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Phase relationships between millennial-scale events 64,000-24,000 years ago

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Abstract. A core recovered on the Iberian margin off southern Portugal can be correlated with Greenland ice cores using oxygen isotope variability in planktonic foraminifera which closely matches the ice core records of temperature over Greenland. Our age model identifies the base of every interstadial between 64,000 and 24,000 years ago and uses the Greenland Ice Core Project (GRIP) timescale. The oxygen isotope signal in benthic foraminifera (on this GRIP-based timescale) is quite different from the planktonic record and resembles the temperature record over Antarctica when this is synchronized with Greenland using the record of methane in the atmospheric air in the polar ice cores. We interpret the benthic record as indicating significant fluctuations in ice volume during millennial events, and we suggest that Antarctic temperature changed as a function of ice volume.

1. Introduction

There have been two impediments to obtaining paleoceanographic records that may be compared in detail with the remarkable records that have been recovered from the Greenland ice sheet [*Dansgaard et al.*, 1971, 1993; *Mayewski et al.*, 1997]. First, many climate events recorded in the Greenland ice cores are relatively brief, lasting a few centuries. Such short events are only recorded in marine sequences in areas where the accumulation rate is unusually high. Second, over much of the North Atlantic, productivity was severely reduced during deposition of the so-called Heinrich layers, so that microfossils recording these events are disproportionately rare. We have investigated a core taken off southern Portugal, where productivity was apparently maintained at a high level throughout the last glacial cycle and where the sedimentation rate has remained very high (~20 cm/kyr). Indeed *Zahn et al.* [1997] show by accelerator mass spectrometry (AMS) ^{14}C dating that on the Portuguese Margin, sedimentation rates actually increased during Heinrich events.

Core MD95-2042 was taken during the 1995 International Marine Global Change Study (IMAGES) cruise [*Bassinot et al.*, 1996] on the Iberian Margin at 37°48'N, 10°10'W in a water depth of 3146 m. A preliminary study of this 32 m core was undertaken by O. Cayre [*Cayre et al.*, 1999], who showed a clear oxygen isotope stratigraphy covering stages 1-6 in the uppermost, undisturbed 27 m of the core, below which the sediment is flow-in. The study by *Cayre et al.* [1999] was based on a sampling interval of 20 cm; even at this relatively coarse sampling interval, it was apparent that the core preserves a very reliable record. *Cayre et al.* [1999] developed an age model for the core partly by correlation with nearby core SU81-18, which had been the subject of a very detailed AMS ^{14}C dating study [*Bard et al.*, 1987], and partly using the oxygen isotope stratigraphy. These workers also estimated sea surface temperatures (SST) on the basis of the analysis of the foraminiferal assemblages in the sediment. During interstadials, reconstructed sea surface temperature was close to present-day values, while during stadials, SST was ~10°C lower. Oxygen isotope values for *Globigerina bulloides* were observed to vary in parallel with SST. The range in δ^{18}O is not quite as large as would be predicted for the estimated temperature variability alone. *Cayre et al.* [1999] predict a peak-to-peak δ^{18}O range of ~1.8‰ on the basis of their SST estimates, whereas we observe a peak-to-peak range of ~1‰ (Figure 1). This implies that although surface salinity may have been reduced during the cold intervals, in this region, temperature was the dominant control on rapid δ^{18}O variability.

2. Methods

Core MD95-2042 was collected using the CALYPSO Kullenberg corer aboard *Marion Dufresne*. The working half was sliced into 1 cm pieces and, for this study, analyzed with a 4 cm (or 3 cm) resolution over the upper 28 m. Samples were disaggregated in deionized water and washed over a 63 μm sieve. For the planktonic δ^{18}O record the low-resolution suite of measurements was based on *G. bulloides* selected from the 250-350 μm range by Cayre [*Cayre et al.*, 1999]. For the new analyses of this species, specimens were selected from the 300-355 μm range; 20 specimens were analyzed, except in the few samples that contained fewer than this number. The *G. bulloides* measurements were performed in a VG SIRA mass spectrometer using a common acid bath at 90°C. Calibration to Vienna Peedee Belemnite (VPDB) was through the NBS19

