Orbitally Paced Climate Variability During the Middle Miocene: High Resolution Benthic Foraminiferal Stable-Isotope Records From the Tropical Western Pacific

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We generated a high resolution (~8 ky) benthic record from a West Pacific marginal basin to investigate the detailed structure and spectral characteristics of deep water isotope fluctuations during the middle Miocene. The benthic record from ODP Site 1146 allows unprecedented resolution of the structure of the middle Miocene \( \delta^{13}C \) excursion, as well as tighter control on the chronology of climatic events. Spectral analysis of the variance in the \( \delta^{18}O \) and \( \delta^{13}C \) records from ODP Site 1146 reveals spectral power concentrated in the eccentricity band (400-, ~100-ky) over the time interval between 13 and 17 Ma. The amplitude evolution in the 400-ky band is strikingly similar to that of the long eccentricity in Laskar’s solution. There is an abrupt switch to the obliquity band in the \( \delta^{18}O \) record at ~14.9 Ma, suggesting a shift in the ocean/climate response to orbital forcing (from low latitude eccentricity to high latitude obliquity forcing). The obliquity signal is pervasive in the \( \delta^{18}O \) record until ~13.9 Ma, when a sharp increase in \( \delta^{18}O \) values indicates a major climatic transition. Comparison of \( \delta^{18}O \) and \( \delta^{13}C \) profiles from DSDP Site 588 (SW Pacific Ocean), ODP Site 761 (E Indian Ocean) and ODP Site 1146 (South China Sea) reveals significantly cooler deep water in the NE Indian Ocean throughout the middle Miocene and a restricted deep water exchange between the Pacific Ocean and Indian Ocean.

INTRODUCTION

The Cenozoic \( \delta^{13}C \) record is punctuated by some high-amplitude excursions, which indicate major changes in the marine carbon reservoir and global perturbations of the carbon cycle. The enigmatic long-term positive carbon isotope excursion between ~17 and 13.5 Ma (“Monterey excursion”, Figure 1) coincided with an initial period of extreme warmth and high sea level (mid-Miocene climate optimum), which was followed by global cooling and sea level fall, probably linked to the growth of the East Antarctic ice sheet [Shackleton and Kennett, 1975; Vincent and Berger, 1985; Vincent et al., 1985; Kennett, 1986; Miller et al., 1991; Woodruff and Savin, 1991; Wright et al., 1992; Flower and Kennett, 1993a; 1994; 1995]. High resolution reconstructions of the succession of events point to a complex relationship between orbital fore-
ing, changes in ocean carbon budget and climate cooling, mediated by a major re-organization of ocean circulation patterns [Kennett et al., 1985; Woodruff and Savin, 1989; Flower and Kennett, 1994; 1995; Flower, 1999]. However, the precise chronologies of events as well as the ocean’s role in carbon cycling and the relation between enhanced carbon burial, $\delta^{13}$C maxima, orbital forcing and global cooling and warming events in the early Neogene history of the Earth are still intensely debated.

The middle Miocene global carbon excursion and climatic change offer one of the most intriguing case studies to test the hypothesis of eccentricity forcing of the global carbon cycle [cf. Shackleton, 2000]. The pacing of long term climate change by periodic variations in Earth’s orbital parameters (eccentricity, obliquity, precession) has become widely accepted to explain climate variability in the Plio-Pleistocene [Hays et al., 1976; Imbrie et al., 1984; Raymo et al., 1989; Ruddiman et al., 1989; Shackleton et al., 1990; Hilgen, 1991; Shackleton, 2000] and also in older periods of Earth’s history with different climate boundary conditions [Beaufort, 1994; Hilgen et al., 1995; 1999; Zachos et al., 1997; Shackleton et al., 1999; Paul et al., 2000; Röhl et al., 2000; Zachos et al., 2001a; 2001b]. High resolution time series have indicated that obliquity controlled climate variations (linked to high-latitude processes) may be stronger during glaciated intervals, whereas the climate system becomes more responsive to changes in insolation induced by precession and modulated by eccentricity (linked to low-latitude processes) during periods with only small ice volume [Tiedemann et al., 1994; Clemens and Tiedemann, 1997; Lourens and Hilgen, 1997; Röhl et al., 2000]. However, the widely fluctuating volume in global ice caps, changing modes of ocean circulation, unknown variations in deep-water temperatures and different land-ocean configurations in pre-Pleistocene times still present some major challenges for the interpretation of stable isotope records and for their calibration to an astronomical time scale. Additionally, the scarcity of expanded, undisturbed, continuous sedimentary successions due to carbonate dissolution, diagenetic alteration or the presence of hiatuses and coring gaps have strongly hampered the resolution of orbitally driven climate variability in the middle Miocene.

