The mid-Brunhes transition in ODP sites 1089 and 1090 (subantarctic South Atlantic). In: Marine Isotope Stage 11: An...

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The Mid-Brunhes Transition in ODP Sites 1089 and 1090 (Subantarctic South Atlantic)

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We studied cores from ODP sites 1089 and 1090 in the subantarctic South Atlantic to reconstruct paleoceanographic changes during the mid-Brunhes in the context of climate evolution of the Pleistocene. The "mid-Brunhes event" is marked by an abrupt shift toward lower $\delta^{18}O$ values during interglacial stages beginning with MIS 11, consistent with *Jansen et al.* [1986] who first proposed a mid-Brunhes transition to more humid, interglacial conditions in the southern hemisphere. In addition, we identified the "mid-Brunhes dissolution cycle" as part of a long-period oscillation that is expressed in dissolution indices and planktic $\delta^{13}C$, which reach maximum values during interglacial stages 13 and 11. Taking advantage of the high sedimentation rates at site 1089 (15 cm/kyr), we enumerate the sequence of events that occurred during Termination V and MIS 11 and speculate about their cause(s). A comparison between site 1089 and the Vostok ice core suggests that peak conditions of stage 11 are accurately captured in the ice core record, and that temperatures in the high-latitude southern hemisphere and global pCO_2 levels during stage 11 were similar to the Holocene. Furthermore, a remarkable correlation between Vostok pCO_2 and % foraminiferal fragmentation at site 1089 suggests a strong coupling of the marine carbonate system and atmospheric pCO_2 during the mid-Brunhes. Although stage 11 and the Holocene share some similarities (e.g., orbital configuration, pCO_2, etc.), caution is advised in using stage 11 as an analog for the Holocene because the maximum in dissolution and $\delta^{13}C$ during the mid-Brunhes indicate that the marine carbonate-carbon cycle was fundamentally different than today.

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INTRODUCTION

A complete understanding of stage 11 requires placing it in the context of climate evolution of the Pleistocene. Specifically, stage 11 is part of a long-term climate trend that is observed during the Brunhes Chronozone. *Jansen et al.* [1986] first reported a climatic event in the mid-Brunhes, which they proposed was marked by a transition to more humid, interglacial conditions in the southern hemisphere. A long-term oscillation has also been recognized in deep-sea carbonate records from all ocean basins with maximum dissolution centered on ~400 kyrs in the mid-Brunhes [*Adelseck*, 1977; *Crowley*, 1985; *Peterson and Prell*, 1985; *Farrell and Prell*, 1989; *Droxler et al.*, 1990; *Bassinot et al.*, 1994a]. This long-term oscillation may be related to the 413-kyr cycle of eccentricity of the Earth's orbit, but such a period is difficult to identify in the absence of long time series. Alternatively, the oscillation may not be periodic and, instead, display a variable wavelength between 425 and 550 kyrs [*Bassinot et al.*, 1994a].

The time of most profound change in the mid-Brunhes was Termination V -- i.e., the transition from Marine Isotope Stage (MIS) 12 to 11, which represents the largest deglaciation of the late Pleistocene. Sea level may have been as much as 140 m lower than today during MIS 12 (i.e., 20 m lower than the last glaciation; *Rohling et al.*, 1998) and rose to levels up to 20 m higher than today during MIS 11 [*Hearty et al.*, 1999; *Kindler and Hearty*, 2000]. This potentially represents a change in global ice volume equivalent to 160 m of sea level rise at Termination V, or about 1/3 greater than that experienced during the last deglaciation. Yet Termination V occurred at a time when insolation forcing was weak, giving rise to a paradox referred to as the "Stage 11 problem" [*Imbrie et al.*, 1993]. This inconsistency has led some to question the Milkankovitch theory of the ice ages and, specifically, whether changes in Earth's eccentricity were responsible for the observed 100-kyr cycle in late Pleistocene climate records [*Muller and MacDonald*, 1997].

Termination V was followed by MIS 11 that may have been the warmest and/or longest interglacial of the Pleistocene [see reviews by *Howard*, 1997; *Droxler and Farrell*, 2000]. Although there is considerable evidence that stage 11 was longer than most other interglacials [for alternate view, see *Winograd et al.*, 1997], warmer-than-present conditions may not have prevailed everywhere as sea surface temperatures in some regions clearly indicate similar or cooler temperatures than the Holocene [*Oppo et al.*, 1998; *McManus et al.*, 1999; *Bauch et al.*, 2000; *Hodell et al.*, 2000; *King and Howard*, 2000].

Here we examine MIS 11 and Termination V in the context of climate change for the last 1 myrs at Ocean Drilling Program (ODP) sites 1089 and 1090 in the subantarctic South Atlantic. Our strategy is to use the expanded section at site 1089 to obtain records of millennial-scale resolution during the mid-Brunhes and to use the long record from site 1090 to place the mid-Brunhes period in the context of Pleistocene climate evolution. Taking advantange of the high sedimentation rates of site 1089 (15 cm/kyr), we reconstruct the sequence of events that occurred during Termination V and MIS 11. In doing so, we speculate about the answers to several vexing questions concerning the mid-Brunhes: Why was ice volume greater during stage 12 compared to other glacials of the late Pleistocene? What triggered Termination V during a time of weak insolation forcing? What was the role of the high-latitude southern hemisphere in Termination V and stage 11? What role did the marine carbonate system play in pCO_2 variations during the mid-Brunhes? Was temperature and/or pCO_2 higher during MIS11 compared to other interglacials? Is stage 11 really such a good analog for present and future climate change in the Holocene?

MATERIALS AND METHODS

Sites 1089 and 1090 are located in the subantarctic zone between ~41° and 43°S (Figure 1). Site 1089 was drilled in 4600 m of water on a sediment drift in the southern Cape Basin and is marked by high sedimentation rates averaging ~15 cm/kyr. Site 1090 was drilled nearby on the northern flank of the Agulhas Fracture Zone Ridge in a water depth of ~3700 m. Sedimentation rates average 3 cm/kyr during the Brunhes.

At both sites 1089 and 1090, a continuous spliced record was constructed during Leg 177 by aligning features in the records of closely-spaced physical properties measurements [*Shipboard Scientific Party*, 1999]. The upper 12.1-m of the composite splice at site 1090 consists of piston core TTN057-6-PC4, which was recovered at site 1090 during the site survey cruise for Leg 177. Cores from the composite section were sampled at a constant interval of 1 sample every 5 cm, yielding an average temporal spacing of approximately 300-400 years for site 1089 and ~3000 years for site 1090.

At site 1089, we analyzed three species of planktic foraminifera: *Globigerina bulloides, Globorotalia inflata,* and *Globorotalia truncatulinoides* (sinistral). In TTN057-6-PC4, *G. bulloides* and *Neogloboquadrina pachyderma* (sinistral) were analyzed, whereas only *G. bulloides* was measured from site 1090. All specimens were picked from the 212-295 μm fraction with the exception of *N. pachyderma* where specimens >150 μm were used. In all cores, the benthic foraminifer *Cibicidoides* was analyzed from the >150 μm fraction. The methods and results for TTN057-6-

PC4 and site 1090 are reported in *Hodell et al.* [2000] and *Venz and Hodell* [in press], respectively. For site 1089, all foraminiferal specimens were soaked in 15% H_2O_2 to remove organic matter, cleaned in an ultrasonic bath, and reacted in ortho-phosphoric acid at 70°C using a Kiel III carbonate preparation device. Isotopic ratios were measured using a Finnigan MAT 252 mass spectrometer. All isotope results are reported in standard delta notation relative to VPDB and analytical precision was better than +/- 0.1‰ for all analyses.

Weight percent calcium carbonate was measured by coulometric titration and results are reported by *Hodell et al.* [in press] and *Venz and Hodell* [in press]. Percent fragmentation of planktic foraminifera was determined by counting at least 300 specimens per sample between 45 and 71 mcd in site 1089 and was used as a proxy of carbonate dissolution [*Hodell et al.*, in press].

The abundance of ice-rafted debris was determined by visual counts of at least 400 grains in the 150μm -to-2 mm size fraction [*Kanfoush et al.*, in press]. Apparent mass accumulation rate (mg/cm^{-2} kyr^{-1}) of IRD was calculated following the procedure of *Allen and Warnke* [1991].

CHRONOLOGY

Depths in sites 1089 and TTN057-6-PC4/1090 were converted to age by correlating the benthic $\delta^{18}O$ signals to the low-latitude $\delta^{18}O$ stack of *Bassinot et al.* [1994b] (Figure 2). We chose this reference signal because it resembles more closely our records during the mid-Brunhes than does the SPECMAP stack. The 427- kyr age for Termination V reported by *Bassinot et al.* [1994b] is similar to SPECMAP (423 kyrs) and is consistent with the age range of 416-448 kyrs estimated by $^{40}Ar/^{39}Ar$ [*Karner et al.*, 1999]. The age is also consistent with *Raymo's* [1997] estimate of 423 kyrs derived by assuming constant sedimentation rates during the Brunhes at several ODP sites.

