Last-Glacial-Maximum North Atlantic Deep Water: On, off or Somewhere In-Between? [and Discussion]

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Last-Glacial-Maximum North Atlantic Deep Water: on, off or somewhere in-between?

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SUMMARY

Various papers have been published during the past decade concerning Last Glacial Maximum (LGM) North Atlantic Deep Water (NADW) flow. Using somewhat different methods, they have produced somewhat contradictory results. This review considers both apparent and real conflicts concerning the data and their interpretation, and attempts to resolve them. Despite the earlier (contradictory) interpretations, currently there is a widespread belief that nutrient concentrations in deep cores from the North Atlantic increased during glacial times and that concentrations in the upper-deep and intermediate waters decreased at least slightly. It is also clear that further north in the basin (particularly at upper-deep and intermediate depths), nutrient concentrations were as low or perhaps even lower than those seen today. Data from the Caribbean Sea, ventilated by intermediate waters through an approximately 1800 m sill, indicate that lower nutrient levels were also found at intermediate depths in the North and Tropical Atlantic; this data is supported by continental margin data. The recontoured δ^{13}C data of Duplessy *et al.* (*Paleoceanography* **3**, 343–360 (1988)) remain a valid expression of the broad-scale LGM Atlantic nutrient distribution. Data from the South Atlantic has been the most contradictory to date, but recent δ^{13}C evidence from a low-productivity South Atlantic site supports Cd data indicating a relative stability in the nutrient chemistry of waters that are presently influenced by low-nutrient NADW. Sedimentary ^{231}Pa/^{230}Th data appear to require the continued export of Atlantic-generated ^{231}Pa from the Atlantic into the Southern Ocean. Finally, radiocarbon evidence from paired planktonic/benthic foraminifera indicates that the ventilation time of the North Atlantic remained low and that the ventilation time of the entire ocean did not change much beyond the uncertainty of the ^{14}C data. Taken together, this evidence suggests that the NADW became 'Glacial North Atlantic Deep/Intermediate Water' (GNAIDW) during glacial times, with perhaps a greater flux through intermediate waters than currently combined with a lesser flux through deeper waters. Although one cannot say much with confidence about the total GNAIDW flux, the data are consistent with a persistent but perhaps somewhat diminished role for NADW in the global thermohaline circulation during glacial times. A review of recent evidence concerning the response of the deep North Atlantic during the Younger Dryas concludes that there is no inconsistency between the new evidence and the occurence of a Younger Dryas NADW event in the deep western North Atlantic.

1. INTRODUCTION

For some time palaeoceanographers have investigated late Quaternary North Atlantic circulation using palaeochemical tracers in benthic foraminifera. During this period, established isotopic tracers in benthic foraminifera have been refined and an extensive database published; newer methods such as cadmium, barium and the planktonic/benthic ^{14}C contrast have also had some influence on discussions. However, despite these studies there is surprisingly little agreement in literature concerning the behaviour of the North Atlantic limb of the global thermohaline circulation during the Last Glacial Maximum (LGM). Over the past few years relevent literature states variously that NADW remained steady, shut off entirely, or fell somewhere in-between these extremes. One can, therefore, conclude that the literature agrees with the statement that the LGM NADW flux was 0.5 ± 0.5 of its present flux.

To an outsider it may seem that the same range of possibilities existed before much work was done (although it seems that currently the belief that NADW was more intense during glacial times is not held). Despite this, some progress has been made; the evidence upon which the argument rests has made some significant evolutionary progress, and certain aspects of the LGM Atlantic are almost universally agreed upon. The aim of this discussion is: first, to review the literature on LGM NADW behaviour so that anyone can understand the shifting ground of evidence upon which this debate is based; and second, to put the case that although a broad range of viable scenarios are consistent with the evidence, the most plausible

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scenarios are that NADW flux either reduced in magnitude – but did not shut down – or that NADW maintained the present flux but shifted to a shallower depth range. Here, the shorthand expression 'low nutrient content' will be used for water masses low in P and Cd and more positive in $\delta^{13}C$, and 'high nutrient content' for water masses high in P and Cd and more negative in $\delta^{13}C$.

2. DEEP WATER EARLY HISTORY: BENTHIC FORAMINIFERAL PALAEOECOLOGY

In the 1970s and early 1980s, attempts to understand the changes in deep ocean properties were based largely on micropalaeontologist's studies of ecological shifts in fossil benthic foraminifera populations. Various scenarios were proposed ranging from the proposition that the LGM deep North Atlantic was warmer than at present to the notion that the Antarctic Circumpolar current had turned on and off during late Quaternary times. With hindsight it is easy to see that these early studies were doomed by the complexity of the response of benthic foraminiferal populations to changes in environmental parameters. Unlike planktonic foraminifera, which are highly correlated to sea-surface temperature on a global basis, benthic foraminifera populations probably respond to a host of environmental parameters including quantity and variability of food supply, as well as matters related to the character of the bottom environment (bottom water motions and microtopography of the sediment surface) and even the chemical characteristics of the subsurface sediment. Although relatively simple correlations between bottom-water properties and benthic populations of benthic foraminifera are seen in restricted geographic regions, these correlations almost always break down on a global basis. Hence the use of benthic foraminiferal palaeoecology has proved difficult as a means of reconstructing past bottom-water characteristics.

One palaeoecological study deserves particular mention as it should be credited with starting off the modern debate on LGM NADW variation. Streeter & Shackleton (1979) noted a marked increase in the population abundance of *Uvigerina peregrina* during glacial oxygen isotope states 2–4 and 6 in core V29-179 (44° N, 24.5° W, 3331 m). Based on the modern day occurrence of higher relative populations of this species in lower-oxygen waters in the Atlantic ocean, Streeter & Shackleton proposed that glacial-stage oxygen contents at this site were much lower. They proposed that the cause of this decrease was 'that North Atlantic deep water production was much reduced or eliminated' leading to a filling of the deep North Atlantic with low-oxygen Antarctic/Pacific waters. Although now the link between *Uvigerina* species and bottom-water oxygen would be considered qualitatively adequate but quantitatively imprecise, and despite the fact that there may be some concern over the extent to which other factors such as the food supply and sedimentary carbon contents influence *Uvigerina* species abundance, there is widespread agreement among palaeoceanographers that chemical shifts somewhat akin to those proposed by Streeter & Shackleton did occur.