We use high resolution paleoclimatic benthic records from a West Pacific marginal basin (Ocean Drilling Program (ODP) Site 1146) to investigate the detailed structure and spectral characteristics of deep water isotope fluctuations during the middle Miocene. The relatively shallow location of ODP Site 1146 in a marginal spreading basin and its proximity to a part of SE Asia receiving a high river discharge led to the accumulation of an expanded and continuous sequence of middle Miocene hemipelagic nanofossil clays that are relatively rich in carbonate. Thus, the high accumulation rate sedimentary archive recovered from South China Sea (SCS) ODP Site 1146 offers the opportunity to assess paleoceanographic changes with unprecedented resolution in a part of the ocean
climate system that is particularly sensitive to variations in tropical climate and to changes in Pacific circulation, but which remains essentially unknown. Our main objectives are:

1. To generate a high resolution (<10 ky) benthic record and to determine the frequency and amplitude of middle Miocene deep water isotope fluctuations in the SCS.
2. To test the hypothesis that the middle Miocene "Greenhouse climate" was mainly driven by eccentricity forcing of the carbon cycle.
3. To compare records from the western Pacific and eastern Indian Ocean in order to monitor long- and short-term trends in the deep-water circulation.

GEOPHYSICAL AND PALEOECEANOGRAPHIC SETTING

ODP Site 1146 (19º 27.40’ N, 116º 16.37’ E) was drilled in a water depth of 2092 m within a small rift basin on the midcontinental slope of the northern SCS (Figure 2). Coring at ODP Site 1146 recovered a continuous Miocene sequence of relatively carbonate-rich hemipelagic sediments, which grade from green nannofossil clay in the lower Miocene to light brownish gray foraminifers and nannofossil clay in the upper Miocene [Wang, Prell, Blum et al., 2000]. The succession was recovered by XCB (extended core barrel) piston coring, and core recovery averaged 100.7% over the interval.

The SCS is the largest marginal sea in the western Pacific. It originated in the late Eocene, when oceanic crust started to form in the central part of the basin and crustal subsidence gave rise to the deposition of transgressive sequences at the margins [Brixais et al., 1993]. A free connection existed between the SCS and the western Pacific until the modern Bashi Strait (sill depth ~2600 m) formed between Luzon and Taiwan at ~6.5 Ma, as a result of the Luzon Arc collision [Wang, Prell, Blum et al., 2000]. The geological evolution of the SCS has been strongly marked by intense tectonic activity related to the collision between Australia and SE Asia, which caused rotations of blocks and accretion of microcontinental fragments to SE Asia since about 25 Ma ago [Hall, 1996; 2002; Kuhnt et al., this volume).

Today, the deep water mass in the SCS is derived from Pacific intermediate water entering the SCS through the Bashi Strait. The comparatively old, nutrient enriched deep water mass in the SCS is characterized by present day δ13C values of ~0.0–0.3‰ [Wang et al., 1999]. Glacial δ13C values were significantly lower, reaching extremes of ~0.5% to ~1.6% in the southern SCS during MIS 2 [Wang et al., 1999]. Benthic δ13C fluctuations in the SCS during the last 800 ky [Wang et al., 2003, Figure 1 therein] probably reflect local glacial/interglacial fluctuations in nutrient fluxes in the strongly sea-level influenced semi-enclosed estuarine system of the SCS, which probably override the long-term cyclicity in global nutrient/carbon budgets. Conditions were probably different prior to the "Mid Pleistocene Revolution", when glacial/interglacial sea-level contrasts were less pronounced and dominated by obliquity variations [Jansen et al., 1986; Berger and Jansen, 1994; Mudelsee and Schulz, 1997]. The Pliocene and Miocene deep water isotope records from the SCS are likely to be more representative for monitoring the global carbon cycle, since a deep-water connection with the W Pacific Ocean existed at that time [Wang, Prell, Blum et al., 2000].

METHODS

Micropaleontological samples (~20–30 cm³) were dried, weighed, then wet-sieved through a 63 μm sieve. Residues were dry-sieved into 63–150 μm, 150–250 μm and 250–630 μm fractions. Benthic foraminifers were picked and counted from the >250 μm fractions. We also checked assemblage composition in the smaller fractions of selected samples to ensure that smaller species such as pulsed detritus feeders were not overlooked. An average of 3 to 8 well preserved tests (>250 μm fraction) of benthic foraminifers were selected for stable isotope analyses, except in rare cases, when foraminiferal density was extremely low and a smaller number (1–2) of specimens was analyzed. Most of the measurements were made on Planulina wuellerstorfi or Cibicidoides mundulus, except in a small number of samples, where C. barnetti, C. robertsonianus or C. incrassatus were analyzed. Replicate measurements carried out on samples from ODP
Site 1146 and ODP Site 761 [Holbourn et al., 2004], which contained sufficient numbers of P. wuellerstorfi and C. mundulus, indicate mean offsets of less than 0.1% for carbon and less than 0.07% oxygen between these species. Due to the low abundance of tests in the >250 μm fractions at ODP Site 1146, we could only perform a small number of replicate measurements to check intraspecific variability. These indicated mean offsets of ~0.1% for carbon and oxygen. Tests were checked for cement encrustations before being broken into large fragments, cleaned in an ultrasonic bath, rinsed with alcohol, and finally dried at 40°C. Stable carbon- and oxygen-isotope measurements were made with the Finnigan MAT 251 mass spectrometer at the Leibniz-Labor für Altersbestimmung und Isotopenforschung in Kiel. The instrument is coupled on-line to a Carbo-Kiel device for automated CO₂ preparation from carbonate samples for isotopic analysis. Samples were reacted by individual acid addition. Precision of the isotope measurement (on the δ scale) is at least ± 0.08% for oxygen and ± 0.05% for carbon isotopes. Results were calibrated using the National Institute Bureau of Standards and Technology (Gaithersburg, Maryland) carbonate isotope standard NBS 20 and in addition NBS 19 and 18, and are reported on the PeeDee belemnite (PDB) scale. Isotope data sets are archived with the World Data Center for Marine Environmental Sciences.