RESULTS

Site 1090

The long $\delta^{18}O$ records of site 1090 reveal several features of the mid Brunhes transition in the South Atlantic. The $\delta^{18}O$ signal of *G. bulloides* clearly shows that MIS12 has the greatest $\delta^{18}O$ values of the last million years (Figure 3). Benthic $\delta^{18}O$ values are also higher during stage 12 than any other glacial period with the exception of stage 16, which shows equivalent values. As reported by *Hodell et al.* [2000], oxygen isotope values of *G. bulloides* during MIS 11 are no lower than other interglacials of the last 400 kyrs; however, stage 11 displays significantly lower values than interglacials prior to 420 kyrs. In fact, stage 11 marks a shift toward lower $\delta^{18}O$ values during interglacials after ~420 kyrs. A similar decrease in interglacial $\delta^{18}O$ values is also observed in the site 1090 benthic signal (Figure 3).

One of the most distinctive features of the mid-Brunhes is the high $\delta^{13}C$ values of both planktic and benthic foraminifera (Figure 4). The $\delta^{13}C$ signal of *G. bulloides* shows a long-term oscillation during the last 1 Ma with relatively high values at 900-1000 kyrs, low values centered on ~700 kyrs, maximum values in the mid-Brunhes centered on ~500 kyrs, and low values in the late Brunhes centered on ~150 kyrs (Figure 4). The heaviest planktic $\delta^{13}C$ values occur during stages 13 and 11, and then steadily decline reaching minimum values at ~150 kyrs.

Site 1089

The high sedimentation rates (15 cm/kyr) at site 1089 offer the opportunity to obtain a detailed record of paleoceanographic changes during the mid-Brunhes. The benthic $\delta^{18}O$ record is remarkably similar to the low-latitude stack of *Bassinot et al.* [1994b] (Figure 2). Maximum benthic $\delta^{18}O$ values occur during stage 12 and decrease by ~2.1 ‰ across Termination V. This compares with an amplitude of ~1.9 ‰ over Termination I at the same location [*Ninneman*

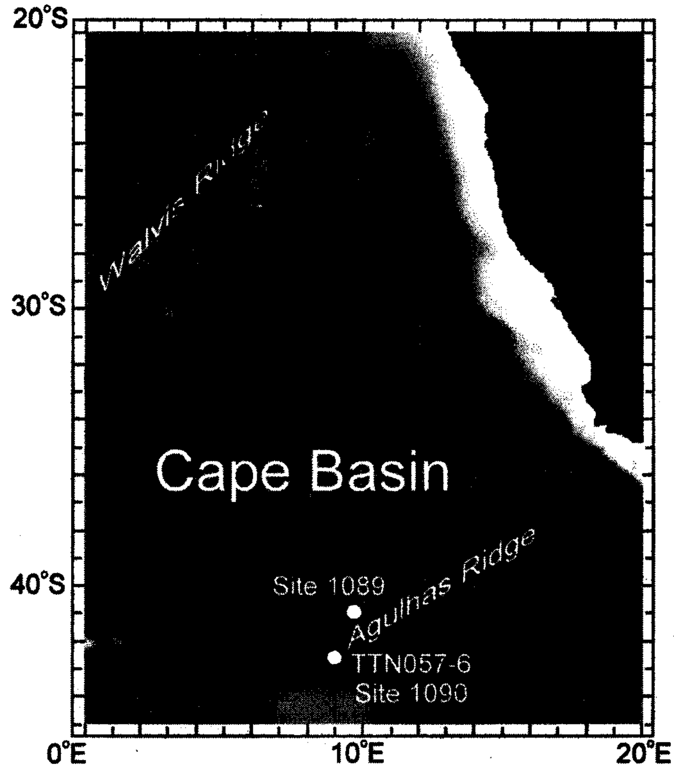

Figure 1. Map of the Cape Basin showing the location of piston and ODP cores used in this study.

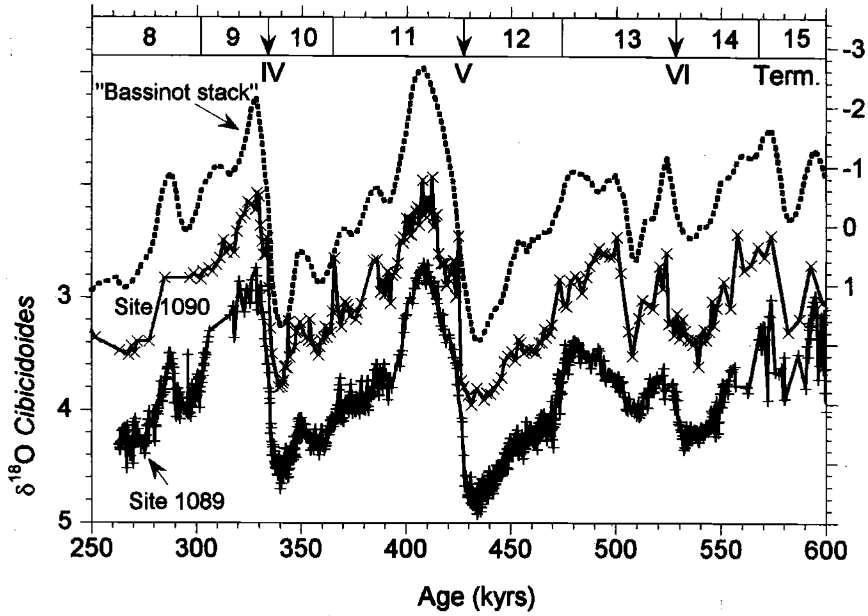

Figure 2. Oxygen isotopes of the benthic foraminifer *Cibicidoides* from sites 1089 (+) and the spliced record of TTN057-6/1090 (X) correlated to the low-latitude stack of Bassinot et al. [1994b]. Position of glacial terminations are indicated by arrows and roman numerals.

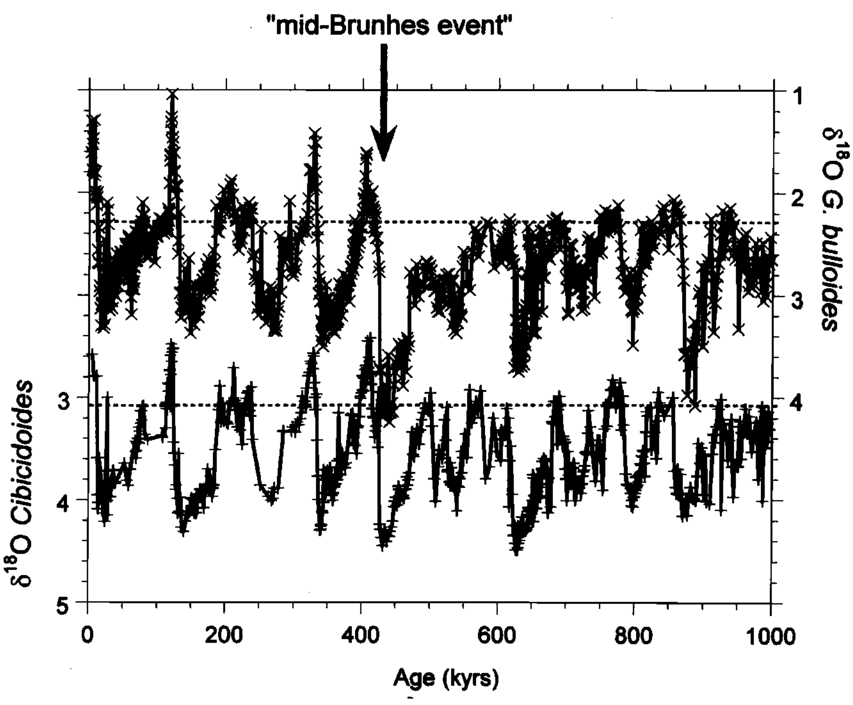

Figure 3. Oxygen isotope records of the benthic foraminifer *Cibicidoides* (+) and planktic foraminifer *G. bulloides* (X) for the last million years from the spliced record of TTN057-6/1090. Horizontal dashed lines indicate approximate interglacial value prior to 420 kyrs for each record. Note the decrease in interglacial values following the "mid-Brunhes event" in both the planktic and benthic records.

