar Terminations 1A and 1B (6). The $\delta^{13}C$ of *Cibicidoides* was close to zero during the LGM (0.06 ± 0.10‰), but, during HS1, it decreased by about 0.5‰ and stayed low until ∼13.5 ka, well into the Allerod. That half-permil decrease is comparable to the difference in $\delta^{13}C$ of ΣCO_2 between AABW and NADW in the modern ocean (7). Following the minimum in *Cibicidoides* $\delta^{13}C$, values increased late in the Bolling/Allerod epoch, decreased into the YD, and increased again in the Holocene. AMS ^{14}C dates on *Cibicidoides* at 15.0 and 20.4 ka are, respectively, 1,300 and 1,200 ^{14}C years older than the *G. inflata* in the same samples.

Previous Work

Recently, as new core sites with higher-resolution sampling and more precise dating have become available, studies have identified temporal, spatial, and depth variability in stable isotope ratios of *Cibicidoides* that result from differences in bottom water properties during the LGM and deglaciation (8–11). These studies demonstrate it is possible to distinguish temperature and salinity effects on $\delta^{18}O$ to show evolving bottom water temperature and salinity at different times and places. For example, it was reported that $\delta^{18}O$ may have decreased earlier in the North Atlantic (17 ka on the Iberian Margin) than in the southwest Atlantic (15 ka) for sites at

Significance

Understanding glacial ocean circulation is tied to understanding heat transport in the North Atlantic, growth and maintenance of ice sheets, and atmospheric CO_2 content. The proxy data are sparse, but, for decades, it has been thought that the North Atlantic did not produce deep water during the Last Glacial Maximum, unlike today. New C isotope results from a core at 5 km in the western North Atlantic indicate a young, glacial deep water may have been formed in the surface Labrador Sea by freezing and brine rejection. These data call for a revised circulation scheme where southern source water centered at 4.2 km would have been sandwiched between glacial North Atlantic intermediate water and the new dense bottom water.

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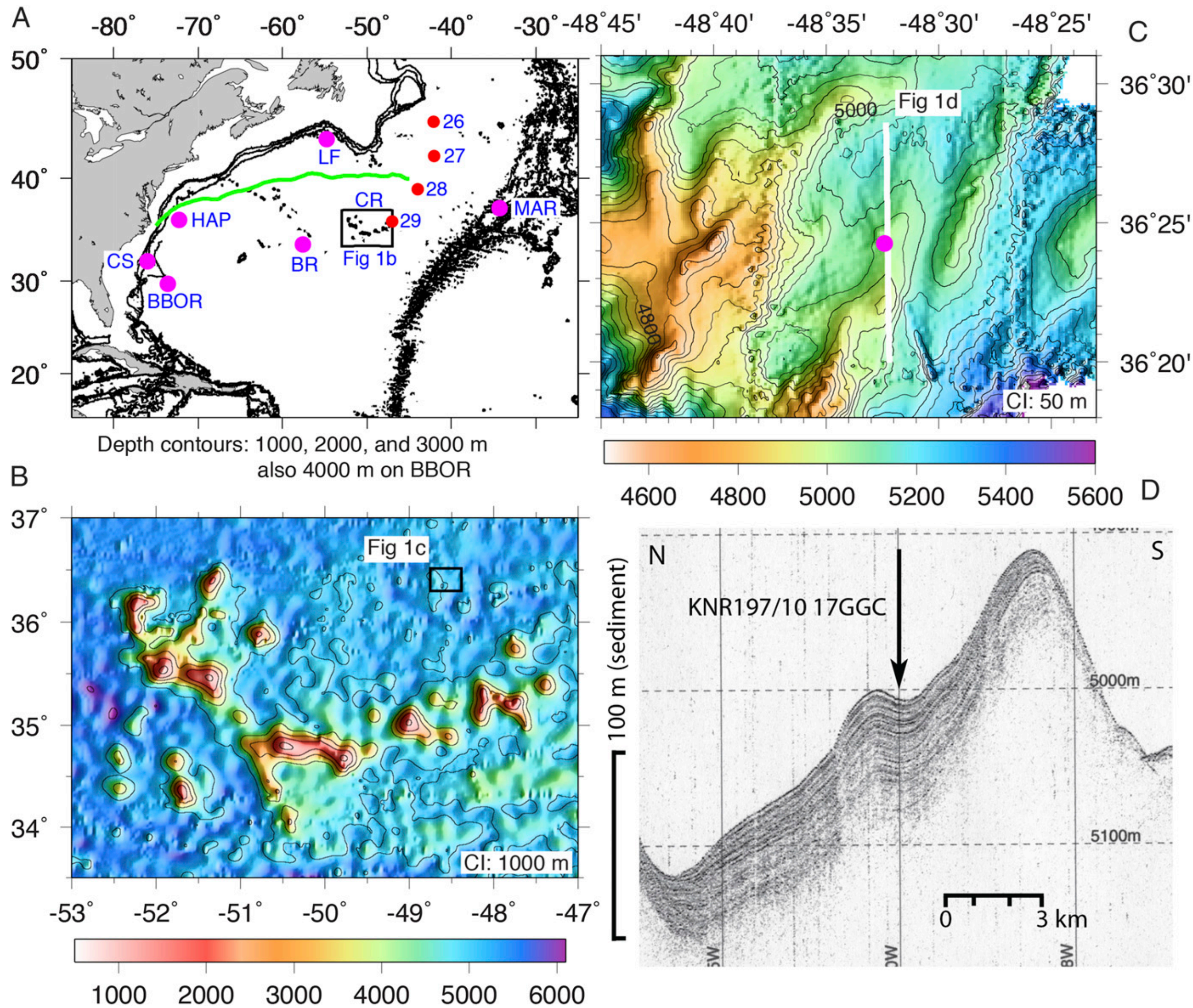