A shipboard composite depth scale (mcd) was constructed for ODP Site 1146 using magnetic susceptibility, natural gamma ray and color reflectance data [Wang et al., 2000]. Although the cores from Holes 1146A and C could not be tied to the continuous composite depth scale below 266.7 mcd, they could be placed on a discontinuous composite “floating” depth scale, using correlative features. This correlation revealed only few small coring gaps between cores from Hole 1146A. However, shipboard correlation was somewhat ambiguous in the lowermost part of the spliced record from ODP Site 1146, where core-logging data showed little structure. Thus, to avoid any duplication or omission of records, we continuously sampled Hole 1146A and bridged one obvious coring gap between Cores 1146A-54X and -55X with samples from Hole 1146C, based on the shipboard correlation and the match of our isotope records.

Temporal changes in amplitude and phase of signal components in the Milankovitch band were estimated using a modified harmonic-filtering algorithm [Ferraz-Mello, 1981], which fits sinusoidal waves to a time series by means of least-squares. This method can process unevenly spaced time series directly, that is, without the requirement of prior interpolation. To obtain time-dependent amplitude estimates, the input time series is analyzed within a moving window of width $T_w = w \times T_f$, where $w = 3$ is a width-factor and $T_f$
Table 1. Biostratigraphic depth control points used for revised chronology of Miocene cores from ODP Site 1146.
Calcareaous nanofossil datums (NP) from Nathan and Leckie [2003]. Planktonic foraminiferal datums (PF) revised herein.
NF = Calcareaous nanofossils; PF = Planktonic foraminifers; FO = First occurrence; LO = Last occurrence

<table>
<thead>
<tr>
<th>Datum</th>
<th>Source</th>
<th>Age (Ma)</th>
<th>Depth (mbsf)</th>
<th>Uncertainty up (m)</th>
<th>Uncertainty down (m)</th>
</tr>
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<tr>
<td>FO C. coevalis</td>
<td>NF</td>
<td>11.49</td>
<td>35.10</td>
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<td>LO D. kugleri</td>
<td>NF</td>
<td>11.68</td>
<td>36.00</td>
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<td>0.25</td>
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<tr>
<td>LO Globorotalia foksi s.l.</td>
<td>PF</td>
<td>12.88</td>
<td>39.50</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>FO D. kugleri</td>
<td>NF</td>
<td>13.18</td>
<td>39.80</td>
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<tr>
<td>FO T. rugosus</td>
<td>NF</td>
<td>13.42</td>
<td>46.60</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>FO Globorotalia foksi robusta</td>
<td>PF</td>
<td>14.00</td>
<td>42.20</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>LO C. floridanus</td>
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</tr>
<tr>
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<td>14.20</td>
<td>42.40</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>LO S. heteromorphus</td>
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<td>14.23</td>
<td>42.50</td>
<td>0.25</td>
<td>0.25</td>
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<td>44.70</td>
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<tr>
<td>FO Praeorbulina sicana</td>
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<td>46.00</td>
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<td>48.00</td>
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denotes the signal periodicity of interest (e.g. 400 ky). The window is shifted consecutively by one data point along the time axis of the input time series. Each “window segment” is linearly detrended prior to tapering with a Welch-Shape-1 window [Welch, 1967]. The resulting amplitude and phase of the best-fit sinusoid are saved vs. the average of the observation times within the current segment and are used to reconstruct the signal component as function of time. The result of this procedure is equivalent to band-pass filtering [cf. Hinnoy et al., 2002]. The selected value of w offers a good compromise between statistical and systematic errors and results in a half-amplitude bandwidth of approximately 0.5/Tf cycles/Ma. Note that due to the finite window width, a step-like increase in signal amplitude appears w x Tf wide. Applying the above filtering algorithm over a predefined range of frequencies allows us to detect changes in signal components in time-frequency space [Schulz et al., 1999]. The dependence of window width, T_w, on frequency leads to a change in temporal resolution with frequency. At low (high) frequencies wide (narrow) windows result in a low (high) temporal resolution. This scale dependence of the temporal resolution is similar to that of wavelet analysis.