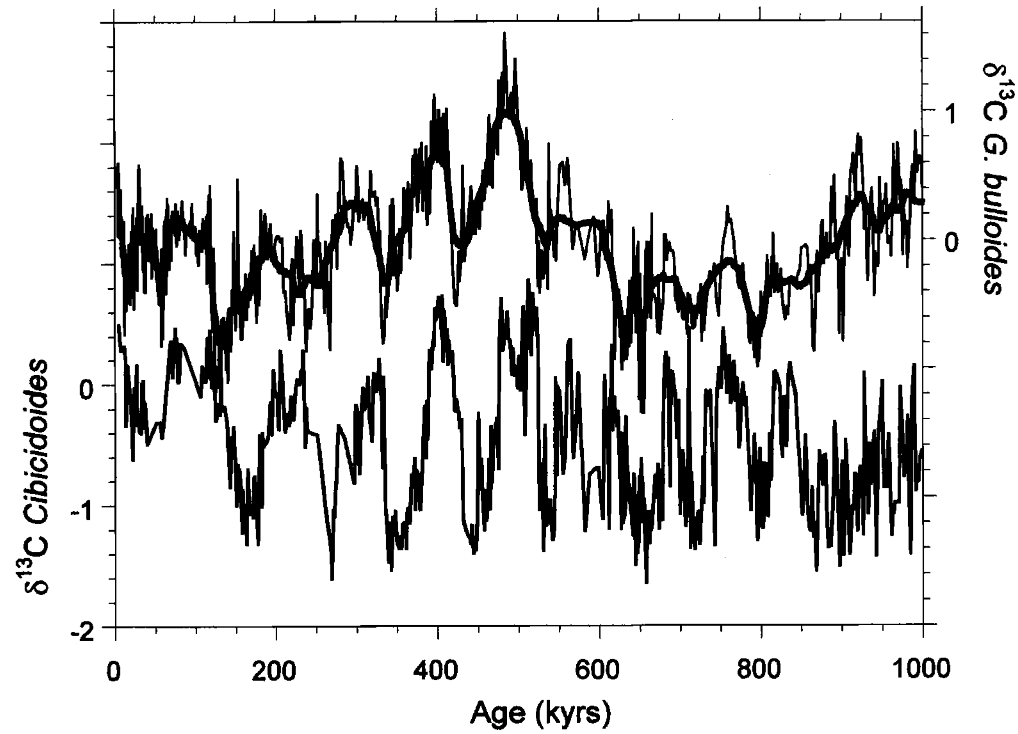

Figure 4. Carbon isotope records of the planktic foraminifer *G. bulloides* (upper signal) and benthic foraminifer *Cibicidoides* (lower signal) for the last million years from the spliced record of TTN057-6/1090. Bold line through the planktic δ^{13}C record is a 20-point running average to emphasize the long-term changes.

et al., 1999]. Benthic δ^{18}O values average 2.7 ‰ during substage 11.3, which is similar to MIS 9 and other interglacial values of the latest Pleistocene (once δ^{18}O values are corrected by 0.4 ‰ to account for a systematic interlaboratory offset between UF and Scripps; [*Mortyn et al.*, in press]). The amplitude of the benthic δ^{18}O signal is distinctly lower prior to stage 12 with a glacial-to-interglacial change of only ~1 ‰ between glacial stage 14 and interglacial stages 13 and 15 (Figure 2).

The δ^{18}O signal of *G. inflata* shows considerable millennial-scale variability during stage 12 (Figure 5), similar to that reported by other studies [*Oppo et al.*, 1998; *King and Howard*, 2000]. Between ~ 432 and 428 kyrs, the δ^{18}O record of *G. inflata* is the first signal to decrease indicating the start of Termination V. Thereafter, the δ^{18}O record of *G. inflata* closely follows the benthic signal except that the magnitude of δ^{18}O change between MIS 12 and 11 is only 1.4 ‰ compared to 2.1 ‰ for benthic δ^{18}O. Millennial-scale δ^{18}O variability is diminished for *G. inflata* during Termination V and substages 11.3 and begins again at ~390 kyrs (Figure 5).

Severe dissolution during substage 11.3 limits the continuity of the planktic δ^{18}O signals of *G. bulloides* and G. *truncatulinoides*. The δ^{18}O record of *G. bulloides* generally follows that of *G. inflata* except during the early part of substage 11.3 when δ^{18}O values of *G. bulloides* are more than 0.5‰ lower than those of *G. inflata.* The change in *G. bulloides* δ^{18}O between MIS 12 and 11.3 is 2.2‰, similar to the benthic signal.

The δ^{18}O record of *G. truncatulinoides* is spotty and displays the greatest variability of all signals. For example, the δ^{18}O difference between MIS 12 and 11 is 2.8 ‰. The earliest part of substage 11.3 at 413 kyrs is marked by the lowest δ^{18}O values and is followed by loss of signal owing to dissolution. A distinct increase in δ^{18}O at ~395 kyrs marks the start of substage 11.24. Two additional δ^{18}O minima occur near substages 11.23 and 11.1 at ~384 and 371 kyrs, respectively.

Carbon isotope values are low during stage 12 and all signals begin to increase at Termination V (i.e., substage 12.0 at 423 kyrs; Figure 6). The increase is most abrupt in the benthic record, which rises by 0.8 ‰ at 427 kyrs. Benthic δ^{13}C reaches maximum values during substage 11.3, although there are distinct millennial-scale oscillations throughout this period. The δ^{13}C signal of *G. inflata* reaches a maximum between 396 and 401 kyrs. Planktic carbon

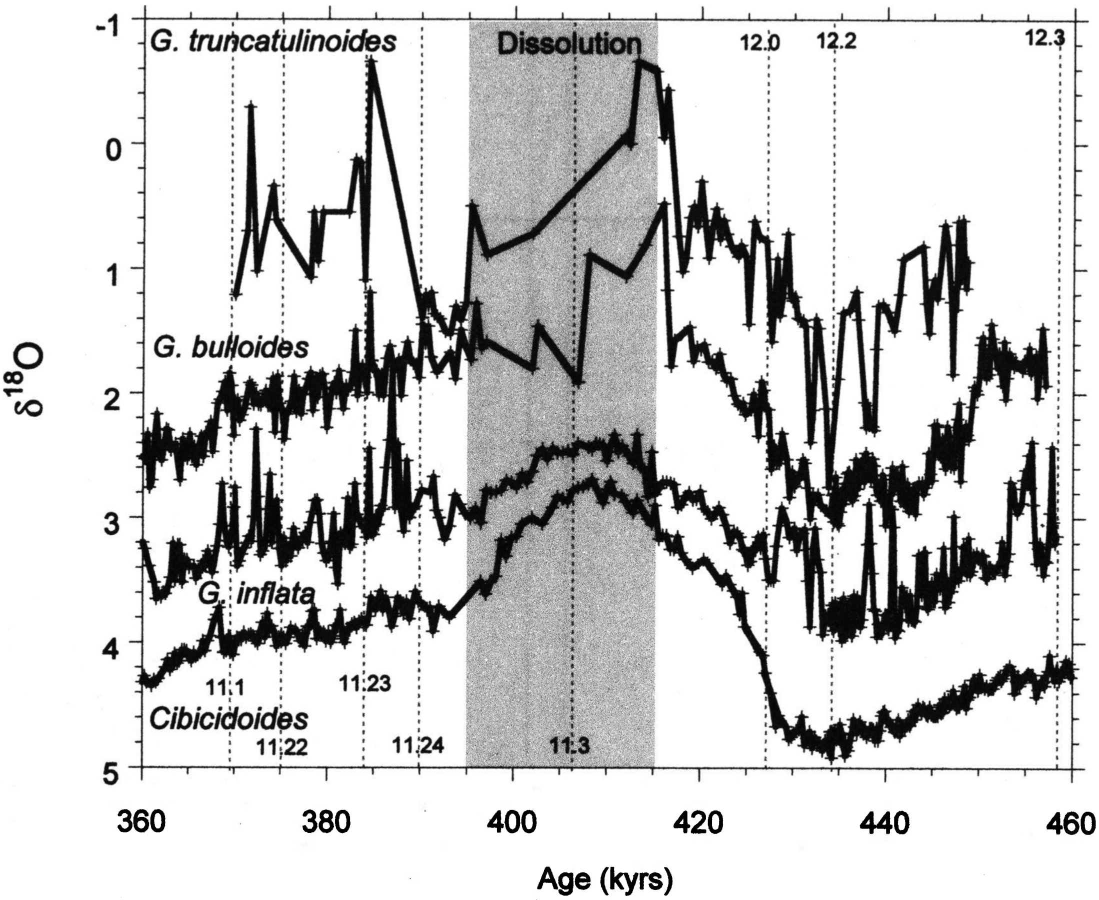

Figure 5. Oxygen isotope records of planktic and benthic foraminifera at site 1089 during MIS 12 and 11. For illustration purposes, 1 ‰ was added to the $\delta^{18}O$ values of *G. bulloides* and 1.5 ‰ was added to *G. truncatulinoides*. Marine isotope stage designations follow Bassinot et al. [1994b]. Shaded area indicates the interval of maximum carbonate dissolution at site 1089.

isotopic values gently decline from their maximum during substage 11.3 towards minimum values in MIS 10. Benthic $\delta^{13}C$ decreases in two steps at 398 and 375 kyrs.

Carbonate Dissolution Indices

Site 1089 displays a "Pacific-type" carbonate stratigraphy with generally high carbonate concentrations (i.e., enhanced preservation) during glacials and low carbonate concentrations (i.e., enhanced dissolution) during interglacials [*Hodell et al.*, in press]. Fragmentation of planktic foraminifera is at a minimum during stage 12 and increases at the start of Termination V reaching a peak at 426 kyrs (Figure 7). A brief decrease in fragmentation occurs during the middle of Termination V (centered on 420 kyrs) and fragmentation increases again at 415 kyrs, reaching maximum values between 415 and 387 kyrs during substage 11.3. The average percent fragmentation decreases slowly throughout the remainder of stage 11 and into glacial stage 10.