Fig. 1. Western North Atlantic locations discussed in this paper (Table 1), and details of the CR core location in the western North Atlantic. (*A*) General location of the CR seamounts in small box. For other core locations: BBOR and CS, core locations along Blake and Bahama Outer Ridges and Carolina Slope (32); BR, northeast corner of BR; HAP, Hatteras Abyssal Plain; LF, Laurentian Fan; MAR, Mid Atlantic Ridge. Red dots mark GEOSECS stations. Green line shows the historical position of the north wall of the Gulf Stream. (*B*) Bathymetry of the CR region, with a box showing the expanded view of core 17GGC location on (*C*) an abyssal hill. (*D*) A 3.5-kHz profile across the location of gravity core KNR197/10 17GGC reveals about 50 m of sediment draped on the north side of the hill, suggesting deposition from a southward-flowing benthic nepheloid layer.

>3 km, and the decrease was larger (0.6‰) than can be accounted for by the secular change due to ice sheet melting (9). The decrease in $\delta^{18}O$ at 17 ka is confirmed at CR, although the lead over South Atlantic $\delta^{18}O$ is not significant because of uncertainty in the chronology there (9). However, the $\delta^{18}O$ and Mg/Ca evidence for early freshening at 3.15 km along the Iberian Margin (12) suggests that some fraction of bottom waters at >3 km must have been generated by glacial melting and brine rejection during sea ice formation at a freshened high northern latitude surface, not the Southern Ocean (9). Before the present study, the early deglacial decrease in *Cibicidoides* $\delta^{18}O$ had not been noted in the northwestern (NW) Atlantic because that genus is not consistently present in cores from its western margin.

Synthesis of Western North Atlantic C Isotopes

Although the $\delta^{18}O$ on CR is typical of deep North Atlantic sites during the LGM, $\delta^{13}C$ is higher than expected. This difference is seen by comparing the CR data to *Cibicidoides* data from other sites in the NW Atlantic in a depth profile for the LGM (Fig. 3 and Fig. S3). However, this compilation assumes little difference in properties between eastern and western locations in the NW Atlantic, which we can only support for paired analyses at about 2 and 3 km (Fig. S4). We interpret C isotopes in benthic foraminifera as quasi-conservative tracers for paleocirculation (5), although the data could reflect, in part, remineralization of biogenic C (13). The most recent analysis by Gebbie et al. (14) indicates that remineralization is less significant than previously thought, in essential agreement with Marchal and Curry (15), who estimated that organic matter remineralization makes little contribution today to the $\delta^{13}C$ of ΣCO_2 in the deep (>1 km) Atlantic.

