Carbon reservoir changes preceded major ice-sheet expansion at the mid-Brunhes event

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ABSTRACT

The beginning of the mid-Brunhes event ca. 430 ka coincided with the largest-amplitude change in δ^{18}O in the global ocean over the past 6 m.y. This large δ^{18}O change recorded a major ice-sheet expansion that cannot be explained by small changes in orbital forcing. Our recent studies at Ocean Drilling Program Site 1143 from the South China Sea show that this large δ^{18}O change was preceded by a significant negative δ^{13}C shift. A global survey of long deep-sea records has revealed periodic δ$^{13}C_{max}$ episodes (i.e., maximum positive values of δ^{13}C), and both major ice-sheet expansion events in the Pleistocene (the mid-Brunhes event and the middle Pleistocene revolution) were preceded by δ$^{13}C_{max}$ episodes followed by negative δ^{13}C shifts. This new finding suggests that disturbance in carbon reservoirs leads to major growth of ice-sheet size and challenges the prevalent concept of Arctic control of glacial cycles. Because Earth is now passing again through a δ$^{13}C_{max}$ episode, it is crucial to understand the causal relationship between the successive δ^{13}C changes and ice-sheet growth events.

Keywords: carbon isotopes, ice sheet, mid-Brunhes event, South China Sea.

INTRODUCTION

The largest-amplitude change in oxygen isotope composition (δ^{18}O) of the past 6 m.y. occurred in the global ocean ca. 430 ka, the marine oxygen isotope stage (MIS) 12-11 boundary (Droxler and Farrell, 2000). From 20 m below the last glacial minimum low-stand (Rohling et al., 1998), the global sea level rose to 20 m above the present high-stand, probably at the expense of Antarctic ice by partial ice-sheet collapse (Hearty et al., 1999). The great expansion of ice-sheet size was followed by a period of enhanced deep-water carbonate dissolution in the ocean, known as the mid-Brunhes event (Jansen et al., 1986). The event cannot be explained simply by the Milankovitch response to the orbital forcing, because the total change of that response at the MIS 12-11 boundary was much too small to account for the large-amplitude effects (Stage 11 problem; Imbrie et al., 1993), and the origin of the mid-Brunhes event remains enigmatic.

Our studies on deep-sea cores from the South China Sea have found that the mid-Brunhes event was preceded by significant changes in the oceanic carbon reservoir. All long-term deep-sea records of the global ocean show enriched carbon isotope values (δ^{13}C) during MIS 13 followed by a negative δ^{13}C shift that ended at the mid-Brunhes event. This new finding suggests that the great ice-sheet expansion at the mid-Brunhes event might have been a response to the changes in the global carbon system that in turn were related to changes in the low-latitude upper ocean.

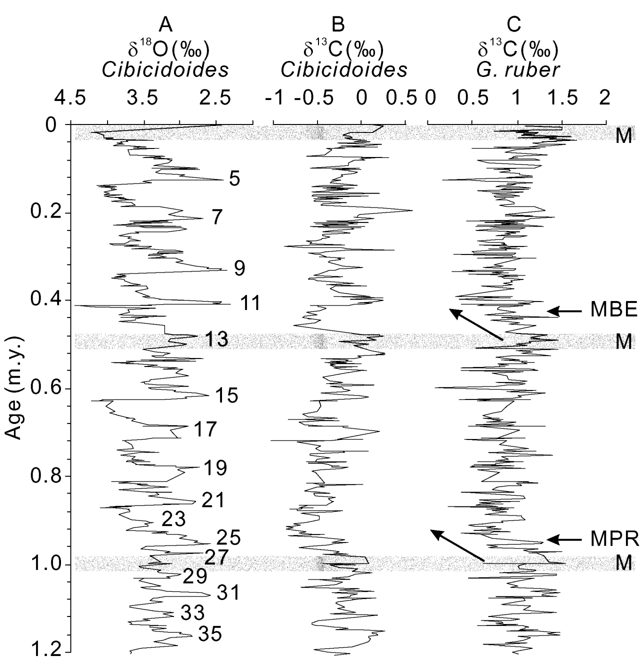

Figure 1. Isotope records spanning 1.2 m.y. from Ocean Drilling Program Site 1143, South China Sea. A: δ^{18}O values of *Cibicidoides* spp. B: δ^{13}C values of *Cibicidoides* spp. C: δ^{13}C values of *Globigerinoides ruber*. Gray bands denote δ$^{13}C_{max}$ events (M) that preceded mid-Brunhes event (MBE) and mid-Pleistocene revolution (MPR). Numbers labeling δ^{18}O curve indicate marine oxygen isotope stages.