Percent carbonate is relatively high during glacial stage 12 and peaks during Termination V at 423 kyrs when percent fragmentation declines (Figure 7). Carbonate content decreases rapidly between 423 and 415 kyrs and low values coincide with maximum fragmentation during early stage 11. At site 1089 (4600 m water depth), planktic foraminiferal assemblages are dominated by the dissolution-resistant species *G. inflata* during stage 11. Similarly, MIS 11 planktic foraminiferal assemblages at site 1090/TTN057-6 (3700 m water depth) are also dominated by *G. inflata*, indicating an increase in dissolution and presumed shoaling of the lysocline [*Hodell et al.*, 2000; *Becquey and Gersonde*, in press].

Ice-Rafted Detritus

Ice-rafted grains consist dominantly of quartz with minor amounts of ash. Distinct millennial-scale variability in IRD accumulation is apparent, similar to that observed

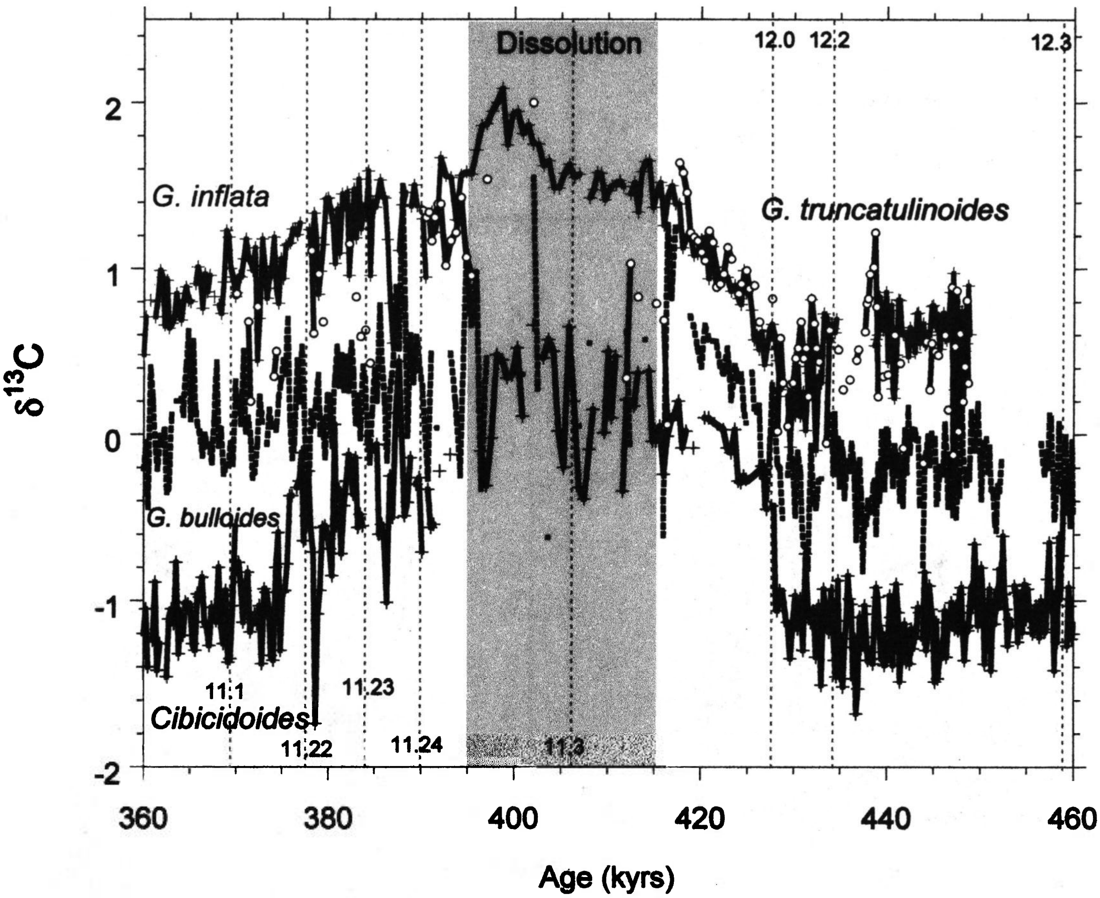

Figure 6. Carbon isotope records of planktic and benthic foraminifera at site 1089 during MIS 12 and 11. Marine isotope stage designations follow Bassinot et al. [1994b]. Gray solid line = *G. bulloides*; open circles = *G. truncatulinoides*; broken line = *G. bulloides*; black solid line = *Cibicidoides*

during the last glaciation (Figure 8; *Kanfoush et al.*, 2000). IRD is abundant during MIS12 until 432 kyrs when it abruptly diminishes, coinciding with the initial decrease in $\delta^{18}O$ values of *G. bulloides* at the onset of Termination V. The disappearance of IRD precedes the increase in benthic $\delta^{18}O$ by several kyrs. Virtually no IRD was delivered to site 1089 between 432 and 395 kyrs, and IRD resumed with the onset of substage 11.24 at ~395 kyrs. This ~37-kyr long period of ice-free conditions during Termination V and MIS 11.3 at site 1089 is similar to results from North Atlantic site 980 where the longest (30-40 kyr) interval of ice-free conditions and damped millennial-scale variability occurred during stage 11 [*McManus et al.*, 1999].

DISCUSSION

The Mid-Brunhes Transition (Site 1090)

The planktic and benthic oxygen isotope results from site 1090 provide strong support for a mid-Brunhes climate event in the subantarctic South Atlantic. Beginning with MIS 11, interglacial stages were marked by warmer temperatures and/or less ice volume than those before 420 kyrs (Figure 3). Our results are supported by the long planktic $\delta^{18}O$ record at ODP site 704 on Meteor Rise at 47°S that also indicates substantially warmer interglacials in the South Atlantic after 400 kyrs [see Figure 6 of *Hodell*, 1993]. This trend is also apparent in the low-latitude stack of *Bassinot et al.* [1994b] (Figure 2), suggesting that the mid-Brunhes event was not limited to the South Atlantic. Our results are consistent with *Jansen et al.* [1986] who suggested that the mid-Brunhes event marked a transition to more humid, interglacial conditions in the southern hemisphere.

Unlike the abrupt change in the $\delta^{18}O$ record during the mid-Brunhes, the changes in carbon isotopes were part of a longterm oscillation that reached a maximum in the mid-Brunhes. High $\delta^{13}C$ values have been reported during the mid-Brunhes in records of planktic and benthic foraminif-

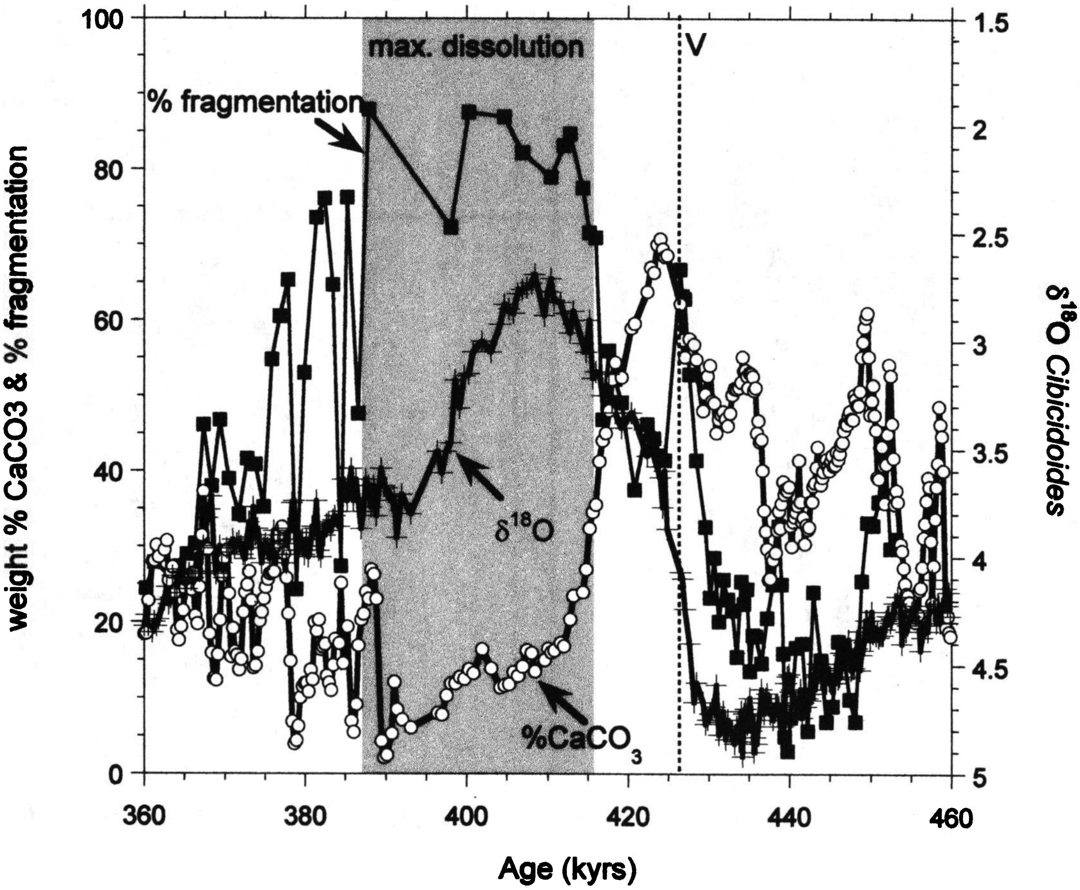

Figure 7. Weight percent $CaCO_3$, percent fragmentation of planktic foraminifera, and benthic $\delta^{18}O$ at site 1089 during MIS 12 and 11. Vertical dashed line represents substage 12.0.