RESULTS

Age Model

The chronology for ODP Site 1146 is based on biostratigraphic datums (Table 1, Figure 3). We revised the shipboard foraminiferal datums, based on higher resolution sampling, and integrated the revised datums with shorebased nanofossil biostratigraphy [Nathan and Leckie, 2003] to derive a new age model for ODP Site 1146, using a smooth interpolation. For planktonic foraminiferal datums, we used the tuned ages of Chaisson and Pearson [1997], Pearson and Chaisson [1997] and Curry et al. [1995] for ages younger than 13.42 Ma. Ages older than 13.42 Ma were not tuned and taken directly from Berggren et al. [1995a] and Berggren et al. [1995b]. We refrained from tuning our benthic foraminiferal isotope record to avoid introducing artificial cyclicity. The revised age model indicates relatively consistent sedimentation rates of ~2 to 2.5 cm/ky for the interval between 12 and 18 Ma (cf. Figure 3).

Stable Isotope Time Series

δ18O and δ13C records for ODP Site 1146 are shown in Figure 4. Isotope values plotted on the mbsf scale do not indicate significant hiatuses at the boundaries between cores in Hole 1146A and the spliced interval from Hole 1146C, although we cannot rule out the presence of small coring gaps despite full recovery. The most prominent features of the time series are the positive excursion in δ13C between ~16.4 and 13.6 Ma, the abrupt increase in δ18O and δ13C values at ~13.9 Ma and the high frequency variability of the δ18O and δ13C records between 16.6 and 13 Ma. Variations in δ18O and δ13C values at timescales of several 105 years are overall in phase during the duration of the global δ13C excursion. The δ13C excursion comprises a series of high frequency oscillations of vari-
Figure 4. Benthic δ¹⁸O, δ¹³C profiles in middle Miocene cores from ODP Site 1146. δ¹⁸O and δ¹³C values plotted on the mbsf scale do not indicate significant hiatuses at the boundaries between cores in Hole 1146A and the spliced interval from Hole 1146C. Most prominent features are the positive excursion in δ¹³C between ~16.4 and 13.6 Ma and the abrupt increase in δ¹⁸O values at ~13.9 Ma. Horizontal dark gray lines indicate core boundaries.

Variable amplitude superimposed on lower frequency fluctuations, which have minimum and maximum values close to 0.5 and 1.5%, respectively, and recurrence time of several 100 ky. However, low-frequency fluctuations are slightly less distinct in the interval from ~15.4 to 14.9 Ma, where δ¹³C maximum values reach only ~1.2%. The base of the δ¹³C excursion (~16.4 Ma) is marked by a sharp increase in δ¹³C values (from 0.5 to 1.5%), whereas a stepwise decrease in values (from 1.4 to 0.5%) occurs between 13.6 and 13.0 Ma, following the last δ¹³C maximum. Background δ¹³C values below and above the main δ¹³C excursion (prior to 16.4 Ma and after 13.0 Ma) fluctuate around 0.5%.

The δ¹⁸O curve is also characterized by high-frequency oscillations of variable amplitude as well as lower-frequency variations with recurrence time on the order of several 100 ky. Between ~16.6 and 14.5 Ma, the low-frequency variations generally have minimum and maximum values close to 0.5 and 1.5%, respectively. The amplitude of these fluctuations decreases slightly between 14.5 and 14 Ma, when δ¹⁸O values show an overall increasing trend of ~0.2–0.3%. The beginning of the global δ¹³C excursion is preceded by a marked decrease in δ¹⁸O values (from 1.3 to 0.4%) between ~16.6 and 16.4 Ma. At ~13.9 Ma, an abrupt increase in δ¹⁸O values occurs (from ~1.1 to 2.0%), which is followed by a series of oscillations with amplitude ~0.5–0.7% and apparent recurrence time ~100 ky between ~14.1 and 13.0 Ma.

Benthic Foraminiferal Distribution

The middle Miocene benthic foraminiferal assemblages from ODP Site 1146 are dominated by relatively well preserved calcareous forms. They typically contain bathyal taxa such as Bulimina tuxpanensis, C. mundulus, C. bradyi, Orbitoides umbonatus, P. wuellerstorfi, P. renzi, Stilostomella
abyssonum, S. subspinosa, Uvigerina hispida and U. peregrina. Benthic foraminiferal distribution patterns reveal distinct changes in species distribution that can be correlated to variations in isotopic values. Based on the relative abundance of Planulina, Stilostomella, Uvigerina and Cibicidoides, three main biofacies can be discriminated (Figure 5).

Biofacies 1, which is characterized by relatively high numbers of Stilostomella and Uvigerina and the absence of Planulina, occurs between ~16.4 and 15.5 Ma during an interval which corresponds to the first three main maxima in δ¹³C values of the global excursion.