3. GEOCHEMICAL TRACERS IN BOTTOM WATERS: THE EARLY YEARS

During the 1980s, geochemical tracers in benthic foraminiferal shells – at that time, $\delta^{13}C$ and the cadmium–calcium ratio (Cd/Ca) – came to the fore. Early investigations, during the 1950s, of $\delta^{13}C$ in foraminifera had been discouraging because shells were not at thermodynamic equilibrium with the water in which they formed. Hence, despite the fact that a measurement of $\delta^{13}C$ is required for every measurement of $\delta^{18}O$, very little attention was paid to the concomitant $\delta^{13}C$ data. Shackleton's (1977) work changed all this; it became conceivable that despite the lack of equilibrium, it may be possible to derive palaeoenvironmental information from foraminifera by using empirical disequilibrium calibrations. With the increasing stable isotope capability of the palaeoceanographic community in the late 1970s, many studies of the response of benthic foraminifera to bottom water $\delta^{13}C$ were reported. These studies were perhaps best summarized in the paper by Duplessy *et al.* (1984) which concluded that although $\delta^{13}C$ in the benthic foraminifera *Uvigerina* species and *Cibicidoides* species were offset from one another (at that time, apparently by a constant amount), they both displayed systematic responses to bottom water conditions. Hence Shackleton, Imbrie & Hall (1983) felt justified in concluding that the absence of a carbon isotope difference between *Uvigerina* species in the Eastern Tropical Pacific core V19-30 (3°23′ S, 82°21′ W, 3071 m) and in the deep eastern Atlantic core M12392 (25°10′ N, 16°50′ W, 2573 m) during glacial intervals signified that the eastern basin of the North Atlantic 'was filled by a relatively cold water mass which was no richer in dissolved oxygen than deep Pacific water' (see figure 1). Mix & Fairbanks (1985) also presented a *Uvigerina* species $\delta^{13}C$ record from core V30-97 (41° N, 34° W, 3371 m) which, similarly, indicated no LGM Atlantic/Pacific gradient (when compared to V19-30) (see figure 2).

Almost simultaneously, it was proposed that the Cd content of benthic foraminifera shells was related to the

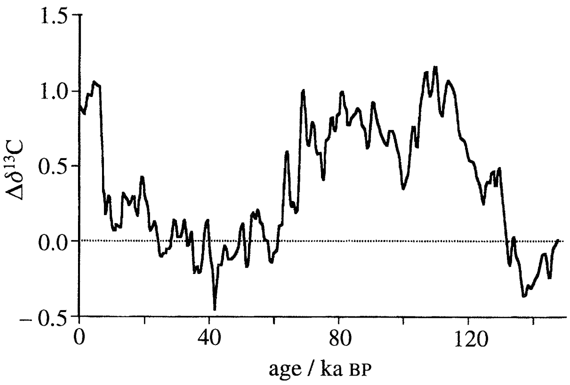

Figure 1. Atlantic (M12392) and Pacific (V19-30) *Uvigerina* species $\delta^{13}C$ difference curve of Shackleton *et al.* (1983).

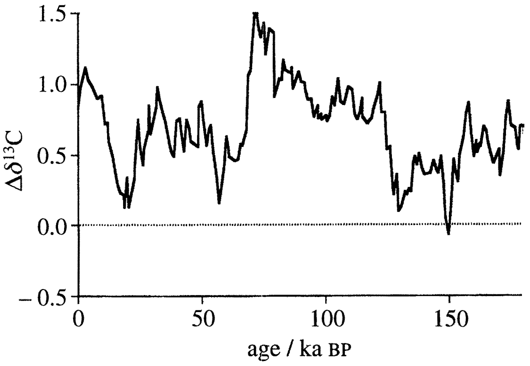

Figure 2. Atlantic (V30-97) and Pacific (V19-30) *Uvigerina* species $\delta^{13}C$ difference curve of Mix & Fairbanks (1985).

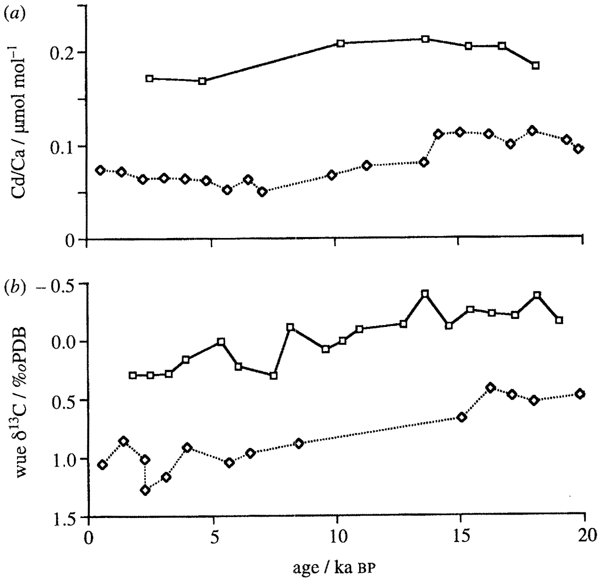

Figure 3. Atlantic/Pacific (*a*) Cd and (*b*) *C. wuellerstorfi* $\delta^{13}C$ taken from Boyle & Keigwin (1985, 1986): squares, Pacific; diamonds, Atlantic.