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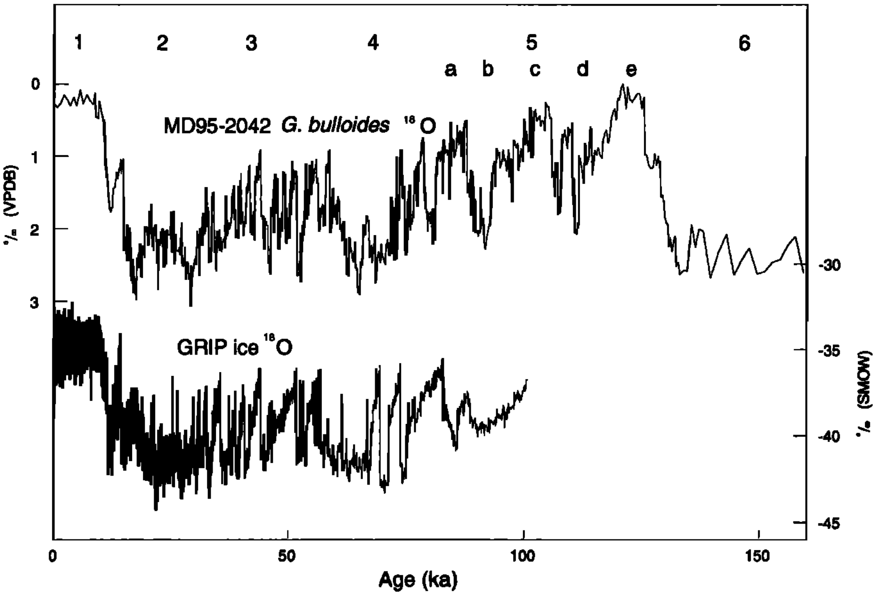

Figure 1. Planktonic oxygen isotope stratigraphy of core MD95-2042 identifying isotope stages, timescale of *Cayre et al.* [1999], and Greenland Ice Core Project (GRIP) $\delta^{18}O$ [*Johnsen et al.*, 1992].

standard [*Coplen*, 1995]. Over Marine isotope stage (MIS) 3 we made ~360 analyses of monospecific benthic foraminifera (>250 μm) from 245 sediment samples. Specimens were cleaned with hydrogen peroxide. Benthic specimens were analyzed in a VG PRISM mass spectrometer using the MULTIPREP system, where each sample is analyzed in a separate container. The occasional unacceptable measurements probably arise when the vial caps are not adequately sealed.

It initially appeared to be difficult to develop a benthic $\delta^{18}O$ record because neither *Cibicidoides* nor any *Uvigerina* spp. are present in the samples in sufficient quantities for isotope analysis throughout the core. However, *Globobulimina affinis* is present in nearly all stage 3 samples, and we developed a continuous record by analyzing this species (typically, six specimens) in nearly every sample and, in addition, analyzing *Cibicidoides wuellerstorfi* and/or *Uvigerina peregrina* when possible.[1]

By long convention the $\delta^{18}O$ value of *C. wuellerstorfi* is adjusted by + 0.64 to bring it close to values obtained for - *Uvigerina* spp. [*Shackleton and Opdyke*, 1973]. We compared the $\delta^{18}O$ value of *C. wuellerstorfi* with coexisting *G. affinis* (Figure 2) over the whole isotopic range represented in the core. The slope of a regression is indistinguishable from unity and the mean difference is 0.94‰, so that the $\delta^{18}O$ value for *G. affinis* must be adjusted by about -0.3‰ in order to be consistent with the 0.64‰ offset for *C. wuellerstorfi*. The $\delta^{13}C$ data for *G. affinis* are not useful as a water mass tracer because this species has an infaunal microhabitat within the sediment [*Corliss*, 1985].