CARBON ISOTOPE EVIDENCE

Ocean Drilling Program (ODP) Site 1143 is located in the southern South China Sea (9°22′N, 113°17′E; water depth 2772 m), within the Nansha (''Dangerous Ground'') coral reef area (Wang et al., 2000). High-resolution (nearly 2.5 k.y. interval) stable isotope analyses of planktonic (*Globigerinoides ruber*) and benthic foraminifers (*Cibicidoides* spp.) in the upper, 189.47-m-long core section, in combination with biostratigraphic data, show that the section covers the last 5 m.y. (Tian et al., 2002). A distinguished feature in the δ^{13}C curves is the occurrence of long-term cycles of 400–500 k.y. superimposed on high-frequency fluctuations, and the δ^{13}C sequence is periodically punctuated by ^{13}C-rich values that we refer to hereafter as carbon isotope maximum, or δ$^{13}C_{max}$. An example is the δ$^{13}C_{max}$ value at MIS 13 (530–470 ka). As seen from Figure 1, the plankton δ^{13}C reached almost 1.5‰ at MIS 13, then decreased to ~0.4‰ at the end of MIS 12 with a baseline shift of ~0.3‰, and increased again until the next δ$^{13}C_{max}$ was reached at MIS 1–3. The benthic δ^{13}C was ~0.2‰ at MIS 13, followed by a drastic negative excursion of 0.8‰ during MIS 12, and then an increase again up to MIS 11; the baseline shift of 0.3‰ was similar to that of the plankton. The unprecedented expansion of ice sheets at MIS 12, as shown by benthic δ^{18}O values, occurred at the end of the δ^{13}C shift (Fig. 1), suggesting a possible causal relationship between the δ$^{13}C_{max}$ and the mid-Brunhes event.

A similar sequence of events is seen also in the middle Pleistocene. A δ$^{13}C_{max}$ episode corresponding to MIS 25–28, ca. 1.00–0.95