Biofacies 2 contains relatively high numbers of Cibicidoides, Stilostomella and Uvigerina as well as variable numbers of Planulina. The numbers of Planulina increase from ~14 Ma, following the sharp increase in δ¹⁸O values. Biofacies 2 coincides with the upper part of the global δ¹³C excursion between ~15.5 and 13.6 Ma and final decrease in δ¹³C values from 13.6 to 13.0 Ma.

Biofacies 3 is characterized by relatively low numbers of Stilostomella and Uvigerina, and high numbers of Planulina and Cibicidoides. Biofacies 3 occurs above the global δ¹³C excursion between ~13 and 11 Ma, and coincides with an interval characterized by the highest δ¹⁸O values and lowest δ¹³C values.

**Time-frequency Analyses and Correlation With Laskar’s Eccentricity Solution**

We applied a time-frequency analysis to the δ¹⁸O and δ¹³C time series, based on the original biostratigraphic age model (Figures 6 and 7). The δ¹³C record exhibits high amplitude in the 400-ky band between ~14.4 and 13.6 Ma and between ~16.5 and 15.8 Ma. This amplitude evolution in the 400-ky band is strikingly similar to that of Earth’s eccentricity [Laskar, 1993], which exhibits similar course of 400-ky amplitude maxima and minima between ~16.5 and 13.6 Ma. While the 100-ky signal in the δ¹³C time series is less structured than in the 400-ky signal, it exhibits clear minima at ~13.8 Ma and ~16.4 Ma that correspond to amplitude minima in the 100-ky band of Laskar’s solution. In contrast to the amplitude minima however, the prominent 100-ky amplitude maxima between ~14.9 and 14.4 Ma in the Laskar’s solution are not expressed in the δ¹³C record at ODP Site 1146.

The 400-ky and 100-ky signals in the δ¹⁸O record are weaker, but show a similar amplitude modulation with maxima at ~14 and 16 Ma for the 400-ky eccentricity cycles. The 100-ky signal is well expressed in the δ¹⁸O time series between ~16.3 and 15 Ma (Figure 7). This apparent shift towards lower frequencies during this time interval may be due to problems with the untuned biostratigraphic age model. A striking feature of the δ¹⁸O signal evolution is the sudden switch in the climate/ocean response to orbital forcing (from high amplitude in the 100-ky eccentricity band to high amplitude in the obliquity band) at ~14.9 Ma. The amplitude of the obliquity signal remains high until ~13.9 Ma, when a major increase in δ¹⁸O values occurs.

**Phase Relationships Between the δ¹⁸O and δ¹³C Time Series and Laskar’s Eccentricity Solution**

To determine the phase relations between the 400-ky signals in the benthic δ¹⁸O and δ¹³C time series, we applied a 400-ky band-pass filter to extract variations related to the long eccentricity cycle (Figure 8). Both filtered time series show distinct 400-ky signal components with amplitudes of up to ~0.25% and 0.15% for δ¹³C and δ¹⁸O, respectively. The presence of such signals is not surprising, since even filtered random time series generally vary at the periodicity of the band-pass filter. However, evidence for an orbital origin of the 400-ky signals is provided by the fact that the amplitude of both filtered series is modulated by a ~2.4 my period (Figure 8), that is the same period, which modulates eccentricity [e.g. Schwarzacher, 1993]. Furthermore, the 400-ky signal components of the two isotope records are largely in phase over the entire record, which also suggests a non-random origin of the signals.

To further investigate the phase relations between the benthic isotope 400-ky signals and the eccentricity cycle in Laskar’s solution, we applied a 400-ky band-pass filter to the eccentricity time series (Figure 8). Between 17 and ~15 Ma, the 400-ky signal components in both isotope records are in phase with the corresponding eccentricity cycle. In contrast, the phase relationship between the orbital signal and both proxy records is not maintained between ~15 and 13 Ma. The transition goes along with a continuous phase shift between 400-ky signal components in eccentricity and the two isotope series (not shown). It is noteworthy that the phase shift does not occur in a steplike fashion. Whether or not this phase shift reflects a true climatic response or is related to inconsistencies in the (untuned) age model cannot be ascertained as yet.

**DISCUSSION**

**Periodicity in Benthic Stable Isotope Records and Orbital Forcing**

Woodruff and Savin [1991] recognized six δ¹³C maxima (CM1 to CM6) within the main global δ¹³C excursion, which they related to 400-ky eccentricity cycles, based on estimates of the approximate ages of successive δ¹³C maxima. How-
Figure 5. Distribution of benthic foraminifers in middle Miocene cores from ODP Site 1146. Three main biofacies are discriminated, based on the relative abundance of Planulina, Stilostomella, Uvigerina and Cibicidoides.
ever, most of the records examined by these authors were of comparatively low temporal resolution and incomplete, due to diagenetic overprints, carbonate dissolution or presence of stratigraphic gaps, particularly within the intervals of CM1-CM2 and CM4-CM5, corresponding respectively to the base of the main excursion and major increase in δ18O. In contrast, the benthic record from ODP Site 1146 provides a highly detailed record of the structure of the middle Miocene δ13C excursion (Figure 3), as well as tighter age control on the succession of climatic events.