Cd content of bottom water (Hester & Boyle 1982). The oceanic distribution of Cd is very similar to that of phosphorus (see, for example, Boyle *et al.* 1976; Bruland 1978, 1980; Bruland & Franks 1983) and hence the potential exists to reconstruct past nutrient distributions from Cd in benthic foraminiferal shells. Boyle & Keigwin (1982) used Cd data from a North Atlantic sediment core (42.3 ° N, 31.7° W, 3209 m) and $\delta^{13}C$ data from *Cibicidoides* species (alongside the assumption that the oceanic Cd inventory had remained approximately constant) to argue that the nutrient concentrations of the deep North Atlantic had increased during glacial periods. However, this increase was never so large as to bring the Atlantic composition to that of the Pacific. Hence, they argued that 'the glacial NADW, while exhibiting a continuous flow with no evidence of cessation, is diminished relative to the flux of Antarctic water sources'. Later, the assumption that the oceanic Cd inventory did not change much was confirmed by data from the Pacific (Boyle & Keigwin 1985, 1986; Boyle 1988) (see figure 3).

So, almost as soon as they had been established, the data produced by geochemical tracers of bottom water properties were contradictory. There was conflict between those who believed that during the LGM, NADW had shut down and those who believed that it had continued to flow with a diminished flux. This particular conflict of evidence was resolved by the work of Zahn *et al.* (1987) who demonstrated that the organic carbon flux to the seafloor influenced the $\delta^{13}C$ of *Uvigerina* species, but at that time, apparently not *Cibicidoides* species. The very light glacial stage *Uvigerina* species $\delta^{13}C$ observed in the Atlantic cores M12392 (25°10′ N, 16°50′ W, 2573 m) accompanied by a high LGM organic carbon flux was not seen in *Cibicidoides* species $\delta^{13}C$ data from the same core (Shackleton 1977; Boyle & Keigwin 1985, 1986; Zahn *et al.* 1987), nor was it seen in the *Uvigerina* species data from cores with low LGM organic carbon accumulation rates (M13519: 5°40′ N, 19°51′ W, 2862 m) (figure 4). Hence the anomalously light *Uvigerina* species $\delta^{13}C$ in M12392 and V30-97 is attributed instead to an organic carbon flux artefact at those sites. Based upon *Cibicidoides* species data, the deep North Atlantic clearly had more positive glacial stage $\delta^{13}C$ values, consistent with the Cd evidence for a persistent Atlantic–Pacific Cd gradient. At this point, it seemed settled that there was a source of nutrient-depleted water to the north Atlantic, suggesting the persistent supply of at least some NADW to the deep ocean.

Curry & Lohmann (1983) noted that the deepest eastern Atlantic had lower $\delta^{13}C$ than waters at 3 km depth; they attributed this to a combination of more sluggish ventilation and more intense organic decomposition during glacial times. Later, Oppo & Fairbanks (1987) suggested that the lower $\delta^{13}C$ in the deep eastern basin might instead result from lower $\delta^{13}C$ in the western basin waters flowing in over the sill into the eastern basin.

At this time it was also discovered that upper waters ($z < 2000$ m) of the LGM North Atlantic were nutrient depleted in comparison to the deeper waters (Boyle & Keigwin 1986, 1987). This observation was based on Cd and $\delta^{13}C$ data from the Caribbean Sea, which is ventilated by Atlantic waters from roughly 1800 m depth. The first data which showed this characteristic belonged to Duplessy *et al.* (1984) whose carbon isotope data from the previous interglacial Caribbean were more positive than core top values; however, they did not discuss the significance of this data. Cofer-Shabica & Peterson (1986) had also presented evidence that Caribbean $\delta^{13}C$ was more positive during glacial times but they interpreted this data quite differently, suggesting that an LGM reduction in organic decomposition in the Caribbean was responsible for lower nutrient levels. Because there is hardly any observable effect of organic decomposition on P and N in the deep Caribbean today, however, a reduction of nutrients in the deep waters of this basin cannot be achieved by reducing organic decomposition rates. The only way to change the Caribbean $\delta^{13}C$ and Cd to the more nutrient-depleted values observed is for the source waters to have changed their characteristics.

The structural characteristics of the (mainly eastern Basin) glacial Atlantic became evident with data presented by Duplessy *et al.* (1988), although the recontouring of that data by Broecker (1989) is