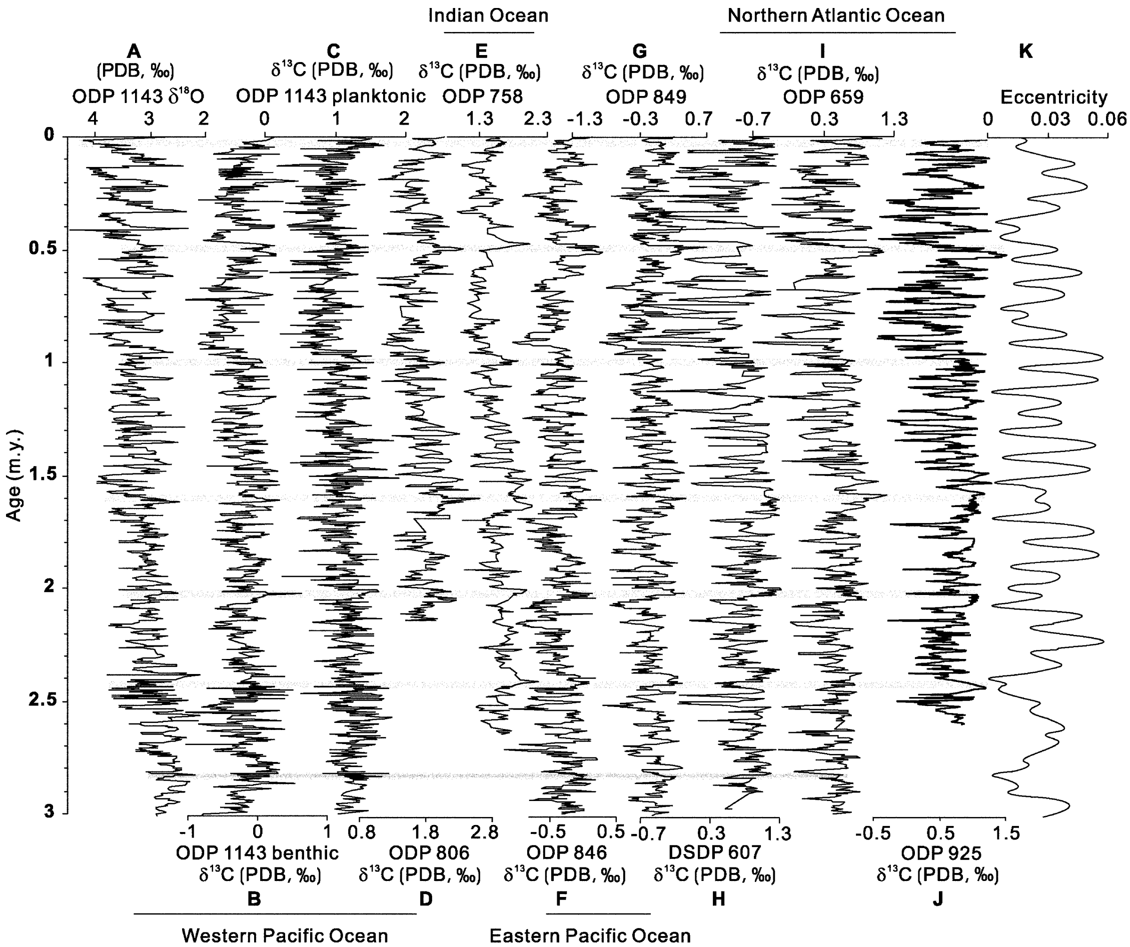

Figure 2. Global correlation of deep-sea (A) $\delta^{18}O$ and (B–J) $\delta^{13}C$ curves for past 3 m.y. All benthic foraminiferal data are based on *Cibicidoides wuellerstorfi*, or *Uvigerina* spp. data corrected to *C. wuellerstorfi* values by original authors. Western Pacific: (A) Ocean Drilling Program (ODP) 1143 benthic $\delta^{18}O$; (B) ODP 1143 benthic $\delta^{13}C$; (C) ODP 1143 planktonic $\delta^{13}C$, *Globigerinoides ruber*; (D) ODP 806 (0°19′N, 159°22′E; water depth 2534 m) planktonic, *Globigerinoides sacculifer* (Schmidt et al., 1993). Indian Ocean: (E) ODP 758 (5°23′N, 90°21′E; water depth 2925 m) planktonic, *G. sacculifer* (Chen et al., 1995). Eastern Pacific: (F) ODP 846 (3°06′S, 90°49′W; water depth 3296 m) benthic (Shackleton et al., 1995); (G) ODP 849 (0°11′N, 110°31′W; water depth 3851 m) benthic (Mix et al., 1995). Northern Atlantic: (H) Deep Sea Drilling Project 607 (41°00′N, 32°58′W; water depth 3427 m) benthic (Raymo et al., 1989); (I) ODP 659 (18°05′N, 21°02′W; water depth 3070 m) benthic (Tiedemann et al., 1994; Schulz, 1988); (J) ODP 925 (4°12′N, 43°29′W; water depth 3041 m) benthic (Bickert et al., 1997). Low-frequency periodicity of 400–500 k.y. (marked with gray bars) is common to all records available from global ocean and generally corresponds to (K) eccentricity variation in orbital forcing. PDB—Peedee belemnite.

Ma, was followed by a negative $\delta^{13}C$ shift, leading to the first 100-k.y.-long glacial cycle and large-scale deglaciation at the MIS 22-21 boundary (Fig. 1), an event known as the middle Pleistocene revolution (Berger et al., 1993) or middle Pleistocene transition (Raymo et al., 1997).

To ascertain whether the just-described $\delta^{13}C$ maxima were local or global in nature, available long-term $\delta^{13}C$ sequences from eight sites over the global ocean are compared (Fig. 2). Sequences from the western Pacific (ODP Site 806, Schmidt et al., 1993; ODP Site 1143, this study), Indian Ocean (ODP Site 758, Chen et al., 1995), eastern Pacific (ODP Site 846, Shackleton et al., 1995; ODP Site 849, Mix et al., 1995), and Atlantic (Deep Sea Drilling Project [DSDP] Site 607, Raymo et al., 1989; ODP Site 659, Tiedemann et al., 1994; Schulz, 1988; ODP Site 925, Bickert et al., 1997), spanning the past 3 m.y., all display these two $\delta^{13}C_{max}$ episodes; moreover, the occurrence of long-term cyclicity of 400–500 k.y. is characteristic of the entire sequence. The only differences are the larger amplitude of $\delta^{13}C$ variations in the Atlantic than in the Indo-Pacific, and the absence of the MIS 12 excursion in plankton records.