From Carolina Slope sites (1 km to 2 km water depth), $\delta^{13}C$ steadily decreased down Blake Ridge to 4.2 km (Fig. 3*A*). Below that depth, the trend reversed, with higher $\delta^{13}C$ at 4.5 km on BR, 4.7 km on Bahama Outer Ridge, and 5.0 km on CR. The large

Table 1. Core locations in the western North Atlantic

Core name	Location abbreviation	Depth, m	Latitude	Longitude
KNR178 GGC-2	HAP	3,927	36°07.21′N	72°17.52′W
KNR197/10 CDH-10	MAR	2,955	37°11.998′N	34°15.903′W
KNR197/10 CDH-42	LF	3,870	43°27.871′N	54°45.344′W
KNR197/10 GGC17	CR	5,010	36°24.3′N	48°32.39′W
HU89003 PC8	BR	4,425	33°41.2′N	57°36.8′W
KNR140 JPC12	BBOR	4,260	29°04.446′N	72°53.933′W

uncertainty in δ^{13}C from BR is most likely related to the high accumulation rate of organic matter as revealed by preserved diatoms and bivalves (16) and the possible effects of organic matter oxidation and bioturbation on δ^{13}C. The slight decreasing trend in δ^{18}O below 3 km may not be significant, although it would be consistent with the Iberian Margin evidence for freshening (12). However, the δ^{13}C reversal below 4.2 km is large and suggests the largest fraction of southern source (low δ^{13}C) water was centered on 4.2 km, with increased mixing of a relatively high δ^{13}C source below that depth.

In addition to δ^{13}C, other geochemical proxies for deep ventilation and circulation during the LGM point to a blend of southern and northern source waters in the NW Atlantic. For example, Pa/Th results (2) and Nd results (17) from BR consistently show that the glacial mixture of bottom water must have contained a northern component. This finding is at variance with the prevailing view that there was little or no northern deep water present in the glacial North Atlantic (18, 19), but a recent synthesis of Nd isotopes in the western Atlantic has also been interpreted as evidence for a glacial source of NADW (20). Furthermore, Böhm et al. (21) found that some interstadials and the last interglacial on BR had lower εNd than in the modern ocean. This very low εNd could indicate there were both warm and cold climate processes that formed deep water in the North Atlantic that are inactive today.

Ventilation estimates based on the difference in conventional ^{14}C age between pairs of planktonic and benthic foraminifera (or bivalves) ($^{14}C_{B\text{-}P}$) during the LGM are consistent with the δ^{13}C data (Fig. 3*B*). When the new CR data are added to previously published results from the NW Atlantic (16), and new results from the Laurentian Fan, Hatteras Abyssal Plain, and Blake Ridge (Figs. S5–S7, respectively), a similar pattern emerges that is interpreted here as decreasing ventilation down to 4.2 km, and increasing ventilation below that. McManus et al. (2) suggested that northern source export during the LGM was at intermediate depths over BR (glacial North Atlantic intermediate water), a result that was supported by later data (22). Our new CR results point to enhanced ventilation at least as deep as 5,010 m. Furthermore, lowest δ^{13}C and highest $^{14}C_{B\text{-}P}$ at 4.2 km is consistent with grain size results in three depth transects of Blake Ridge cores that indicate the fast-flowing deep western boundary current of modern circulation (3 km to 4 km) deepened to >4 km during the LGM (23).

Unlike shallower locations where northern ventilation is thought to have resumed at about 14–15 ka (12), ventilation at 5 km on CR as represented by δ^{13}C in Fig. 2 remained weak (between that of LGM and HS1) until ∼13.5 ka. However, results are ambiguous on BR. Whereas Pa/Th data indicate ventilation resumed 14–15 ka (2), δ^{13}C indicates a 1-ky delay (Fig. S3). Either way, the available data suggest that postglacial resumption of ventilation in the North Atlantic evolved from the top down. That is, the tongue of glacial North Atlantic intermediate water thickened downward as suggested earlier (24), and more recently at sites >2.5 km off Brazil (10). Eventually, ventilation by convection in the Norwegian–Greenland Seas would have resumed, probably near the beginning of the Holocene.