3. Planktonic $\delta^{18}O$ Stratigraphy

The high-resolution $\delta^{18}O$ data for *Globigerina bulloides* are shown in Figure 1 on the timescale of *Cayre et al.* [1999]. Figure 1 also shows the $\delta^{18}O$ record of the Greenland Ice Core Project (GRIP) ice core from central Greenland [*Johnsen et al.*,

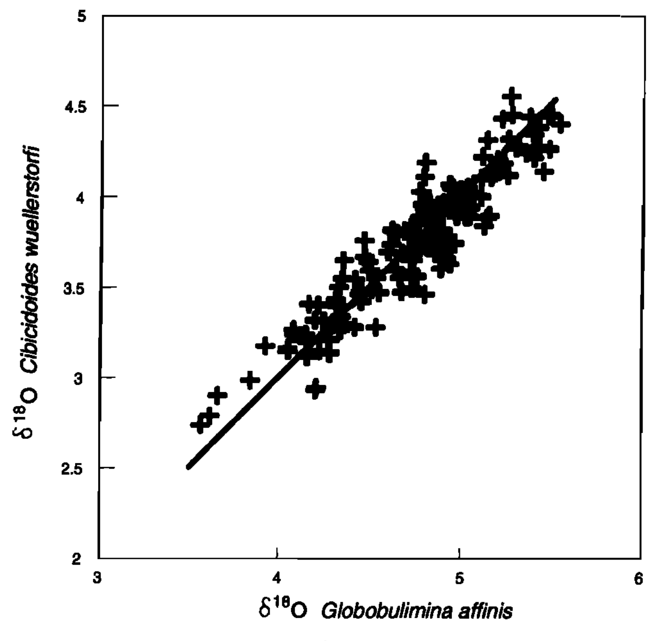

Figure 2. Comparison of $\delta^{18}O$ in coexisting specimens of *Globobulimina affinis* and *Cibicidoides wuellerstorfi* in core MD95-2042. The line represents a mean difference of 0.94‰.

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[1] Supporting analytical data from core MD95-2042 are available electronically at World Data Center-A for Paleoclimatology, NOAA/NGDC, 325 Broadway, Boulder, CO 80303 (URL: http://www.ngdc.noaa.gov/paleo; e-mail: paleo@mail.ngdc.noaa.gov) and from our web site (URL: http://delphi.esc.cam.ac.uk).

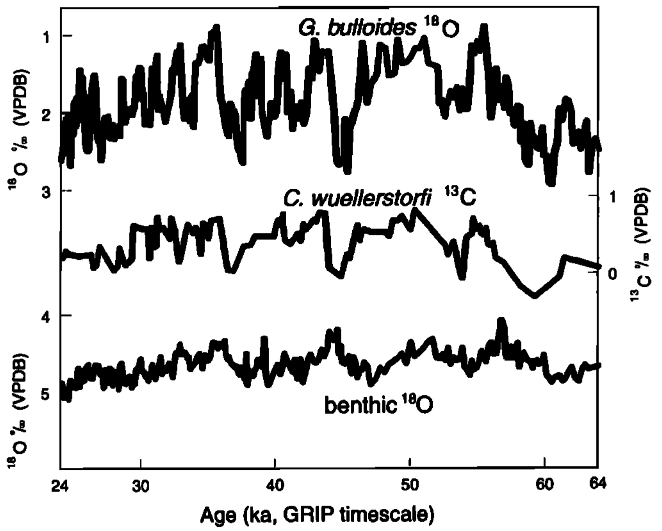

Figure 3. Benthic and planktonic $\delta^{18}O$ plus benthic $\delta^{13}C$ for stage 3 in core MD95-2042, GRIP-based timescale from Table 1.

1992]. It is apparent that our new, high-resolution $\delta^{18}O$ record can be readily correlated in detail with the Greenland record. A striking feature of the Greenland record is that the beginning of each interstadial is very abrupt [*Severinghaus and Brook*, 1999; *Lang et al.*, 1999], implying that the polar front must have migrated northward extremely rapidly. It therefore seems reasonable to develop a higher-resolution GRIP-based timescale for stage 3 by assuming that the rapid warming events recorded in core MD95-2042 are synchronous with those observed in Greenland. Table 1 shows the age controls that we used to plot the data on the GRIP age scale. Equivalent ages for the Greenland Ice Sheet Project (GISP) timescale [*Meese et al.*, 1997] are also given.