PALEOCEANOGRAPHIC CHANGES

To decipher the environmental meaning of $\delta^{13}C_{max}$ episodes, we again take MIS 13 as an example. The beginning of MIS 13 was distinguished by a large freshwater discharge to the ocean, as evidenced by an exceptional ^{18}O-depletion peak (event Y, Fig. 3I) at 525 ka in core MD 900963, equatorial Indian Ocean (5°03′N, 73°53′E; water depth 2446 m). This ^{18}O-depletion peak was followed by an ^{18}O-enrichment peak (event X, Fig. 3I) at 510 ka. The total amplitude of the ^{18}O shift was 2‰ (Bassinot et al., 1994a). At the same time, a thick layer of sapropel dated as 528–525 ka was deposited in eastern Mediterranean (Fig. 3H). The sapropel deposition was abnormal because of the low tropical summer insolation then, and is ascribed to unusually heavy monsoon rainfall over Africa and Asia (Rassignol-Strick et al., 1998). All these findings are indicative of a large, regional-scale monsoon anomaly. At Ceara Rise, equatorial Atlantic, abnormally enhanced terrigenous sediment flux at MIS 13 was recorded in ODP holes (Fig. 3G), implying unusually heavy precipitation and erosion in the Amazon drainage basin (Harris et al., 1997). Deep weathering at MIS 13 was reported from the Chinese Loess Plateau, shown by the highest values of magnetic susceptibility of paleosol S5-1 (Fig. 3F) (Guo et al., 1998). The enhancement of carbonate deposition in MIS 13 following laminated diatom ooze layers at the end of MIS 14 in the southern Atlantic (Schmieder et al., 2000) provided additional evidence for this event of extremely warm and humid conditions in the low latitudes probably of the entire ocean.

The extreme conditions of MIS 13 were by no means stable. The 60-k.y.-long $\delta^{13}C_{max}$ interval was followed by a negative shift in plankton $\delta^{13}C$ values and a drastic excursion in benthic $\delta^{13}C$ values within ~35 k.y. of MIS 12 (Figs. 1 and 2), leading to the glacial maximum at MIS 12.2. Then an extremely rapid increase in benthic $\delta^{13}C$ values, most probably caused by enhancement of the North Atlantic Deep Water, led to the highest interglacial (MIS 11.3) in 25 k.y. The rapid reorganization