Ocean and Climate Implications

What ventilation process could account for relatively young and nutrient-depleted water in the LGM NW Atlantic at 5 km? In the modern ocean, the densest waters are produced in the Nordic Seas by heat loss and mixing with cold Arctic waters, and around Antarctica by upwelling, heat loss, and brine rejection by freezing in polynyas and under ice shelves. During the LGM, much of the ocean heat transport to the Nordic Seas is thought

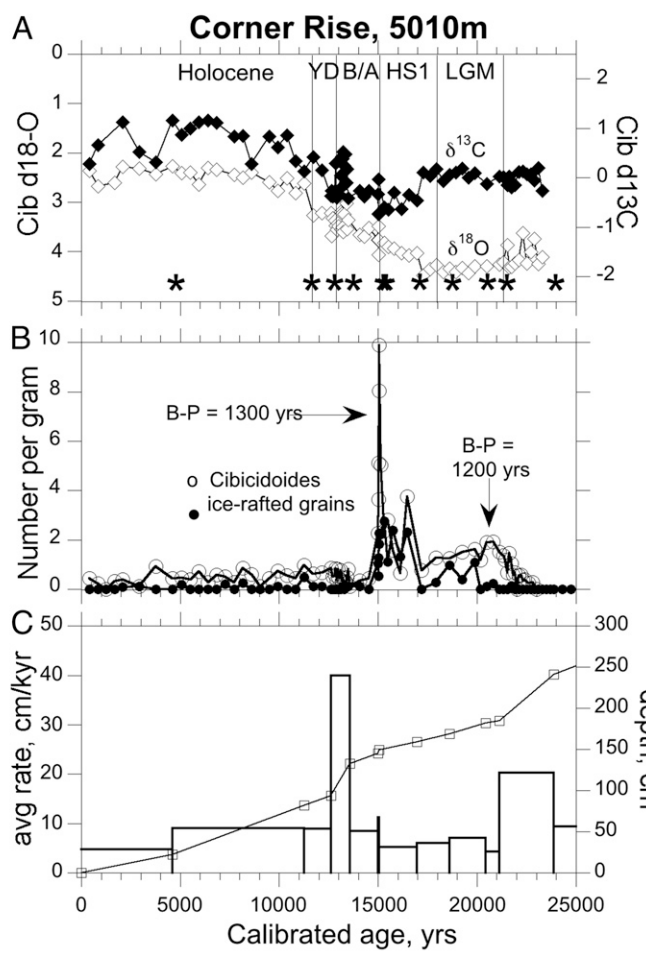

Fig. 2. Analytical results from core KNR197/10 17GGC near CR. (*A*) Important features in the stable isotope data include δ^{13}C of near 0‰ during the LGM (solid diamonds), the delayed increase of δ^{13}C (at ∼13.5 ka) relative to the ∼14.5 ka onset of Bolling/Allerod (B/A) warming, and the postglacial decrease in δ^{18}O (open diamonds) that began at ∼17 ka. Asterisks mark radiocarbon age control. (*B*) Abundance of *Cibicidoides* (open circles) and IRD grains (solid circles) (both >150 μm). The age difference between benthic and planktonic foraminifer ($^{14}C_{B\text{-}P}$) is only 1,300 y at 15 ka and 1,200 y during the LGM. (*C*) Maximum rates of sedimentation occurred at the beginning of both the LGM and the YD. The sedimentation rate at >24 ka is constrained by an AMS ^{14}C date at 28 ka. Data are compiled in Dataset S1 and are also shown vs. depth in Fig. S2.