4. Discussion: Benthic $\delta^{18}O$ Record

Figure 3 shows the $\delta^{18}O$ record for *Globigerina bulloides* over stage 3 on the GRIP-based timescale of Table 1 and, below, the $\delta^{18}O$ record for benthic species (calibrated as described above) on the same timescale. It is obvious that the two oxygen isotope records are very different. There are several important aspects of this difference. First, the range of variation is much less in the benthic record than in the planktonic record. Second, there is a phase difference, such that lightest values in the benthic record occur close to the planktonic cold-to-warm transitions. Third, the transitions in the benthic record are gradual, whereas the transitions in the planktonic record appear to be rapid (as the transitions in Greenland temperature undoubtedly were). Figure 3 also shows the benthic $\delta^{13}C$ record for *C. wuellerstorfi* (at a slightly lower resolution, owing to the number of samples containing no specimens of this species). It is evident that the $\delta^{13}C$ record is consistent with earlier data showing that the ventilation of North Atlantic Deep Water was suppressed during cold events over the North Atlantic; values change in near synchrony with planktonic $\delta^{18}O$. It also appears that the changes in benthic $\delta^{18}O$ are unrelated to this phenomenon since the benthic $\delta^{13}C$ changes are synchronous with planktonic $\delta^{18}O$ changes but not with the benthic $\delta^{18}O$ changes.

We suggest that the benthic $\delta^{18}O$ record provides evidence of changes in continental ice volume; during stadials when the surface of the North Atlantic was very cold, the surrounding ice sheets were starved of precipitation, and they declined in volume, whereas during the interstadials when the surface was warm, increased precipitation caused these ice sheets to grow. This hypothesis explains the phasing of the benthic $\delta^{18}O$ record as well as its character and is also consistent with the observation that the largest amplitude events in the benthic $\delta^{18}O$ record are associated with the surface temperature events with the longest duration (in the Greenland record, all events have about the same amplitude, but the durations vary significantly).

Such rapid variations in ice volume could not be instantly mixed through the oceans, and the amplitude of the variability (~0.5‰) that we observe cannot be directly converted to a sea level equivalent, as can be done for slower changes over orbital timescales. The true ice volume changes in this time interval will probably be most reliably estimated from the morphology of coral deposits on New Guinea and may account for only about half the $\delta^{18}O$ range that we observe (J. Chappell, personal communication, Feb. 2000). We cannot exclude the possibility that deep water temperature variability driven from the Southern Hemisphere also makes a contribution.

5. Discussion: Comparison with Vostok

The lowest record shown on Figure 4 is the D/H record from the Vostok ice core from central east Antarctica, indicating air temperature *Jouzel et al.* [1987], also presented on the GRIP timescale. From 24 to 47 ka the timescale is that of *Blunier et al.* [1998]; from 47 to 64 ka the timescale is obtained by making slight adjustments to the timescale of *Bender et al.*

Table 1. Age Control Points for Correlating MD95-2042 to the GRIP Record (Including GISP Equivalents)[a]

Depth m	GRIP Age, ka	GISP Age, ka	Basis
0.00	0.00	0.00	top of core
3.05	11.57	11.63	base Holocene
4.34	14.52	14.59	base Bölling
10.14	25.57	27.91	base 3
10.54	26.61	29.09	base 4
11.78	29.99	32.37	base 5
12.18	31.19	33.72	base 6
12.71	32.90	35.33	base 7
13.02	33.96	36.33	top 8
13.38	35.72	38.50	base 8
14.42	38.97	41.22	base 10
14.86	40.83	42.63	base 11
15.58	44.36	45.36	base 12
16.18	46.69	47.07	base 13
16.84	51.97	52.23	base 14
17.55	55.73	56.67	base 17 mod[b]
18.76	61.70	62.22	base 18
19.60	66.99	66.16	base 19

[a] Between controls, age is estimated by linear interpolation.

[b] We have placed this control point above the prominent cooling at ~55.8Ka in the GRIP record; see Figure 4.