era, fine-fraction carbonate, and bulk carbonate from a variety of locations [*Mead et al.*, 1991; *Hodell*, 1993; *Shackleton and Hall*, 1991; *Hodell et al.*, 2000]. The planktic $\delta^{13}C$ signal at site 1090 correlates remarkably well with the well-known mid-Brunhes dissolution cycle (Figure 9), which shows maximum preservation centered at ~150 and 700 kyrs and maximum dissolution centered at ~400 and 950 kyrs [*Droxler et al.*, 1990; *Bassinot et al.*, 1994a].

The similarity of the planktic $\delta^{13}C$ and "Brunhes dissolution cycle" suggests that they may be causally linked (Figure 9). *Bassinot et al.* [1994a] concluded that the change in carbonate ion concentration during the Bruhnes occurred in all ocean basins and affected the entire water column [*Droxler et al.*, 1990]. If so, the link between $[CO_3^{2-}]$ and $\delta^{13}C$ may be direct in that the $\delta^{13}C$ of *G. bulloides* has been shown to increase by -0.013 ‰ per μmol kg^{-1} decrease in dissolved $[CO_3^{2-}]$ [*Spero et al.*, 1997]. Carbon isotope values during stage 11 are ~0.4 ‰ higher than the Holocene which would mean that $[CO_3^{2-}]$ was ~30 μmol kg^{-1} lower during stage 11 than Holocene values if all the $\delta^{13}C$ difference were due to the "carbonate ion effect." Benthic $\delta^{13}C$ during stage 11 is only 0.2 ‰ lower than the Holocene but the magnitude of the "carbonate ion effect" for *Cibicidoides* is not known. The saturation horizon today in the Cape Basin is at 4300 m and evidence of dissolution at site 1090 (3700 m) during stage 11 suggests that the lysocline shoaled by at least 600 m relative to the Holocene. Carbonate saturation decreases linearly in the Cape Basin today at a rate of about 20 μmol kg^{-1} per km, suggesting that $[CO_3^{2-}]$ during stage 11 was at least 12 μmol kg^{-1} lower than today. This could account for a minimum of 0.16 ‰ increase in the $\delta^{13}C$ of *G. bulloides* if $[CO_3^{2-}]$ decreased by the same amount in surface waters.

Alternatively, the observed changes in $[CO_3^{2-}]$ and $\delta^{13}C$ may result from fundamental long-term changes in the marine carbonate-carbon cycle that involves transfers between global reservoirs. For example, increased carbonate and organic matter deposition on the shelves during high stands of sea level would both increase dissolution in the deep sea ["Coral Reef Hypothesis" of *Berger*, 1982] and the $\delta^{13}C$ of

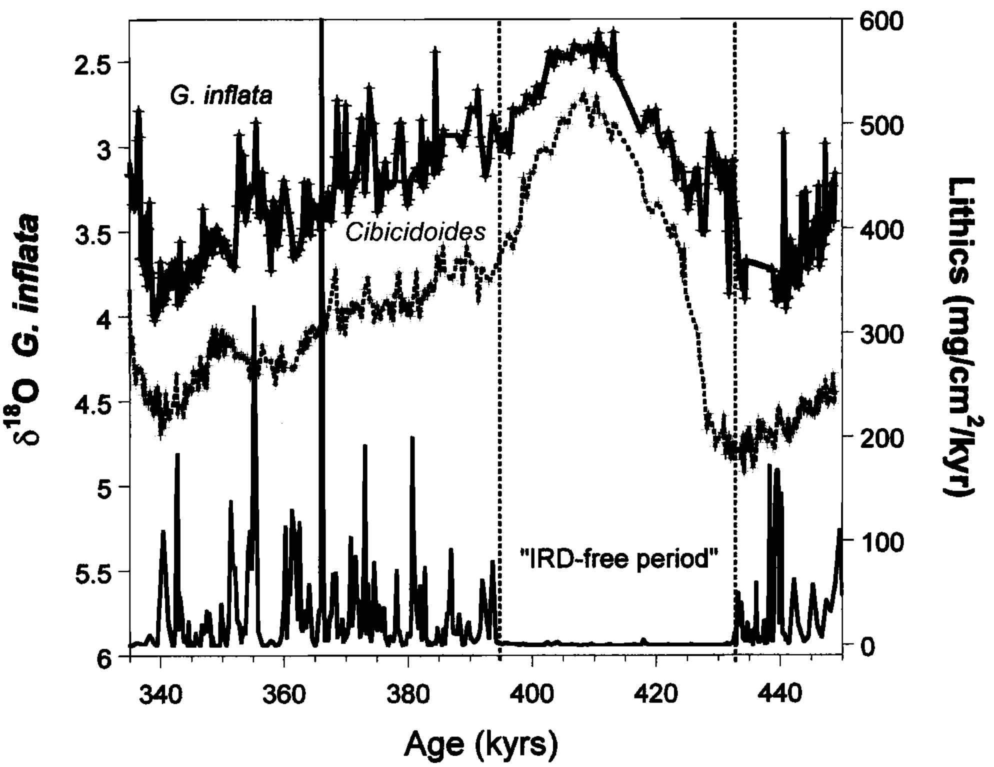

Figure 8. Accumulation rate of ice-rafted detritus at site 1089 compared to the $\delta^{18}O$ of benthic (*C. wuellerstorfi*) and planktic (*G. inflata*) foraminifera. Note the extended period of IRD-free conditions between 432 and 395 kyrs.

oceanic HCO_3^-. Although this may explain carbonate dissolution and high $\delta^{13}C$ during stage 11 when evidence exists for +20-m higher sea level than today [*Hearty et al.*, 1999; *Brigham-Grette*, 1998], there is no evidence for high sea level during stage 13. In fact, MIS 13 was a weak interglacial with presumably lower sea level than interglacials after 420 kyrs, yet carbonate dissolution was intense and $\delta^{13}C$ values were at their highest (Figure 9). *Bassinot et al.* [1994a] suggested that the long-term dissolution cycle may have resulted from changes in Ca^{2+} flux delivered to the ocean by rivers that, in turn, were related to long-term isostatic adjustment or past changes in the intensity of chemical weathering. An increase in oceanic carbonate production relative to alkalinity delivered by rivers would also cause a rise in the lysocline and CCD, but these processes alone can not account for the attendant increase in $\delta^{13}C$ values unless the change was due to the "carbonate ion effect" [*Spero et al.*, 1997].

Sequence of Events at Termination V and MIS 11

The timing of change during Termination V and MIS 11 provides information on leads and lags in the climate system and can aid in identifying the mechanisms of climate change. Figure 10 shows the change in each of the measured parameters relative to summer insolation at a latitude of 65° in both hemispheres. Because we employed the chronology of *Bassinot et al.* [1994b], an implicit assumption in this comparison is that global ice volume is forced by summer insolation at 65°N [*Imbrie and Imbrie*, 1980]. Nonetheless, the relative phase relationships among parameters in site 1089 will hold regardless of which time scale is used. The chronological sequence of events beginning with MIS 12 presented below is numerically keyed to Figure 10 and includes discussion of the possible causes for each event.