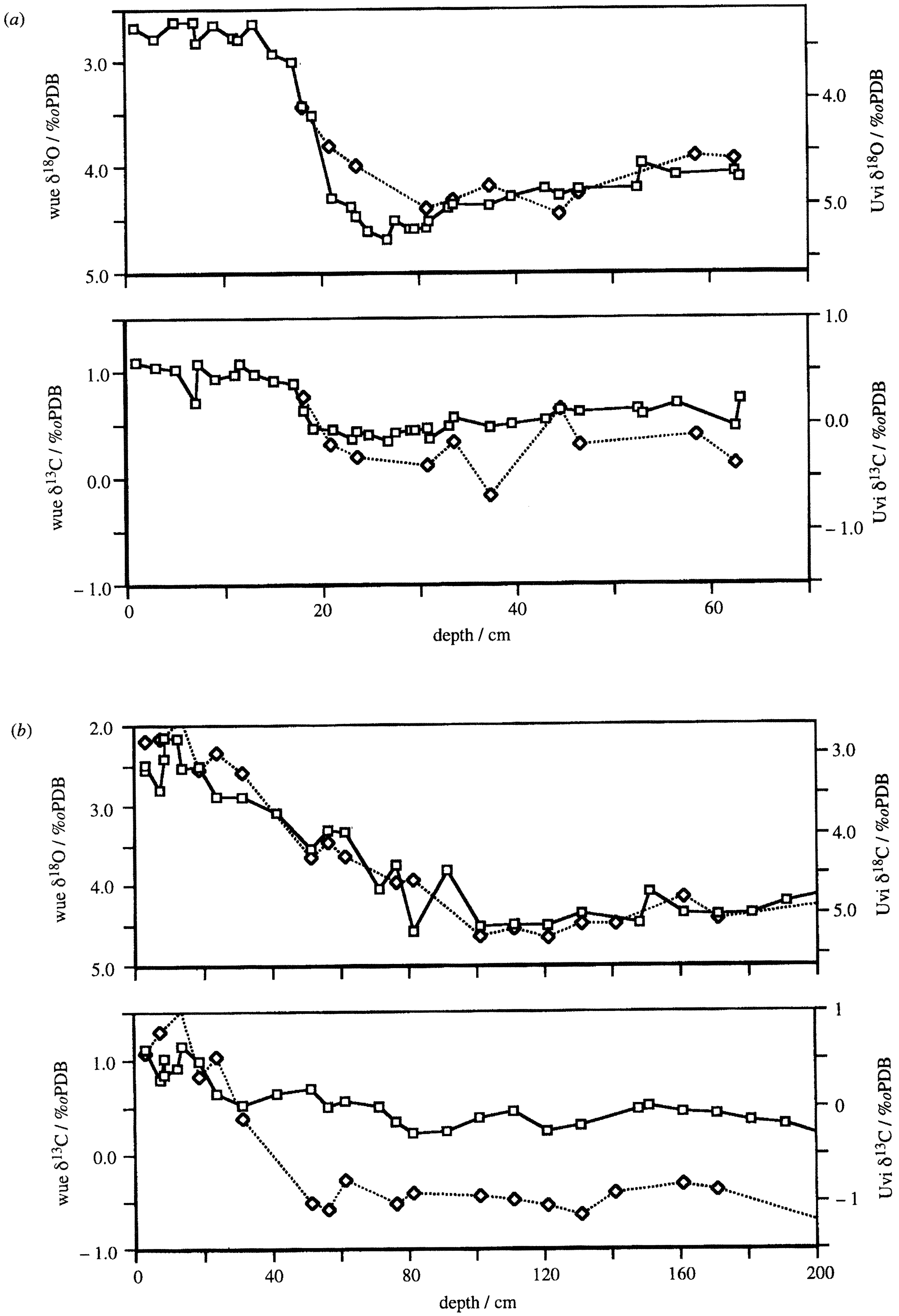

Figure 4. *Uvigerina* species (diamonds) and *C. wuellerstorfi* (squares) $\delta^{18}O$ and $\delta^{13}C$ data from cores with low (M13519) and high (M12392) levels of LGM carbon flux. (*a*) M13519, low glacial productivity; (*b*) M12392, high glacial productivity. Note offset 'double-Y' scales are set to have the Holocene $\delta^{13}C$ values overlap. Note also that *C. wuellerstorfi* is similar in both records but that *Uvigerina* species data in the high productivity core is offset in the negative direction. Data from Shackleton (1977) and Zahn *et al.* (1987).

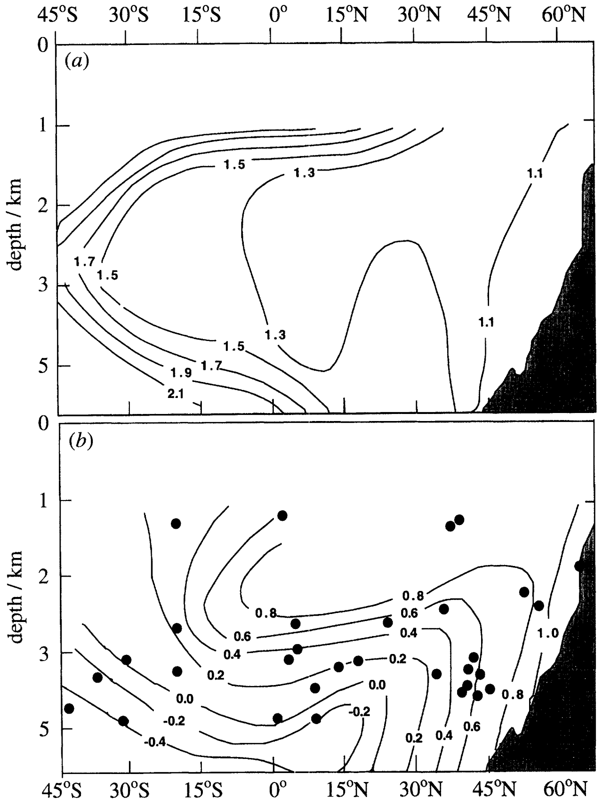

Figure 5. Atlantic modern phosphorus and LGM $\delta^{13}C$ section based on the data of Duplessy *et al.* (1988) as recontoured by Broecker (1989). (a) Modern phosphorus $\mu M\ kg^{-1}$; (b) glacial $\delta^{13}C$ ‰.

preferable because it is based only on the benthic $\delta^{13}C$ data (rather than a mixed planktonic/benthic data set as originally contoured) (figure 5). A strong vertical nutrient gradient was observed throughout the glacial North Atlantic, and it became further evident that there was a strong North–South gradient. In comparison to modern observations, cores in the intermediate depth (more northern regions) showed approximately equal, or perhaps even slightly lower, nutrient concentrations; whereas the cores deeper and further south show high nutrient concentrations. An expanded data set confirms the coarse-scale characteristics of this picture, although it would appear that the downward curving contours in the northernmost regions had been exagerated (Oppo & Lehman 1993; Sarnthein *et al.* 1994) and that the positive carbon isotope values in the upper deep and intermediate waters may have extended well into the South Atlantic (G.P. Lohmann, personal communication).

This $\delta^{13}C$ and Cd evidence was later reinforced by data on the ^{14}C contrast between planktonic and benthic foraminifera (Shackleton *et al.* 1988; Broecker *et al.* 1990). $\delta^{13}C$ and Cd only indicate patterns of deep water characteristics, but ^{14}C indicates patterns and also provides information on the absolute rate at which water is transferred from the surface ocean into the deep sea. This data has resulted in two important findings.

1. The overall ventilation rate of the deep sea during glacial times (based on Pacific data) is about the same or only somewhat higher than it is today (Shackleton *et al.* 1988; Broecker *et al.* 1990). Although the error bar on the estimate is large, no more than a 30% increase in the radiocarbon age of Pacific deep water is possible. In the modern ocean NADW is a prime contributor to deep ocean ^{14}C ventilation – at least half and perhaps as much as two-thirds of global deep-water formation – so either the ventilation rate of the deep Atlantic has not slowed much or another source of deep-water ventilation has arisen.