Based on the parallel course of the amplitude evolution of the 400-ky signal components in Earth’s eccentricity [Laskar, 1993] and the δ13C and δ18O time series from 17 to 13 Ma, it appears that orbital forcing controlled the low-frequency variability in the proxy records (Figures 6–8). The lack of distinct 400-ky signal component in the δ13C record between ~15.5 and 14.9 Ma coincides with an interval when the 400-ky eccentricity forcing is relatively weak (Figure 6). The 100-ky eccentricity forcing is prominent between ~16.3 and 14.9 Ma in both the δ13C and δ18O records (Figures 6–7) despite a shift towards longer periods which we attribute to uncertainties in the untuned age model (see above). At ~14.9 Ma, there is an abrupt switch from the 100-ky eccentricity band to the obliquity band in the δ18O record. Subsequently, the obliquity signal is pervasive in the δ18O record until ~13.9 Ma, when a sharp increase in δ18O values indicates a major climatic transition. Remarkably, land and offshore records from southern Victoria Land in Antarctica indicate that the interval between ~14.8 and 13.6 Ma coincided with inundation by a full ice sheet, sufficiently thick to override the Transantarctic Mountains and to extend to the edge of the continental shelf [Sugden and Denton, 2003].

Based on the observation that the medium-sized ice sheets during the Pliocene varied predominantly in the obliquity band ("the 41-ky world", e.g. Raymo and Nisancioglu, 2003), we surmise that the arrival of the Antarctic ice edge at the waterfront made this ice cap more vulnerable to calving and to high-latitude obliquity forcing. Moreover, taking the Mid-Pleistocene Revolution as template, one expects a switch from 41 to 100-ky cycles as global ice volume increases [e.g. Mudelsee and Schulz, 1997]. This scenario is thus in contrast with the increase of benthic δ18O values across the 100- to 40-ky transition seen in our record at ~14.9 Ma (Figure 7). Accordingly, a high-latitude origin of both, 100-ky and ~40-ky variability in the middle Miocene is rather unlikely. Following Wang et al. (2003) we assume that the eccentricity-dominated variability prior to ~14.9 Ma is transferred via low-latitude mechanisms into our isotope records. Then, the transition from 100-ky to ~40-ky variability in our δ18O record at ~14.9 Ma indicates a shift from low to high latitude control of our proxy records.

Surprisingly, time-frequency analysis of the color reflectance and magnetic susceptibility records failed to reveal any obvious concentration of variance at particular wavelengths (not shown). This may be due to a lack of periodic variability in the composition and deposition pattern of the sediments, suggesting that monsoonal influence was insignificant during the middle Miocene. However, problems in core quality (such as "biscuiting" and cracking) also exist in the Miocene interval, and may account for the chaotic signals and the lack of recognizable periodicity in the color reflectance and magnetic susceptibility records.

Stepping Into the "Icehouse-World": A Potential Link to Changes in Eccentricity Forcing

Comparison of benthic δ13C records from tropical locations by Wang et al. [2003] indicates that, at least for the last two million years, δ13C maxima generally coincided with eccentricity minima, thus suggesting that the eccentricity cycle is strongly influencing the global carbon cycle. Interestingly, one of the most prominent δ13C maximum occurred at approximately 2.8 Ma, exactly at the change from a dominance of the 100-ky to a dominance of the 400-ky eccentricity cycle in the forcing [cf. Laskar, 1993], and just before the intensification of the northern hemisphere glaciation. During the middle Miocene, the increase in δ18O between 14.5 and 13.9 Ma, which has been linked to rapid development of the East Antarctic ice sheet, also starts with a transition from 100-ky to 400-ky dominance in earth’s eccentricity (Figure 6), and corresponds to a minimum in eccentricity forcing. A common relationship between major glaciation events and changes in the predominance of eccentricity (and obliquity) signals was suggested by Flower et al. [1997] and Zachos et al. [2001b], based on δ13C and δ18O records from ODP Sites 926 and 929 in the western equatorial Atlantic, which show prominent long eccentricity cycles between 22.5 and 25.4 Ma across the Oligocene/Miocene boundary [Paul et al., 2000]. The synchrony of δ13C and δ18O maxima with eccentricity minima implies a direct relationship between carbon cycle, glacial cycles and eccentricity forcing. The coincidence of (1) changes from predominant 100-ky to 400-ky periodicity of earth’s eccentricity, (2) major disturbances in the carbon reservoir, triggering positive δ13C excursions, and (3) global cooling events leading to the onset of glaciations is intriguing. It suggests that similar processes may have triggered the widespread northern hemisphere glaciation around 2.7 Ma, the major expansion of the East Antarctic ice sheet at ~14 Ma, and the M11 Glaciation at 22.9 Ma in the earliest Miocene, which also coincides with a δ13C maximum period [Zachos et al., 2001b].
Figure 6. Time-frequency analysis of middle Miocene δ¹³C record from ODP Site 1146 and of Earth's eccentricity [Laskar, 1993]. The amplitude evolution in the 400-ky band is strikingly similar to that of Earth's eccentricity between ~16.5 and 13.6 Ma.
Carbon Reservoirs and Climate Change