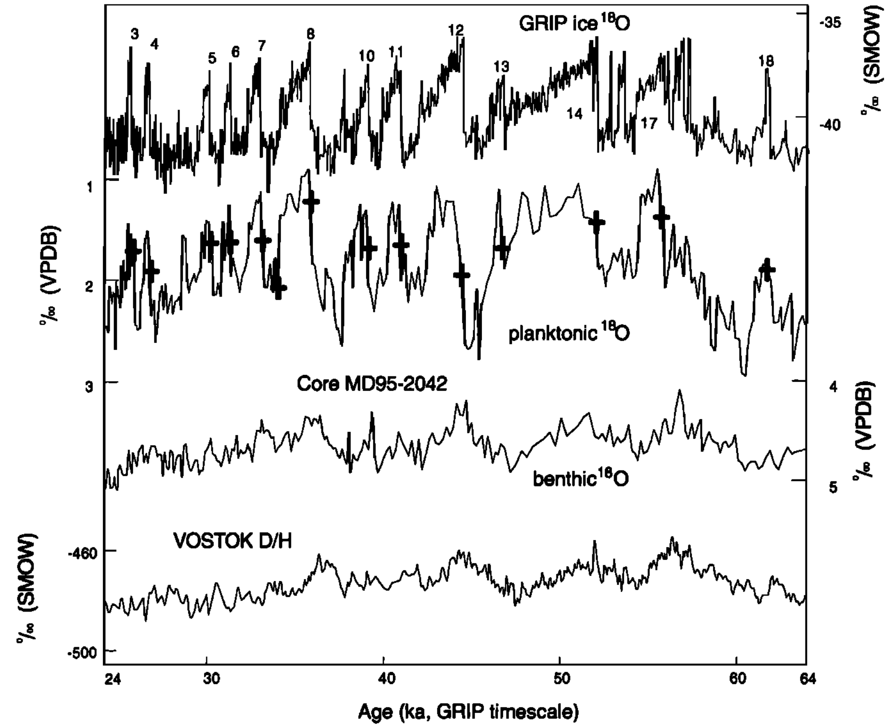

Figure 4. Benthic and planktonic $\delta^{18}O$ stage 3 in core MD95-2042, GRIP-based timescale from Table 1, compared with GRIP $\delta^{18}O$ [*Johnsen et al.*, 1992] and Vostok D/H (data from *Jouzel et al.* [1987], GRIP-based timescale of *Blunier et al.* [1998] extended by modifying *Bender et al* [1999]). Numbering of GRIP interstadials is indicated. Crosses identify the age control points.

[1999] to convert this from the GISP timescale to the GRIP timescale. Both the timescale of *Blunier et al.* [1998] and that of *Bender et al.* [1999] depend on the assumption that rapid changes in the concentration of methane in the atmosphere are globally well- mixed and may be used to synchronize the records. The MD95-2042 benthic $\delta^{18}O$ record does not resemble either the planktonic $\delta^{18}O$ record from the same core or the GRIP record to which this has been correlated, but it is remarkably similar to the temperature record of the Vostok ice core. There are two aspects of the similarity that are significant: first, the principal features of the two records are in phase, and second, the principal events in both the benthic $\delta^{18}O$ record and the Vostok temperature record have a "triangular" form in contrast to the "square-wave" form of the Greenland and North Atlantic temperature records. We suggest that the similarity implies that Antarctic temperature and, perhaps, the temperature of much of the Earth responded to changes in ice volume. It has long been known from modeling studies that the presence of large continental ice sheets has a profound effect on atmospheric circulation and on global temperatures, even if all other boundary conditions are held constant [*Manabe and Broccoli,* 1985].

6. Conclusions

The benthic $\delta^{18}O$ record in a core from the North Atlantic is very different in amplitude, phase, and general character from the planktonic $\delta^{18}O$ record obtained in the same core. The benthic $\delta^{18}O$ record closely resembles the record of surface temperature over Antarctica. Regardless of the relative contributions to the benthic $\delta^{18}O$ record of ice volume and varying deep water temperature, this similarity provides strong support for the time synchronization of *Blunier et al.* [1998]. We consider it likely that changes in ice volume made an important contribution to the high-frequency variations of the North Atlantic benthic $\delta^{18}O$ record because the character of the record implies a response that is associated with a long timeconstant.

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