Event 1. (437 kyrs; Stage 12.2) Summer insolation minimum at 65°N. Not only is substage 12.2 marked by minimum solar radiation at 65°N but insolation is also low at 65°S throughout most of stage 12. Insolation changes due to precession are out of phase between the hemispheres, but the magnitude of the signals is modulated by orbital eccentricity. During the mid-Brunhes when eccentricity was low, the magnitude of interhemispheric assymetry in insolation was reduced resulting in relatively cool summers in both polar regions during stage 12. High-latitude insolation changes were dominated by obliquity and were in-phase for the same season between the hemispheres. This orbital geometry may have permitted the buildup of "excess ice"

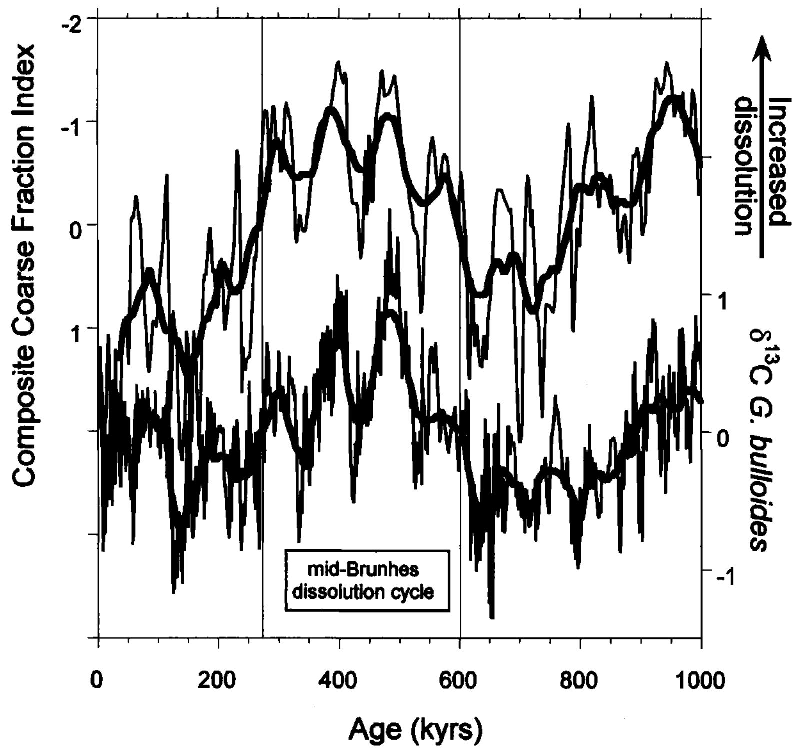

Figure 9. Comparison of the "Composite Coarse Fraction Index" of Bassinot et al. [1994a] with the $\delta^{13}C$ record of *G. bulloides* site TTN057-6/1090. Note general parallel trends in the dissolution index and planktic $\delta^{13}C$ record during the last million years. The "mid-Brunhes dissolution cycle" is indicated between 275 and 600 kyrs.

during stage 12. "Excess ice" is defined as the volume of ice that is greater the last glacial maximum, which may have been as much as 20-m sea level equivalent for MIS 12 [*Rohling et al.*, 1998]. Another contributing factor to the growth of "excess ice" may have been the fact that stage 13 was a relatively weak interglacial (Figures 2 and 3), thereby permitting the rapid growth of large ice sheets during stage 12.

Event 2. (433 kyrs; late stage 12.2) Decrease in planktic $\delta^{18}O$ and cessation of IRD delivery. Warming at 433 kyrs is inferred by a decrease in the planktic $\delta^{18}O$ records of *G. inflata* and *G. truncatulinoides* and, to a lesser extent, *G. bulloides*. This event heralds the start of Termination V. *G. inflata* is an intermediate-dweller that calcifies in a water depth between 100 and 300 m, whereas *G. truncatulinoides* is a deep-dweller that calcifies below 250 m [*Niebler et al.*, 1999]. Therefore, warming occurred in intermediate and deep surface waters, which may reflect increased SST at higher latitude than site 1089 (41°S), perhaps near the Polar Front. Support for warming of Antarctic surface waters comes from diatom SST estimates at 53°S in the South Atlantic that increase at the same time [~433 kyrs; *Kunz-Pirrung et al.*, in press]. This warming of high-latitude surface waters in the South Atlantic coincided precisely with the abrupt decline of IRD in site 1089 (Figure 8), indicating that warm SST prevented icebergs from reaching 43°S. The $\delta^{18}O$ record of *G. bulloides* also indicates the start of a warming trend of surface waters, but the signal is less variable than the deeper-dwelling species. The warming and disappearance of IRD at 433 kyrs clearly preceded the change in ice volume (benthic $\delta^{18}O$) and deep water circulation (benthic $\delta^{13}C$) (Event #3) by about 4 kyrs. This phasing constitutes an early response of the Southern Ocean as has been reported for other deglaciations [*Imbrie et al.*, 1992; 1993] and millennial-scale climate change [*Charles et al.*, 1996].

Event 3. (427 kyrs; Termination V) Summer insolation maximum at 65°N. Decrease in benthic $\delta^{18}O$ and increase in benthic $\delta^{13}C$. At 427 kyrs, ice volume began to decrease and deep-water circulation changed abruptly, signaling an increase in North Atlantic Deep Water (NADW) production. The increase in northern hemisphere summer insolation at 427 kyrs was small, which has led some workers to question how such a small forcing could generate such a large climate response [i.e., the greatest deglaciation of the late Pleistocene; *Muller and McDonald*, 1997]. Because

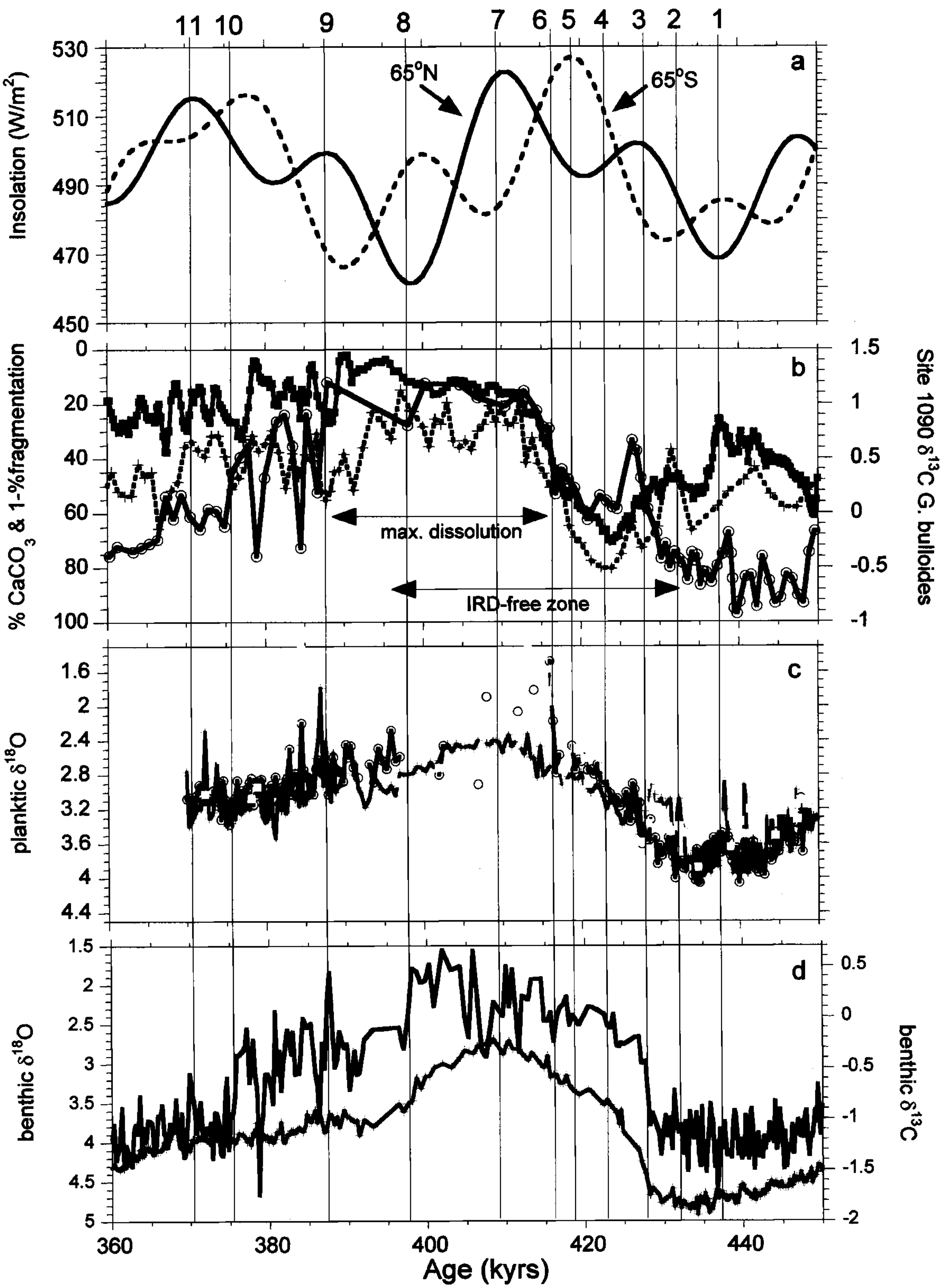

Figure 10. Sequence of events during MIS 12 and 11. Numbered events along top graph are keyed to discussion in text. (a) Summer insolation at 65°N (June 21) and 65°S (Dec. 21); (b) weight percent $CaCO_3$ (gray solid line) and foraminiferal fragmentation (solid black line) at site 1089, and $\delta^{13}C$ of *G. bulloides* (broken line) at site TTN057-6/1090. Fragmentation is expressed as 100-%fragmentation so that lower numbers correspond to increased dissolution as it does for %$CaCO_3$. (c) Oxygen isotopes of *G. bulloides* (solid line, open circles), *G. inflata* (solid gray line), and *G. truncatulinoides* (gray squares) at site 1089. (d) Oxygen (gray line) and carbon (black line) isotopes of the benthic foraminifer *Cibicidoides* at site 1089.

large ice sheets are inherently unstable, the "excess ice" that developed during stage 12 may have been highly susceptible to decay. Even the small increase in northern hemisphere summer insolation at 427 kyrs might have been enough to initiate Termination V [*Paillard,* 1998]. In addition, 427 kyrs marks the start of an increase in summer insolation at 65°S, which would have strongly reinforced the deglaciation process between ~427 and 424 kyrs (Figure 10).