2. The radiocarbon age of the deep Atlantic has not changed much (Broecker *et al.* 1990). Specifically, the data indicate a slight increase in the ^{14}C age of the deep Atlantic relative to surface waters, from approximately 370 years today to approximately 675 years during the LGM. This change is probably within the uncertainty of the estimate, and hence during the LGM there has been a proximate source of young, high-^{14}C waters to the deep North Atlantic just as there is today. Although Broecker (1989) suggested that there might be ways other than strong NADW ventilation to account for the observation of young ^{14}C, the 'minimum astonishment' scenario is that the North Atlantic was ventilated by a northern source of young deep water much as it is at present.

At this point, it might seem that the evidence was clear that the LGM NADW ventilation was similar to that of the modern ocean but that the flux through the upper waters may have been the same (or perhaps somewhat stronger), whereas the flux through the deeper waters was weaker. Although I will later argue that this is the most likely account of the LGM NADW, the recent literature does not support this concept as a consensus solution. To understand this disagreement, first diversions into the southern ocean, $^{231}Pa/^{230}Th$ sediment chemistry, and then a diversion into modelling, are necessary.

4. THE $\delta^{13}C$-Cd SOUTHERN OCEAN CONUNDRUM

By 1992 it had become evident that the agreement between Cd and *Cibicidoides* species $\delta^{13}C$ data seen in the North Atlantic and Eastern Tropical Pacific, did not extend to the Southern Ocean. Data on $\delta^{13}C$ from the surface and deep LGM Southern Ocean (or waters originating from there) presented by Labeyrie & Duplessy (1985), Curry *et al.*(1988), Labracherie *et al.* (1989), Oppo *et al.* (1990) and Charles & Fairbanks (1992) all indicate that the deep and surface Southern Ocean had very negative $\delta^{13}C$ values. Conversely, Cd data from the same region showed values that were similar to those of today (Boyle 1988*a*, *b*; Keigwin & Boyle 1989; Boyle 1992). It is not easy to reconcile these observations, although attempts have been made (Broecker 1993). Further observations on Cd (e.g. Rosenthal 1994; Oppo & Rosenthal 1994) have made the discrepancy more obvious.

Charles & Fairbanks (1992) argued that $\delta^{13}C$ in the Southern Ocean reflects changes in NADW flux, stating that 'the Southern Ocean is perhaps the only region where the global influence of NADW fluctuations can be monitored unambiguously in single locations'. Regarding the observation of ^{14}C-young, nutrient-depleted deepwaters in the LGM North Atlantic they argued (personal communication) that although the North Atlantic was ventilated during the LGM, this circulation comprised a closed circulation cell which did not exit the South Atlantic (instead returning to the surface somewhere within the Atlantic). In this event, the 'global NADW conveyor belt' was short-circuited if not entirely shut down; its influence on the global thermohaline circulation would have been minimal.

Considering the $\delta^{13}C$ evidence only (and disregarding the Cd evidence for the moment), there is a significant problem with the Charles & Fairbanks scenario. As highlighted previously by Curry *et al.* (1988), LGM $\delta^{13}C$ values in the Southern Ocean are more negative than in the eastern tropical Pacific. They argued that this was only possible if 'some alternative source of nutrient-depleted water must have been produced in the Pacific'. Hence the Charles & Fairbanks scenario (that Southern Ocean deepwaters are only a mixture of nutrient-depleted NADW and nutrient-enriched Pacific Deep water, so that the nutrient content of Southern Ocean waters reflects the relative flux of NADW into the southern ocean) cannot apply during the LGM. Charles & Fairbanks acknowledged this problem but chose to minimize its importance arguing that 'a strong relative contribution of NADW is the only means for increasing Circumpolar Deep Water [CPDW] above Pacific (mean ocean) values'. Given that some other factor(s) must be involved, it is not advisable to consider the average $\delta^{13}C$ of CPDW as a direct proxy for NADW flux. Whatever the 'other factor' may be, changes in that factor can also make the Southern Ocean shift towards heavier $\delta^{13}C$ values. If NADW flux does not change at all, changes in Southern Ocean $\delta^{13}C$ may reflect changes in this other factor alone.

Cd evidence indicates that there was little change in the nutrient concentration of the Southern Ocean waters during the LGM compared to the modern. The Charles & Fairbanks interpretation of the $\delta^{13}C$ evidence requires them to ignore the Cd evidence, presumably because of some unknown artefact in the Cd data. Alternatively, it may be that our interpretation of the chemical oceanography of $\delta^{13}C$ or Cd is oversimplified, and that some process might be capable of separating these two properties during the LGM in a way that does not occur in the modern ocean. Recently, it has become evident that gas exchange – which affects $\delta^{13}C$ but does not affect Cd – is more important than previously thought, in controlling the oceanic $\delta^{13}C$ distribution (Charles & Fairbanks 1990; Broecker & Maier-Reimer 1992; Charles *et al.* 1993). Broecker (1993) has considered whether it may be possible that some of the discrepancy between $\delta^{13}C$ and Cd is due to this process. Although it could be possible to shift ocean chemical processes in the direction of the LGM $\delta^{13}C$-Cd discrepancy, it is not easy to reconcile the effect quantitatively. It is still extremely difficult to create very negative $\delta^{13}C$ in the Southern Ocean without making Cd concentrations higher.