The low frequency oscillations in $\delta^{18}O$ and $\delta^{13}C$ at ODP Site 1146 are clearly in phase (Figure 8), suggesting a close link between the benthic $\delta^{18}O$ signal and carbon cycling. Eccentricity forced climate variations are thought to originate from an asymmetrical response mechanism that allows for an amplified response of the climate system to relatively weak eccentricity forcing [Clemens and Tiedemann, 1997]. The covariance of oxygen and carbon isotope maxima within long eccentricity oscillations may be explained by an increased oceanic turnover during periods of decreased high latitude temperatures, leading to overall enhanced upwelling, productivity, organic-carbon fluxes and thus organic carbon burial rates, resulting in an increase of $\delta^{13}C$ values in the oceanic reservoir.

Another possible connection between $\delta^{13}C$ and $\delta^{18}O$ maxima, climate and long eccentricity cycles may be long-term variations in chemical weathering, which changes the silica and nutrient supply from the continent to the ocean and trigger a change from calcareous to siliceous primary producers in the tropics. A main mechanism to increase productivity and to favor siliceous primary producers in the tropics would be an enhanced continental run-off of silica and nutrients during periods of wet climate (intensified monsoon) and lowered sealevel. Higher precipitation and largely exposed shelves in the tropics would flush more silica and nutrients into the tropical ocean and would increase diatom production in particular. An increase in the diatom/coccolithophorid ratio of the phytoplankton and in the organic/inorganic ratio of the particle flux sinking to the ocean floor would lead to an increase in the $\delta^{13}C$ of the oceanic reservoir, which would be compa-
Figure 8. Comparison of filtered 400-ky signal component in $\delta^{18}$O and $\delta^{13}$C records from ODP Site 1146 with 400-ky signal component in Earth's eccentricity [Laskar, 1993]. The 400-ky signal components in both isotope records are in phase with the corresponding eccentricity cycle between 17 and ~15 Ma.

rable to an increase in overall carbon burial. Inorganic (carbonate) carbon, mineralized in surface waters is generally slightly enriched in $\delta^{13}$C, in comparison to the entire ocean carbon reservoir, while organic carbon is significantly depleted in $\delta^{13}$C. This leads to a $\delta^{13}$C depletion during periods of predominant carbonate carbon deposition and to a $\delta^{12}$C enrichment and positive $\delta^{13}$C excursion during periods of predominant organic carbon burial. The huge deposits of diatomsites of the Monterey Formation in the subtropical Pacific provide support that such a process may have been significant during the middle Miocene [Vincent and Berger, 1985; Flower and Kennett, 1993b].

Another interesting suggestion, also providing a link between the terrestrial and marine carbon reservoirs, is that the expansion and decrease of C4 plants as a component of the vegetation of SE Asia might have significantly contributed to periodic declines in the marine carbonate isotope content [Jia et al., 2003]. Changes in clay mineralogy support the idea that a major intensification of the summer monsoon occurred during the middle Miocene [Clift et al., 2002], which was strong enough to influence the photosynthetic pathway [Jia et al., 2003] and would additionally have increased the flushing of nutrients into the ocean. Thus, periodic variations in Summer monsoon intensity and climatic feedbacks on the vegetation in SE Asia (in particular, on the C3/C4 plant ratios) may have caused significant isotopic changes in the terrestrial ecosystem and in due course influenced the amount of light carbon leaving or entering the ocean-atmosphere system.

Deep Ocean Circulation in the Western Pacific and Eastern Indian Ocean

Comparison between the range of $\delta^{13}$C values at three sites in the western Pacific and eastern Indian Ocean with relatively high resolution isotopic records (Deep Sea Drilling Project (DSDP) Sites 588 at 1533 m water depth, ODP Site 761 at 2179 m water depth and ODP Site 1146 at 2092 m water depth) highlight differences in the ventilation of deep waters and the relative distance of these sites to the locus of intermediate/deep water formation. The southern Pacific DSDP Site 588 exhibits the highest range of $\delta^{13}$C values (2.3 to 1.3‰) [Flower and Kennett, 1993], indicating relatively well ventilated deep water and close proximity to a southern high
Figure 9: Comparison of stable isotope records from ODP Site 588 in the South Pacific (Flower and Kennett, 1993), Site 761 in the Indian Ocean (Holbourn et al., 2004) and Site 1146 in SCS (this report). Chronology for Sites 761 and 1146 is based on radiocarbon age models. Chronology for Site 588 is based on tuning of δ18O record to that of Site 1146, using Analyses 1-2 (Finney et al., 1990).
latitude source. By contrast, the markedly lower range of δ13C values at the more northerly ODP Sites 761 and 1146 (1.8 to 0.8% and 1.5 to 0.5%, respectively) reflects their location further away from the source of deep water formation as well as generally poorer ventilation (Figure 9). ODP Site 761, situated in the Indian Ocean at 10° further north than DSDP Site 588, may have been influenced by water masses of different origin, entering the Indian Ocean from a northwest or southwest direction. The low δ13C values at ODP Site 1146 may be attributed to a different origin (N Pacific) for the SCS deep/intermediate water. Nevertheless, the amplitude of the middle Miocene δ13C increases and decreases are overall coherent at the three sites, indicating that δ13C changes had a common, global origin (carbon burial) and no open low latitude deep-water connection between the Indian and Pacific Oceans is required to explain these synchronous changes.