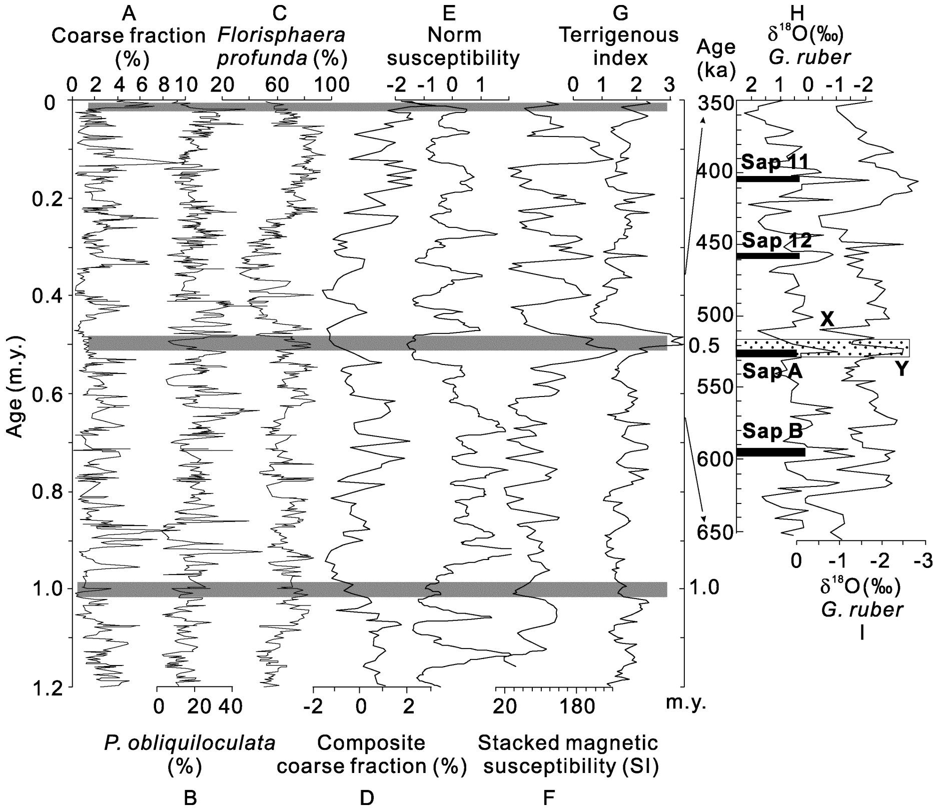

Figure 3. Correlation of past 1.2 m.y. sequences showing paleoeanographic and paleoclimatologic events at marine oxygen isotope stage 13 $\delta^{13}C_{max}$. A: Abundance of coarse fraction (>63 μm) at Ocean Drilling Program (ODP) Site 1143. B: Abundance (in percent) of planktonic foraminifer *Pulleniatina obliqueloculata* at ODP Site 1143. C: Abundance (in percent) of nannoplankton *Florisphaera profunda* at ODP Site 1143. D: Abundance (in percent) of composite coarse fraction (>63 μm) of equatorial Indian Ocean (Bassinot et al., 1994b). E: Normalized magnetic susceptibility of subtropical South Atlantic, reflecting carbonate dissolution (Schmieder et al., 2000). F: Stacked magnetic susceptibility of Loess Plateau, China (Guo et al., 1998). G: Terrigenous index—relative terrigenous mass accumulation rates at ODP Sites 929 and 925, Ceara Rise, equatorial Atlantic (Harris et al., 1997). H: $\delta^{18}O$ record of *G. ruber* with sapropel (Sap) layers in core KC01b, Ionian Sea, Mediterranean (Rassignol-Strick et al., 1998). I: $\delta^{18}O$ record of *G. ruber* in core MD 900963, equatorial Indian Ocean, showing large-amplitude $\delta^{18}O$ changes Y (^{18}O-depletion peak) and X (heavy peak) (Bassinot et al., 1994a).

of deep-water circulation was recorded in sediments. Aside from a sediment hiatus and formation of turbidites at the beginning of MIS 13 (Schmieder et al., 2000), significant variations occurred in carbonate preservation. The coarse fraction (>63 μm) at ODP Site 1143 was lowest during MIS 13 and 11 (Fig. 3A), and the same effect happened in the equatorial Indian Ocean (Fig. 3D) (Bassinot et al., 1994b), suggesting rising of the carbonate lysocline in the Indo-Pacific region. Because the enhanced carbonate dissolution at MIS 13 was also recorded in the aragonite sequence in the Bahamas, Atlantic Ocean, and the Maldives, Indian Ocean (Droxler et al., 1990), the carbonate saturation decline at MIS 13 should have taken place in the entire water column rather than at the bottom only. The dissolution events at MIS 13 and 11 have given rise to the mid-Brunhes dissolution event with maximum dissolution centered at MIS 11. By contrast, magnetic susceptibility in the southern Atlantic deep-water sediments was lowest at MIS 13 and 11 (Fig. 3E) (Schmieder et al., 2000), denoting enhanced carbonate preservation as a result of deep-water circulation, e.g., enhanced production of the North Atlantic Deep Water.