Event 4. (424 kyrs; mid-point of Termination V) Carbonate preservation event and planktic $\delta^{13}C$ minimum. The midpoint of Termination V (stage 12.0) is marked by a carbonate preservation spike. Similar events have been reported for the last deglaciation [*Berger*, 1977] and other terminations [*Peterson and Prell*, 1985; *Hodell et al.*, in press]. The deglacial preservation event has been variously attributed to forest regrowth following glaciation [*Shackleton,* 1977], shelf-carbon extraction [*Broecker*, 1981], changes in the rain ratio of orgC/$CaCO_3$ [*Archer and Maier-Reimer*, 1994], or nutrient utilization in the high latitudes [for review, see *Sigman and Boyle*, 2000]. The transient increase in carbonate preservation may reflect a redistribution of alkalinity and DIC in the ocean, which has been referred to as "carbonate compensation" [*Broecker and Peng,* 1987]. Alternatively, the carbonate signal may represent a lagged response to sea level changes, whereby the lysocline adjusts to maintain alkalinity balance between riverine input and marine carbonate burial [*Hodell et al.*, in press].

The carbonate preservation event on Termination V coincides with a decrease in planktic $\delta^{13}C$, which argues against forest growth or shelf-carbon buildup as the cause because $\delta^{13}C$ should increase as organic carbon is sequestered in either terrestrial or marine environments. The coincidence of increased preservation and low $\delta^{13}C$ is consistent with the "Respiratory CO_2 model", which calls for a decreases in the rain ratio of orgC to $CaCO_3$ at terminations [*Archer and Maier-Reimer*, 1994]. The initial decrease in organic matter rain and burial at Termination V would result in a carbonate preservation event and a decrease in the $\delta^{13}C$ of oceanic HCO_3^-. There is abundant evidence for increased carbonate flux during stage 11 in the Southern Ocean sediments [*Howard*, 1997; *Howard and Prell*, 1994; *Shipboard Scientific Party*; 1999; *Hodell et al.*, 2000], which may have also contributed to the carbonate preservation event on Termination V at site 1089 before dissolution reached its maximum in stage 11.

Event 5. (419 kyrs; stage 11.3) Summer insolation maximum at 65°S. The maximum in summer insolation at high southern latitudes at 419 kyrs reinforced the deglaciation process when northern hemisphere summer insolation declined slightly. *Sarnthein and Tiedemann* [1990] noted that the length of Termination V was longer than other deglaciations. This long duration may be related to the peculiar orbital geometry at the time. Because of low eccentricity and weak insolation forcing, the deglaciation process at Termination V may have required the sequential and alternating increases of high-latitude insolation in both hemispheres between 429 and 410 kyrs (Figure 10).

Event 6. (417 kyrs; stage 11.3) Abrupt decrease in $\delta^{18}O$ of G. bulloides and G. truncatulinoides and start of stage 11 dissolution maximum. Shortly after the southern hemisphere insolation maximum, the $\delta^{18}O$ of *G. bulloides* and *G. truncatulinoides* decreases abruptly indicating a warming of surface waters in the South Atlantic. Curiously, a similar magnitude warming is not recorded by the more continuous record of the intermediate-dwelling *G. inflata*. The pronounced warming in early stage 11.3 probably represents a response to local insolation forcing at 419 kyrs [*Kim et al.*, 1998], and constitutes the warmest period of stage 11 in the subantarctic South Atlantic. The 2-kyr lag between insolation forcing and planktic $\delta^{18}O$ response may be related partly to the assumption of a constant lag between insolation and benthic $\delta^{18}O$ used to construct the age model [*Bassinot et al.*, 1994b]. This time also marks the start of intense carbonate dissolution and the heaviest $\delta^{13}C$ values of planktic foraminifera. Intense dissolution in stage 11 has been attributed to the massive buildup of coral reefs in shallow-water environments [*Droxler et al.*, 1997] and an increase in oceanic carbonate productivity that occurred in the Southern Ocean [*Howard and Prell*, 1994; *Hodell et al.*, 2000]. These processes resulted in a decrease in carbonate ion concentrations, a shoaling of the lysocline and CCD, and perhaps an increase in atmospheric pCO_2 levels [*Droxler et al.*, 1997].

Event 7. (410 kyrs; stage 11.3) Summer insolation maximum at 65°N and minimum at 65°S. Minimum in benthic $\delta^{18}O$. Peak summer insolation in the northern hemisphere occurred at 410 kyrs and coincides with minimum ice volume during stage 11 as indicated by the lowest values of benthic $\delta^{18}O$. This time also marks a minimum in summer insolation at 65°S and the end of the stage 11 altithermal in the southern hemisphere.

Event 8. (398 kyrs; stage 11.24) Summer insolation minimum at 65°N. Increase in benthic $\delta^{18}O$ and decrease in benthic $\delta^{13}C$. Resumption of IRD delivery to site 1089. The end of substage 11.3 at ~398 kyrs is marked by cooling and/or increased ice volume and a reduction in deep-water circulation, probably related to decreased NADW production. This event represents the onset of neoglacial conditions during stage 11 and is marked by substage 11.24 of

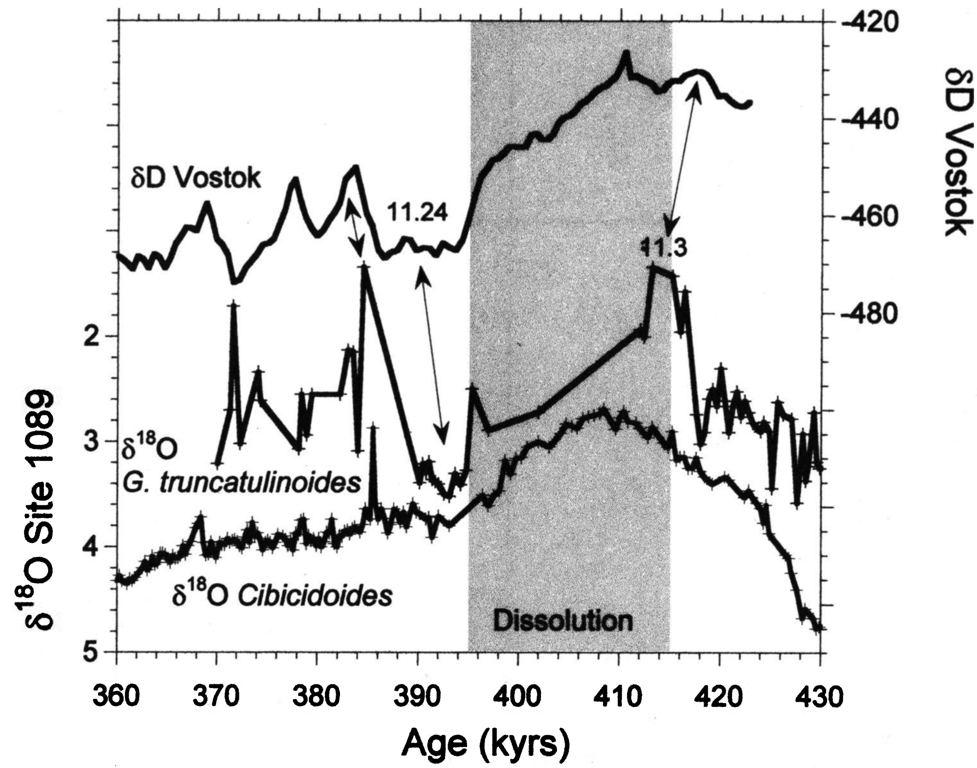

Figure 11. Comparison of the $\delta^{18}O$ records of *G. truncatulinoides* and *Cibicidoides* at site 1089 with the δD record of the Vostok ice core during MIS 11 [Petit et al., 1999].

Bassinot et al. [1994b]. Cooling of high-latitude surface water at ~395 kyrs permitted icebergs to reach 43°S once again and IRD reappeared at site 1089 (Figure 8).

Event 9. (388 kyrs) Summer insolation maximum at 65°N and minimum at 65°S. Millennial-scale planktic $\delta^{18}O$ minima. End of stage 11 dissolution maximum. This event marks the end of cold substage 11.24 and the onset of millennial-scale variability in planktic $\delta^{18}O$. Although the return of millennial-scale variability in planktic $\delta^{18}O$ may be related to a relaxation of intense carbonate dissolution, it is most apparent in the $\delta^{18}O$ record of *G. inflata* that is continuous throughout this interval. A brief warming of surface waters is indicated by the $\delta^{18}O$ records of *G. inflata* and *G. truncatulinoides*, and probably represents substage 11.23 of *Bassinot et al.* [1994b]. Dissolution intensity began to subside as evidenced by a decrease in fragmentation.