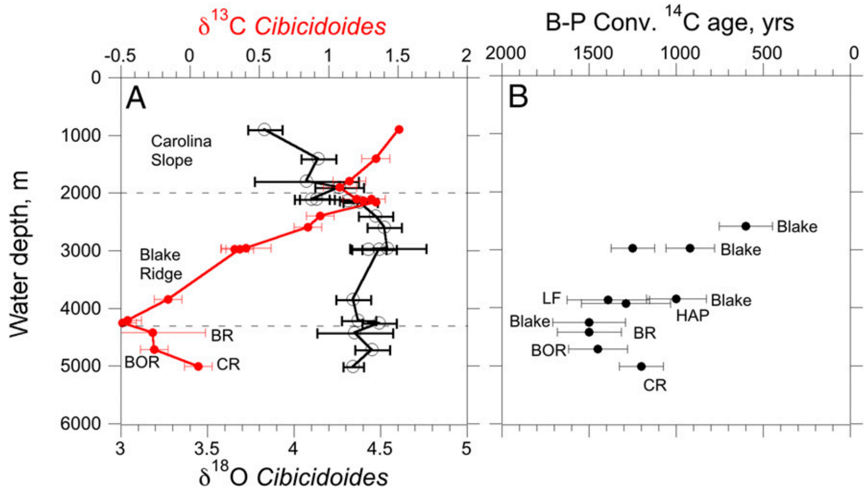

Fig. 3. Compilation of LGM ventilation data from subtropical western North Atlantic core sites (16, 34) with the new data presented here (Dataset S3). (*A*) Stable isotope profiles of *Cibicidoides* $\delta^{13}C$ (filled red circles) and $\delta^{18}O$ (open black circles) on Carolina Slope, Bahama Outer Ridge (BOR), Blake Ridge, and BR. *Cibicidoides* are very rare during the LGM along the western margin, so, in most cases, the $\delta^{13}C$ are single measurements where a few individuals were found. Otherwise, error bars are a nominal $\pm 1\sigma$. Multiple analyses were possible on BR, but the large scatter in *Cibicidoides* $\delta^{13}C$ may represent greater influence of bioturbation and/or the presence of low $\delta^{13}C$ in fluff layers where diatoms are preserved. Because the samples for stable isotope data were not dated, the curves represent average conditions for the LGM (18–21 ka). (*B*) Profile of the difference between benthic and planktonic (B-P) conventional ^{14}C ages from NW Atlantic sediment cores during the LGM. Note similar trends in the two C isotope data sets. It is argued here that the reversal in the trends of $\delta^{13}C$ and $^{14}C_{B\text{-}P}$ below 4.2 km is evidence for a young source of North Atlantic bottom water during the LGM. Figs. S4–S7 put the new $^{14}C_{B\text{-}P}$ data in a stratigraphic framework.

to have been reduced, and new paleo-tracer data show deep Norwegian Sea waters were very old and nutrient rich (25), so we rule out the modern process in the Nordic Seas. Although oxygen isotope data indicate that brine rejection occurred in Nordic Seas (26), there is no evidence that enough dense water accumulated to spill over the sill at Denmark Strait (~600 m).

Radiocarbon ventilation studies in the South Atlantic (27) and southwest Pacific (28) found a deep-water bulge in low $\Delta^{14}C$ that is similar to what we observe in the western North Atlantic. The authors from both studies propose that deep waters during the LGM originated in the south, with relatively young northward flow underlying an aging southerly return flow. However, it should be noted that the bulge in the South Atlantic is defined by data at only three locations, and two have uncertain and different reservoir ages (29). Whereas a southern water mass origin is compatible with our results, the NW Atlantic data are far from the Southern Ocean data, with few between and none of >4 km depth. Instead, we seek a more local explanation, especially in light of the NW Atlantic Pa/Th, Nd, and the early decrease in $\delta^{18}O$ on CR and the Iberian margin (12).

North Atlantic instrumental data suggest an alternative to an estuarine-type circulation driven from the south. The decadal observations that began in 1972 at Geochemical Ocean Sections Study (GEOSECS) Station 27 in Newfoundland Basin (Fig. 1) show that, using dissolved silicate as a tracer for AABW, bottom water between about 4 and 5 km had a variable AABW component (Fig. 4*A*). In 1972, there was a bulge of silicate at about 4.5 km that was undercut by low-silicate water that must have originated at Denmark Strait, according to the water properties mapped by Worthington and Wright (30). Not only is a northern source indicated by low silicate, but it is also supported by high $\Delta^{14}C$ and tritium, each of which undercuts old water between about 4.3 and