Starting with a massive fluvial discharge spilled over the ocean, the MIS 13 event must have had its consequence in the upper ocean structure. At ODP 1143 the percentage of lower thermocline nannoplankton *Florisphaera profunda* reached its maximum at MIS 13 and then drastically dropped in MIS 12 to a minimum in MIS 11, and the lower values continued until MIS 7 (Fig. 3C). The same pattern was observed at ODP Site 1146, northern South China Sea, and an opposite trend of downhole variations was displayed by small *Gephyrocapsa*, a mixed-layer nannoplankton (X. Su, 2001, personal commun.). The predominance of small *Gephyrocapsa* from 480 to 262 ka was found in the global low-latitude ocean (Bollmann et al., 1998) and corresponds to the low *F. profunda* percentages from MIS 13–12 to MIS 8–7 in the South China Sea. Because small *Gephyrocapsa* and *F. profunda* are representative of high and low productivity in the surface ocean, respectively, the mid-Brunhes event is characterized not only by strong dissolution, but also by high productivity. The rapid changes in the upper ocean are evident also in the plankton foraminiferal record. At ODP Site 1143, the thermocline species *Pulleniatina obliqueloculata* rapidly increased its proportion from nearly zero in MIS 13 to almost 40% in MIS 12, and then suddenly vanished toward MIS 11 (Fig. 3B).

DISCUSSION AND CONCLUSIONS

The mid-Brunhes event and the largest amplitude of ice-sheet change at the MIS 12-11 boundary were preceded by a series of events in the low-latitude surface ocean during the $\delta^{13}C_{max}$ episode. As seen from Figure 2, $\delta^{13}C_{max}$ occurred regularly at the minima of 414 k.y. eccentricity cycles in the pre-Quaternary ocean, but the cyclicity was disturbed in the Quaternary, becoming ~500 k.y. in duration, and the two $\delta^{13}C_{max}$ episodes preceding the mid-Brunhes event and middle Pleistocene revolution were significantly earlier than the eccentricity minima. At this stage, the origin of $\delta^{13}C_{max}$ episodes and the nature of the long-term cycles remain unclear, but the coeval variations of $\delta^{13}C$ and carbonate described here strongly suggest carbon reservoir disturbance in MIS 13, and the heavy precipitation and weathering of 540–530 ka implies a surface origin of the series of events. This disturbance in carbon reservoirs might be attributed to changes in phytoplankton functional types, the diatom/coccolith ratio, which determines ''rain ratio,'' or organic versus inorganic ratio in oceanic carbon deposition (Archer et al., 2000). Because the diatom/coccolith ratio depends on the availability of silica for biological uptake in the ocean, and the major contribution of silica is from tropical rivers (Tréguer et al., 1995), eventually the long-term variations of oceanic $\delta^{13}C$ are related to low-latitude climate events such as monsoons. This seems to be in line with the silica hypothesis of the carbon balance in glacial cycles (Harrison, 2000) and is supported by drastic changes of sediment types in the ocean (Fig. 3).

A similar process, but at a much larger scale, took place at the end of the Miocene when a long period of $\delta^{13}C_{max}$ from 6.8 to 6.4 Ma was followed by a $\delta^{13}C$ shift of 1‰ from 6.4 to 6.1 Ma and ended at a glaciation, with the formation of the West Antarctic ice sheet (Hodell and Ciesielski, 1991). The enhanced dissolution of deep-sea carbonate cooccurring with the carbon shift and leading to a low $CaCO_3$ stage is remarkable, a sequence of events similar to those of the mid-Brunhes event in the Pleistocene. It can be speculated, therefore, that a large-scale reorganization of carbon reservoir is a precondition for a major transition in glacial cyclicity. If true, this new concept may help to explain the lag of ice-volume change behind that of CO_2 (Shackleton, 2000), but challenges the prevalent wisdom of Arctic control of glacial cycles. According to the classical orbital theory of glaciation, only the insolation at the Northern Hemisphere high latitudes is essential to glacial cycles, and the carbon reservoir with $\delta^{13}C$ records only responds to the high-latitude changes. Our new finding shows, however, that both glacial forcing and tropical forcing may contribute to global climate periodicities, and the low-latitude processes probably modulate the glacial cycles through carbon reservoirs.

Of particular significance is the nearly periodic occurrence of $\delta^{13}C_{max}$. Earth is now passing through the low precession stage (Berger, 1988), and the South China Sea drillings have uncovered a new $\delta^{13}C_{max}$ episode since MIS 3 (Figs. 1 and 2). If the previous two $\delta^{13}C_{max}$ led to disturbance of the global carbon reservoir and then to major ice-sheet expansion, it is of vital importance to reveal possible mechanisms behind the chain of events and to find out the climate consequences of the current $\delta^{13}C_{max}$.

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