The ranges of δ18O values are quite comparable at Sites 588 and 1146 (0.6 to 1.8% and 0.4 to 1.9%, respectively), but differ markedly at ODP Site 761 (1.1 to 2.4%). The depth difference between the sites cannot account for this contrast, which probably stems from the different origin of deep water masses on either sides of the Indonesian Gateway. Thus, our data indicate restricted intermediate/deep water exchange between the Pacific Ocean and Indian Ocean through the Indonesian Gateway during the middle Miocene climatic optimum and subsequent global cooling. A further remarkable feature is the different shape of the δ18O profile at ODP Site 1146, in comparison to previously published records [Woodruff and Savin, 1991; Flower and Kennett, 1994]. The sharp increase in δ18O values at ~13.9 Ma in the SCS indicates a more rapid and radical shift in deep water circulation than suggested by records from the Southern hemisphere, which show a stepped increase for the interval between 14.5 and 13.9 Ma. This shift points to changes in deep-water mass characteristics that are different from those at sites strongly influenced by Antarctic deep water or may be attributed to the higher resolution and greater completeness of the record from ODP Site 1146.

At ODP Site 1146, an initial improvement in deep-water ventilation is indicated at ~15.5 Ma by a change in the composition of benthic foraminiferal assemblages (transition from Biofacies 1 to 2). From ~15.5 Ma, the assemblages contain higher numbers of epifaunal, suspension feeding forms (Cibicidoides and Planulina) which have ecological preference for well-ventilated deep waters and low carbon fluxes [Kaiho, 1994; Altenbach et al., 1999]. Our results are in agreement with isotopic and sedimentological evidence as well as paleobathymetric reconstructions, which indicate that the deep water of the Pacific Ocean became increasingly influenced by cold Southern Component Water during the middle Miocene, as production of Tethyan Indian Saline Water decreased and North component deep water sources remained either weak or non-existent [Woodruff and Savin, 1989; Wright et al., 1992; Flower and Kennett, 1995; Sykes et al., 1998; Ramsay et al., 1998; Hall et al., 2003; Holbourn et al., 2004].

CONCLUSIONS

The benthic stable isotope records from ODP Site 1146 allow unparalleled resolution of the structure of the middle Miocene δ13C excursion as well as tighter control on the chronology of climatic events. Time-frequency analysis of the δ18O and δ13C records from ODP Site 1146 reveals enhanced variability in the 400-, ~100-ky eccentricity bands over the time interval between 13 and 17 Ma. The δ13C time-frequency analysis exhibits variations in the amplitude of the 400-ky periodicity, which we attribute to the eccentricity forcing. The 100-ky eccentricity forcing is well expressed between ~16.3 and 14.9 Ma in both the δ13C and δ18O records despite a shift towards longer periods, which we ascribe to uncertainties in the unturned age model. At ~14.9 Ma, there is an abrupt switch from eccentricity to obliquity dominated variance in the δ18O record, suggesting a shift in the ocean/climate response to orbital forcing (from low latitude eccentricity to high latitude obliquity forcing of δ18O variations). The obliquity signal in the δ18O record remains prominent over a period of ~1 my, which also corresponds to major extension of the East Antarctic ice sheet. This gradual climatic change also coincides with a transition from 100-ky to 400-ky dominance in earth's eccentricity and relatively weak eccentricity forcing. At ~13.9 Ma, the sharp increase in δ18O marks the end of this major climatic transition and heralds a further step into the "icehouse-world".

Comparison of δ18O and δ13C profiles from DSDP Site 588 (SW Pacific Ocean), ODP Site 761 (E Indian Ocean) and Site 1146 (SCS) reveals marked differences in the characteristics of deep water mass changes at these three sites. These differences indicate restricted deep water exchange between the Pacific Ocean and Indian Ocean and significantly cooler deep water in the NE Indian Ocean throughout the middle Miocene. The δ18O profile at ODP Site 1146 also differs from published records from the Pacific and Indian Ocean, which show a stepped increase between 14.5 and 13.9 Ma. This may reflect differences in the deep-water mass characteristics of the SCS or indicate the recovery of a more complete record at ODP Site 1146.

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