This Southern Ocean Cd–$\delta^{13}C$ conundrum is not yet resolvable by consensus, although recent work by Sarnthein *et al.* (1988), Mackensen, (1993) and by Professors T. Bickert and G. Wefer (presented in 1994 at 'The South Atlantic: present and past circulation' symposium: Bremen, Germany) may resolve this question. Mackensen *et al.* (1993) examined 'living or recently living' (Rose Bengal stained) and fossil benthic foraminifera from core tops from the Atlantic sector of the Southern Ocean. They found that $\delta^{13}C$ in *Cibicidoides* species in both living and fossil benthics was depleted in comparison to the bottom waters beneath zones of high productivity, and suggested that as for *Uvigerina* species, $\delta^{13}C$ in *Cibicidoides* species also was affected by high organic carbon fluxes to the seafloor (although the flux threshold for the *Cibicidoides* species artefact is much higher than for *Uvigerina* species). Sarnthein (1988) first suggested that *Cibicidoides* species $\delta^{13}C$ may be affected by high organic fluxes, based on fossil specimens from a few Atlantic core tops under high productivity environments and more recently suggests (personal communication) that a threshold value of organic carbon flux could be used to indicate when this problem arises. Finally, Bickert & Wefer (1994) have examined $\delta^{13}C$ in a Cape Basin site underlying low-productivity waters and found that in this core, unlike cores closer to high-productivity coastal sites (e.g. RC13–228: Curry *et al.* 1988; RC13–229: Oppo *et al.* 1990), there is no site-specific glacial–interglacial $\delta^{13}C$ shift in *Cibicidoides* species in excess of the global average $\delta^{13}C$ shift. If this latter result is confirmed and extended to other sites, then the conflict between previous southern $\delta^{13}C$ and Cd data may indicate that the Cd evidence (indicating little change in Southern Ocean nutrient concentrations) was on the mark. It may soon be agreed by all concerned that there was little glacial–interglacial change in the nutrient concentration of southern ocean water. The matter of a productivity induced shift of *Cibicidoides* species towards lower $\delta^{13}C$ might also account for the discrepancy (noted by Oppo *et al.* 1990) between the more positive core top $\delta^{13}C$ of core KNR73–3 (Boyle & Keigwin 1985, 1986) compared to core V19-30 and TR163-31B (which underly a higher productivity surface ocean).

5. $^{231}Pa/^{230}Th$ EVIDENCE FOR GLACIAL NADW FLOW

One recent line of evidence has just become available which may settle the matter of whether NADW reaches the Southern Ocean or not. Yu (1994) and E.-F. Yu, M. Bacon & R. Francois (unpublished data) have made measurements on the $^{231}Pa/^{230}Th$ ratio in Atlantic and Antarctic sediments which indicate that ^{231}Pa missing in the Atlantic sediments is found in the Antarctic sediments both during modern and glacial times. Both ^{231}Pa and ^{230}Th are generated at precisely known rates from the decay of ^{235}U and ^{234}U in seawater. Any time from within a matter of decades to several hundred years, these radioactive isotopes then attach to sinking particles and spend most of their time within the oceanic sediment column, until they are lost to radioactive decay. The $^{231}Pa/^{230}Th$ ratio in the sedimentary flux must, therefore, equal the production ratio because the reservoir in the ocean water column is small compared to the production rate. However, in the sediments of both the modern and LGM Atlantic ocean, the ^{231}Pa/^{230}Th ratio is significantly below the production ratio. Yu *et al.* also observed that Southern Ocean sediments have ^{231}Pa/^{230}Th ratios significantly above the production ratio, they noted that quantitatively, the amount missing from the Atlantic is equal within errors (albeit relatively large) to the excess in the Antarctic. Hence they proposed that in the modern ocean, ^{231}Pa in the Atlantic is preferentially transported to the Antarctic by the NADW conveyor belt where it is scavenged by the veil of particles falling under the high productivity zones parallelling the circumpolar current. By extension, because the LGM ^{231}Pa/^{230}Th data are similar to that of the modern ocean, they proposed that ^{231}Pa export by NADW into the circumpolar current must have continued during the LGM.

At the moment it is difficult to specify what flux of NADW is necessary to allow most of the ^{231}Pa to be exported into the Southern Ocean; to make that estimate an ocean model incorporating ^{231}Pa and ^{230}Th behaviour is required. It is possible that some of the excess ^{231}Pa in the Antarctic comes from the Pacific, however it appears that no ^{231}Pa is missing from the Pacific (a statement which needs to be balanced against a relative paucity of data in the Pacific, particularly the South Pacific). So, even though there is a return flow of Pacific Deep Water towards the southern ocean, the flow may be too slow to transport the ^{231}Pa out of the Pacific before it attaches to a particle and falls to the bottom. The residence time of deep water in the Pacific today is about 500 years, and for the Atlantic about 100 years (Stuiver *et al.* 1983). So the Atlantic disperses the ^{231}Pa out just in time to avoid its loss to Atlantic sediments; the Pacific, however, is too slow to do the same. Vigorous NADW is the key to Atlantic loss of ^{231}Pa. Furthermore, it has been argued that productivity in the glacial ocean was higher during the LGM (see Sarnthein *et al.* 1988), in which case it becomes even harder to export ^{231}Pa from the Atlantic. Unless some 'missing sink' of Atlantic-generated ^{231}Pa can be found, then 'drop-dead' scenarios of glacial NADW are eliminated by this new evidence. The ^{231}Pa/^{230}Th evidence indicates that there has always been a significant flux of NADW into the Southern Ocean.

6. INVERSE MODELLING

LeGrand & Wunsch (1995) have recently applied inverse methods to a combined dynamical/box model of the deep north and south Atlantic oceans to discover how palaeo δ^{13}C data constrain their inverse model solution. They found that if one allowed southern boundary conditions to change arbitrarily (for reasons external to the model), then they can fit the LGM δ^{13}C data with a model in which the western boundary current flux is essentially the same as it is today. Hence they argue that the palaeochemical evidence does not require that the deep NADW flux was reduced.