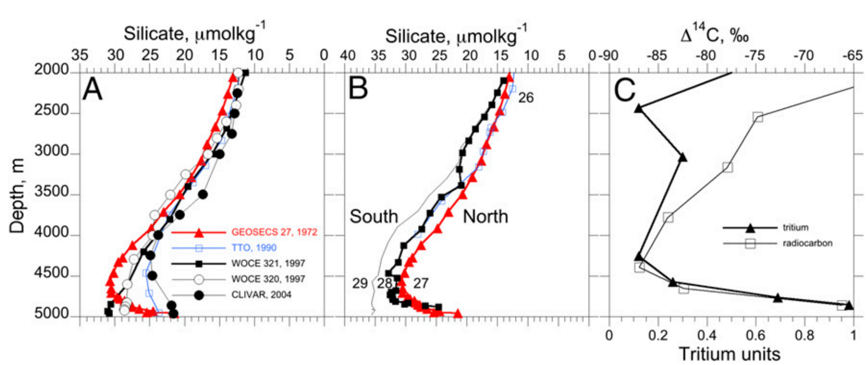

Fig. 4. Repeat geochemical observations in Newfoundland Basin (Fig. 1) since 1972. (*A*) Four decades of repeat dissolved silicate measurements at the location of GEOSECS Station 27 in the Newfoundland Basin. (*B*) Silicate measurements at four 1972 GEOSECS stations that form a roughly north to south transect. In both *A* and *B*, silicate is used as a tracer for water of AABW origin. The GEOSECS Station 27 observations stand out in *A* because of the highest silicate concentrations at about 4,700 m, and the lowest at 5,000 m. The Si profile at Station 27 is similar to that of Station 28 to the south (Fig. 1), but, at southernmost Station 29, there is no evidence of the low Si water at the bottom. (*C*) The radionuclide tracers ^{14}C and tritium at Station 27 show that waters at >4.7 km were younger than waters at ~4.5 km in 1972. The data indicate that strong Denmark Strait Overflow Water (low Si, high $\Delta^{14}C$ and tritium) must have undercut the older southern component in 1972, causing a steep reversal in gradient unlike any later time. Data are from the Global Ocean Data Analysis Project (GLODAP) (cdiac3.ornl.gov/waves/discrete/) and are listed in Dataset S4. CLIVAR, Climate Variability project; TTO, Transient Tracers in the Ocean project; WOCE, World Ocean Circulation Experiment.

4.5 km depth (Fig. 4*C*). This pattern of northern source water undercutting the southern source in Newfoundland Basin in 1972 was recorded by GEOSECS as far south as Station 28, but not as far south as Station 29 (Figs. 1 and 4*B*). Some of the pronounced silicate bulge in 1972 may be related to the negative phase of the North Atlantic Oscillation, which is hypothesized to cause enhanced convection in the Nordic Seas (31). The Newfoundland Basin ventilation changes are not exactly analogous to the LGM situation in the NW Atlantic because of the presumed absence of LGM convection in the Nordic Seas, but they show that the simplest way to produce a bulge in old water in the NW Atlantic is to introduce a local source of relatively young, dense water.

Accepting the evidence for old and warm bottom waters in the Nordic Seas during the LGM (25), we propose the Labrador Sea could have been a site of deep LGM ventilation by brine rejection around its margins. There is no direct evidence for this proposition, but it would have been facilitated by katabatic winds blowing down a Laurentide Ice Sheet that was grounded on the broad Labrador continental shelf. The LGM glacial till along the Labrador shelf is thought to have been deposited ~20 ka by a retreating ice margin that may have formed an ice shelf (32), and a basin such as the Labrador marginal trough could have accumulated brine. Offshore winds also could have promoted ice growth, dispersal, and brine formation similar to the several latent heat polynyas around the Okhotsk Sea that produce, today, the densest water in the North Pacific Ocean (33).

In conclusion, we have shown that there may have been a third component of deep North Atlantic circulation during the LGM, thereby adding a new dimension to our view of water mass distribution in the glacial ocean. The new C isotope results support the same conclusion based on Nd isotopes (20). If this new source of bottom water resulted from brine rejection and not heat loss to the atmosphere, there may not have been the same climate impact as modern NADW production. The new deep northern component is indicated by the reversal in C isotope trends to higher $\delta^{13}C$ and lower $^{14}C_{B\text{-}P}$ below 4.2 km in the western North Atlantic and more vigorous flow (23). Thus, in this view, water of southern source was sandwiched between glacial North Atlantic intermediate water and the new dense bottom water. The spatial extent of the deepest northern component can best be explored by new coring even deeper than 5 km near CR and up the west flank of the Mid-Atlantic Ridge.

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