Event 10. (376 kyrs) Decrease in benthic $\delta^{13}C$. An abrupt decrease in benthic $\delta^{13}C$ at 376 kyrs indicates decreased NADW input to the Southern Ocean. This represents the second of two abrupt changes in deep-water circulation (the first occurred at 398 kyrs) that reduced benthic $\delta^{13}C$ values from their maximum during substage 11.3 to minimum values during stage 10.

Event 11. (371 kyrs) Summer insolation maximum at 65°N. This event is associated with a millennial-scale decrease in planktic and benthic $\delta^{18}O$ (Figure 5) that corresponds to substage 11.1 of *Bassinot et al.* [1994b]. It represents the last brief warming before the end of stage 11 and the progressive increase of $\delta^{18}O$ values into glacial stage 10.

Comparisons to the Vostok Ice Core

The long Vostok ice core record extends through the last four climatic cycles to 420 kyrs, including MIS 11 [*Petit et al.*, 1999]. However, ice disturbance near the base of the core makes it dubious whether the warmest period of MIS 11 was recorded and whether pCO_2 estimates are reliable. By comparing the records from site 1089 with the long Vostok ice core, we can evaluate whether Vostok faithfully captures the peak conditions of stage 11. The δD record of Vostok on the GT4 time scale [*Petit et al.*, 1999] is most similar to the $\delta^{18}O$ record of *G. truncatulinoides* at site 1089 despite the discontinuous record in the stage 11 dissolution maximum (Figure 11). Because *G. truncatulinoides* can live at depths >400m, it is likely recording temperature changes of surface waters from higher latitude than 41°S, perhaps near the Polar Front. The comparison be-

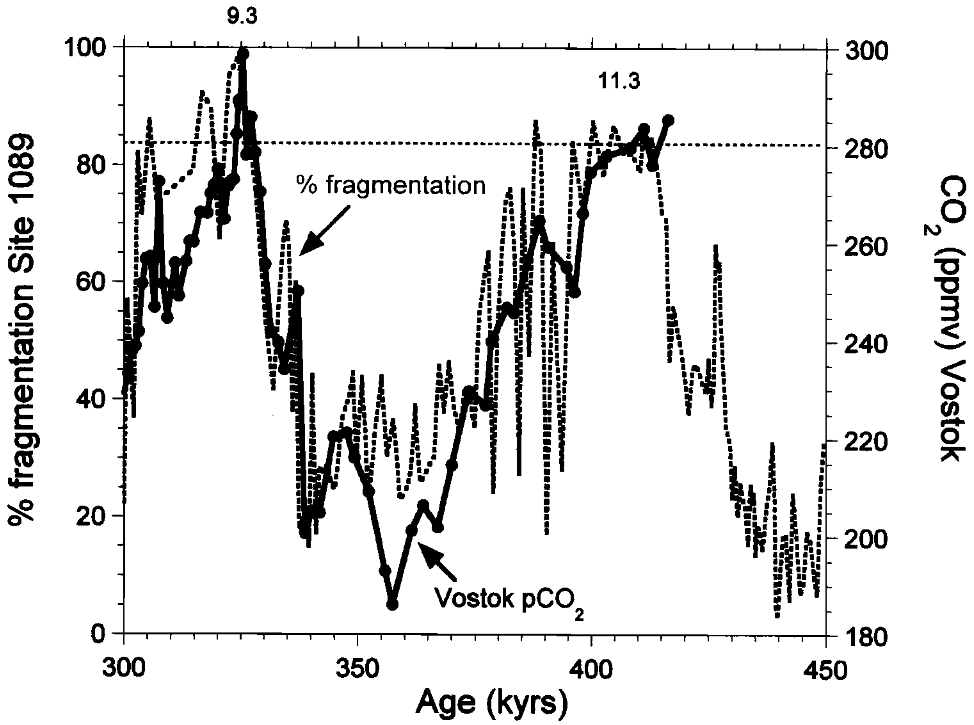

Figure 12. Comparison of the percent fragmentation of planktic foraminifera (a dissolution proxy) at site 1089 with the pCO_2 record of the Vostok ice core [Petit et al., 1999] during MIS 9 through 12.

tween site 1089 and Vostok suggests that the peak warmth of stage 11 is accurately captured at Vostok. This implies that stage 11 was no warmer than other interglacials of the latest Pleistocene, a conclusion supported by oxygen isotope records of Southern Ocean cores [*Hodell et al.*, 2000]. Altithermal conditions between ~420 and 410 kyrs were followed by a gradual cooling throughout substage 11.3. An abrupt decrease in temperature at 395 kyrs marked the beginning of substage 11.24, which is well expressed in both Vostok δD and site 1089 $\delta^{18}O$ records (Figure 11). This was followed by a series of three millennial-scale oscillations in Antarctic temperature during late stage 11.

Even more remarkable is the correlation between Vostok pCO_2 and the % fragmentation record at site 1089 (Figure 12). For example, the detailed structure of the records is nearly identical during Termination IV and stage 9. Atmospheric pCO_2 during stage 11 was 280 ppmv, which is equal to the pre-industrial concentration of CO_2 in the Holocene. In Vostok, pCO_2 levels during stage 9.3 were higher than stage 11.3 by ~20 ppmv. Similarly, the percent fragmentation during stage 9.3 at site 1089 was higher than stage 11.3. The relative magnitude of the differences of %fragmentation and pCO_2 between stages 11.3 and 9.3 supports the observation that pCO_2 was lower in stage 11 than stage 9.3 (and 5.5), and was similar to Holocene values. Furthermore, the high correlation between pCO_2 and %fragmentation suggests a tight coupling of the marine carbonate system and atmospheric pCO_2 during the mid-Brunhes.

During stage 12, the lysocline was below 4600 m as marked by the excellent preservation of foraminifera at site 1089 (Figure 7). During stage 11, the lysocline in the Cape Basin shoaled to at least 3700 m as evidenced by increased carbonate dissolution at site 1090. This represents a shoaling of at least 900 m over Termination V. Calcite saturation decreases linearly in the Cape Basin at a rate of ~20 $\mu mol\ kg^{-1}\ km^{-1}$, which implies a change of $[CO_3^{2-}]$ of at least 18 $\mu mol\ kg^{-1}$ over Termination V. This change is certainly large enough to have had an impact on atmospheric CO_2 (at least a few tens of μatm). Intense carbonate dissolution lasted for an extended period of time (~25,000 yrs) during stage 11 (Figure 7), which may have kept pCO_2 levels high and extended the duration of warmth in the absence of strong insolation forcing due to low eccentricity.

Because carbonate dissolution was more intense during stage 11 than the Holocene, one might expect that pCO_2 would have been higher 400,000 yrs ago. Yet, we have argued that the Vostok pCO_2 record accurately reflects a pCO_2 level of 280 ppmv during stage 11, similar to the Holocene pre-Industrial value. Accompanying enhanced dissolution during stage 11 was an increase in the $\delta^{13}C$ of planktic foraminifera (Figure 9). Planktic $\delta^{13}C$ values during stage 11 are substantially greater than any other interglacial in the Pleistocene except for stage 13. Part of this increase may have been related directly to the "carbonate ion effect" [*Spero et al.*, 1997], but it is also likely that increased organic matter was sequestered in terrestrial and/or marine environments during stage 11. Higher sea level during MIS 11 may have increased organic matter deposition on the shelves and/or more humid conditions on the continents may have increased the size of the terrestrial biosphere [*Rousseau*, 1999]. These processes would have reduced atmospheric pCO_2 and may have counteracted the rise in pCO_2 expected from lowered deep-sea $[CO_3^{2-}]$.

Although the correlation between foraminiferal fragmentation and pCO_2 is suggestive (Figure 12), the causal mechanism cannot be identified until the phasing of carbonate dissolution and pCO_2 can be determined. This will require an independent means to correlate between site 1089 and the Vostok ice core [*Mortyn et al.*, in press].

CONCLUSIONS

Stage 11 has been touted as an analog for Holocene climate because the Earth's orbital configuration 400,000 years ago was similar to that of today. But our analysis of stage 11, in the context of Pleistocene climate evolution, has revealed several differences between stage 11 and the Holocene that suggest caution in carrying the "stage 11-Holocene analogy" too far. Stage 11 followed a substantially stronger glacial period (stage 12) than the Holocene and coincided with the "mid Brunhes event", which marked a mode shift toward stronger interglacial conditions in the late Pleistocene. With respect to the long-term oscillation of dissolution and $\delta^{13}C$ in the Brunhes, stage 11 was at the peak in the cycle whereas the Holocene is near a low or rising limb of the oscillation (Figure 9). As a result, the sequence of events enumerated here for Termination V and stage 11 (Figure 10) may not play out exactly the same for the last deglacial-Holocene sequence even in the absence of anthropogenic effects.

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