Palaeoceanographers who believe that NADW was reduced during glacial times need not argue with the mathematics of the LeGrand & Wunsch scenario; it is simple matter to apply their model in forward mode to show that it is a correct mathematical solution fitting the prescribed boundary conditions. But even a completely correct mathematical solution proves nothing unless the model is complete and includes all relevant processes. Chemical and geological oceanographers can question whether the LeGrand & Wunsch model explains anything, given that the LGM palaeochemical distributions are attributed to an arbitrary change in Southern Ocean boundary conditions (whose cause is external to the model). Although I have indicated previously that I do not accept the Charles & Fairbanks model of the chemical composition of LGM Southern Ocean model, I believe that most chemical oceanographers would accept that the nutrient distributions in the South Atlantic and Southern Ocean reflect the clear influence of NADW and that Southern Ocean chemical distributions would be quite different in the absence of NADW flow. I also suspect that most chemical oceanographers would be at a loss to explain how Southern Ocean boundary conditions would change in the fashion prescribed by the solution of LeGrand & Wunsch without invoking changes in the NADW flux. Also note that LeGrand & Wunsch acknowledge that the palaeoceanographically preferred diminishment of NADW is also a solution consistent with their model and the observations. There may be an understandable tendency for each discipline to ascribe the cause of changes to that which they know the least about: the chemical and geological oceanographers attributing changes to the physical circulation whereas the physical oceanographers invoke magical unexplained transformations of the biogeochemical cycles in the Southern Ocean. Perhaps if both disciplines fight the temptation to be proud of their own ignorance, there will be something to be learned both from inverse models and palaeoceanographic hypotheses.

7. DID NADW CHANGE DURING THE YOUNGER DRYAS?

Boyle & Keigwin (1987) reported that Cd and δ^{13}C from a high accumulation rate (20–200 cm ka^{-1}) core on the Bermuda Rise (EN120 GGC1, 33°40′ N, 57°37′ W, 4479 m) showed a shift to more nutrient-enriched waters during the Younger Dryas cooling event (which occurred about 12000 calendar years ago over an interval of about 1000–1500 years). This observation is important because it demonstrates that the deep North Atlantic circulation is sensitive to abrupt climate changes seen in surface circulation, and it even has been hypothesized that this change in the circulation is the primary cause of the Younger Dryas. Later, more detailed accelerator mass spectrometry (AMS) radiocarbon dating and data from another core were used to refine this argument (Keigwin & Jones 1989; Keigwin *et al.* 1991). However, several newer findings have been proposed, contradicting the occurrence of a deep-water Younger Dryas event. Fairbanks (1989), noting the lack of a meltwater event coincident with the Younger Dryas in his sea-level record, argued that there was no Younger Dryas deep-water response. Jansen & Veum (1990) made carbon isotope observations on a moderately high deposition rate core (15 cm ka^{-1}) with a clear Younger Dryas signal in planktonic palaeoecology (V23-81, 54° N, 16° W, 2393 m) and stated that they could see no Younger Dryas signal in their benthic δ^{13}C data. Sarnthein *et al.* (1994) reported, on the basis of numerous cores from all depths throughout the eastern Atlantic, that 'during the Younger Dryas, the Atlantic circulation and the SCB [Salinity Conveyor Belt] largely approached the interglacial mode'. Do these reports really signify the end of the Younger Dryas deep-water signal? Here, I will argue that the data in these reports simply are not relevant to the existence of a Younger Dryas signal in the deep western North Atlantic.

The Fairbanks sea level argument (based on the lack of a meltwater pulse during the Younger Dryas) is in fact a criticism of the proposal by Broecker *et al.* (1989) that a temporary glacial meltwater diversion to the St Lawrence drainage was the cause of the Younger Dryas cooling. Sea level evidence itself is not germane to whether or not there was a deepwater signal during the Younger Dryas. Deep water events may be accounted for by causes other than St Lawrence meltwater diversion, as was stated explicitly in the original paper reporting the Younger Dryas in the deep western North Atlantic (Boyle & Keigwin 1987), and as well by Broecker subsequently (Birchfield & Broecker 1990; Broecker 1990; Broecker *et al.* 1990). Three comments can be made concerning the lack of a Younger Dryas signal in V23-81.

1. There was no Cd data from the core for comparison. Because of possible δ^{13}C artefacts, and because proper interpretation of δ^{13}C data requires comparison to the global average δ^{13}C which is also rapidly changing, Cd data may be a particularly useful check on deepwater chemical changes during deglaciation because the data does not have to be referenced to a large global average signal. New *Hoeglundina elegans* Cd data from V23-81 is presented here (see table 1). Clearly, there is no enhanced Cd signal at this site during the Younger Dryas event (see figure 6). This is perhaps the least important factor.

2. Although the sedimentation rate at V23-81 is sufficient to allow for a full-strength recording of the amplitude of the event in planktonic organisms, V23-81 has a lower sedimentation rate than the Bermuda Rise, and is sampled for benthics at coarser sample resolution. The planktonic record of this event in V23-81 is clearly modified by bioturbation compared to higher accumulation rate sites (Lehman & Keigwin 1992). Any deep-water signal which may have been present at this site will have been diminished somewhat by bioturbation. Nonetheless, even this problem is of minimal significance.

Table 1. *Hoeglundina elegans* Cd data from core V23-81

depth/ cm	Cd/Ca/ (μmol/mol^{-1})
40	0.040
60	0.030
70	0.031
80	0.035
90	0.027
100	0.033
110	0.036
120	0.033
147	0.043
158	0.033

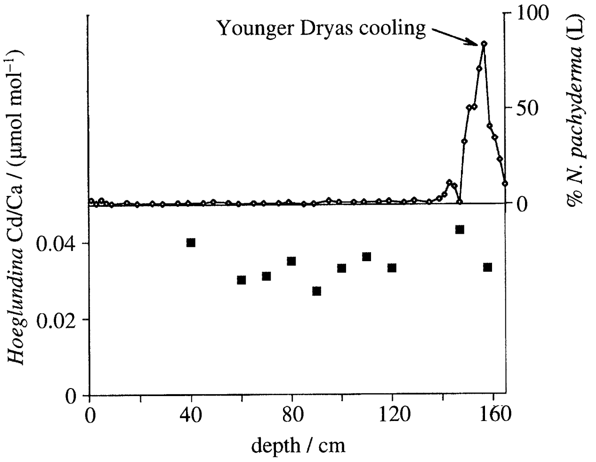

Figure 6. Downcore benthic (*Hoeglundina elegans*) Cd/Ca data for core V23-81 (54° N, 16° W, 2393 m) compared to percent *N. pachyderma* (left) which indicates cold surface waters.

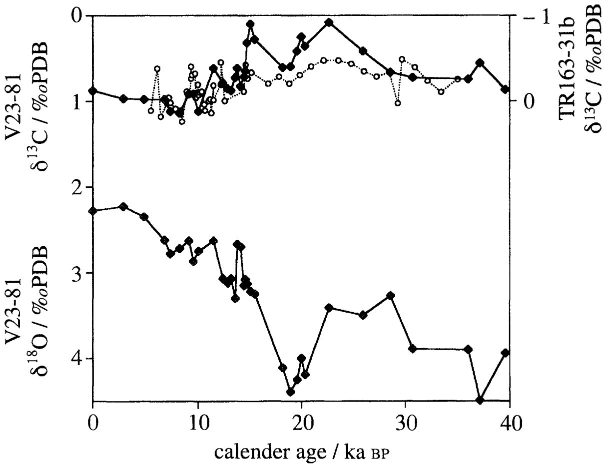

Figure 7. Downcore benthic (*C. wuellerstirfi*) isotope data for core V23-81 (54° N, 16° W, 2393 m, Jansen & Veu 1990) compared to that for core TR163-31b (Curry *et al.* 1988). Filled diamonds denote V23-81 (Atlantic), open circles denote TR163-31b (Pacific).

3. Most importantly, it should be noted that in this region there is no more than a −0.3‰ δ^{13}C signal during the LGM compared to interglacial times compared to the global average δ^{13}C variation (see figure 7), as was first pointed out for a nearby core by Raymo *et al.* (1990). If the Younger Dryas at this site had about half the amplitude of the full glacial signal (as it did on the Bermuda Rise), then it may be expected that the Younger Dryas signal at V23-81 is less than 0.15‰. Hence it is not surprising that a Younger Dryas signal is not seen at V23-81 because it is located at at site that is relatively insensitive to the larger glacial/interglacial chemical signals seen elsewhere in the Atlantic. Attempting to see the Younger Dryas at V23-

81 is like trying to detect the flow out of a firehose by measuring the concentration of water near the mouth of the spout: relatively large fluctuations in flow will make very little difference to the concentration of water. Conversely, at the furthermost reach of the spray small fluctuations can be detected easily. The only effective way to assess the effect of the Younger Dryas on deep-water flow is to map the geographic extent of the event.

Sarnthein *et al.* (1994) adopt, in principle, the approach suggested in the last sentence of the previous paragraph but their strategy is confronted by a major difficulty: most of their cores have lower accumulation rates than V23-81, which is only just good enough for clear Younger Dryas detection. Even in the high accumulation rate cores from the Bermuda Rise, in a region where the Younger Dryas accumulation rate is between 15–30 cm ka^{-1}, the samples comprising the Younger Dryas are found through a depth interval of only approximately 20 cm of sediment, and detected at 2–4 cm sampling intervals. Given the lower accumulation rates and coarser sampling in comparison to the Bermuda Rise, it is not surprising that Sarnthein and coworkers did not detect the Younger Dryas clearly in their cores. This problem highlights a major difficulty in the mapping strategy for studying the deep-water expression of the Younger Dryas: the accumulation rates necessary for detecting the event occur at few sites and one cannot use typical deep sea sediments to map out the real extent of the deep-water Younger Dryas event. Finally, most of their cores are from the eastern basin, and it is not clear whether a Younger Dryas signal affecting the deep western North Atlantic must necessarily affect the eastern basin.

In summary, the Younger Dryas has been clearly observed in *C. wuellerstorfi* δ^{13}C in two high accumulation rate cores from the Bermuda rise that were sampled in detail, and seen as well in Cd data from both *C. wuellerstorfi* and *N. umbonifera* in one of the cores. There is no reason to doubt these observations. The absence of the Younger Dryas signal at shallower sites to the North, and in lower sedimentation rate cores in the eastern basin, does not refute the observation that the Younger Dryas event has an effect on deep-water chemistry in the deep western North Atlantic.

8. CLOSING ARGUMENTS: LGM NADW IS ALIVE AND WELL IN THE GLOBAL THERMOHALINE CIRCULATION (BUT MAY HAVE BEEN SHALLOWER OR WEAKER)

The palaeochemical evidence concerning the increase of nutrients in deep cores from North Atlantic during glacial times is clear. It is also clear that further north (particularly at shallower depths), the nutrient concentration was as low or perhaps even lower than it is today. The data from the Caribbean Sea supported by other data on continental margins, indicate that low nutrients were also found at intermediate depths in the North and Tropical Atlantic. The recontoured data of δ^{13}C Duplessy *et al.* (1988) remain a valid expression of the LGM distributions of nutrients in the Atlantic at coarse scale. Although no consensus yet exists, data from the South Atlantic may be beginning to converge on a relative stability of the nutrient chemistry of waters that are presently influenced by low-nutrient NADW. ^{231}Pa/^{230}Th data support the continued export of ^{231}Pa generated in the Atlantic into the Southern Ocean. Finally, radiocarbon evidence from paired planktonic/benthic foraminifera indicates that ventilation of the deep North Atlantic remained rapid during the LGM and also indicates that the whole-ocean ventilation time did not change much beyond the uncertainty in the data. Taken together, this evidence suggests that the NADW became GNADIW during glacial times, perhaps with a greater flux through intermediate waters than at present, combined with a lesser flux through deeper waters. Although one cannot say much with confidence about the total GNADIW flux, the data are consistent with a persistent but perhaps diminished role for NADW in the global thermohaline circulation during glacial times.

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Discussion

H. Leach (*University of Liverpool, U.K.*). Was there North Atlantic Deep Water before the last glaciation?

E. A. Boyle. Yes.