Cyclostratigraphy and eccentricity tuning of the early Oligocene through early Miocene (30.1–17.1 Ma): *Cibicides mundulus* stable oxygen and carbon isotope records from Walvis Ridge Site 1264

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ABSTRACT

Few astronomically calibrated high-resolution (≤5 kyr) climate records exist that span the Oligocene-Miocene time interval. Notably, available proxy records show responses varying in amplitude at frequencies related to astronomical forcing, and the main pacemakers of global change on astronomical time-scales remain debated. Here we present newly generated X-ray fluorescence core scanning and benthic foraminiferal stable oxygen and carbon isotope records from Ocean Drilling Program Site 1264 (Walvis Ridge, southeastern Atlantic Ocean). Complemented by data from nearby Site 1265, the Site 1264 benthic stable isotope records span a continuous ~13-Myr interval of the Oligo-Miocene (30.1–17.1 Ma) at high resolution (~3.0 kyr). Spectral analyses in the stratigraphic depth domain indicate that the largest amplitude variability of all proxy records is associated with periods of ~3.4 m and ~0.9 m, which correspond to 405- and ~110-kyr eccentricity using a magnetobiostratigraphic age model. Maxima in $CaCO_3$ content, $\delta^{18}O$ and $\delta^{13}C$ are interpreted to coincide with ~110kyr eccentricity minima. The strong expression of these cycles in combination with the weakness of the precession- and obliquity-related signals allow construction of an astronomical age model that is solely based

on tuning the $CaCO_3$ content to the nominal (La2011_ecc3L) eccentricity solution. Very long-period eccentricity maxima (~2.4-Myr) are marked by recurrent episodes of high-amplitude ~110-kyr $\delta^{18}O$ cycles at Walvis Ridge, indicating greater sensitivity of the climate/cryosphere system to short eccentricity modulation of climatic precession. In contrast, the responses of the global (high-latitude) climate system, cryosphere, and carbon cycle to the 405-kyr cycle, as expressed in benthic $\delta^{18}O$ and especially $\delta^{13}C$ signals, are more pronounced during ~2.4-Myr minima. The relationship between the recurrent episodes of high-amplitude ~110-kyr $\delta^{18}O$ cycles and the ~1.2-Myr amplitude modulation of obliquity is not consistent through the Oligo-Miocene. Identification of these recurrent episodes at Walvis Ridge, and their pacing by the ~2.4-Myr eccentricity cycle, revises the current understanding of the main climate events of the Oligo-Miocene.

HIGHLIGHTS

- Oligo-Miocene benthic foraminiferal stable O and C isotope records from Site 1264
- Recurrent episodes of high-amplitude ~110-kyr cycles present in benthic $\delta^{18}O$ record
- Climate and cryosphere variability paced by ~110- and 405-kyr eccentricity cycles
- Carbon cycle pacing by the 405-kyr and ~2.4-Myr eccentricity cycles

KEYWORDS

Integrated stratigraphy; Palaeoclimatology; Oligocene-Miocene Transition; Astronomical Climate Forcing; Ocean Drilling Program Site 1264 (Walvis Ridge); Antarctic Ice Sheet; GPTS calibration

1. INTRODUCTION

The early Oligocene–early Miocene Epoch (here referred to as "Oligo-Miocene") constitutes the earliest phase of Earth's Cenozoic Icehouse, characterised by a continental-size ice-cap on Antarctica (Zachos et al., 1992). Superimposed on secular trends, Earth's high-latitude climate system, cryosphere, and carbon cycle responded to astronomically forced changes in insolation during the Oligo-Miocene on time-scales ranging from 10s to 100s of thousands of years (kyr) (e.g. (Pälike et al., 2006b)). However, seasonal changes in insolation are affected by very long-period amplitude modulations of obliquity and precession that occur on million-year (Myr) time scales and are thought to have also played a critical role in the occurrence of key palaeoclimatic events.

Over the past ~30 years, understanding of Oligo-Miocene climate history from a marine perspective has evolved as new records have become available and new proxy records have been developed. Early interpretations of the Oligo-Miocene climate system were based on relatively low-resolution deep-sea stable isotope records and were described as a series of Oi and Mi oxygen isotope zones, marked by a maximum $\delta^{18}O$ value at their base (Miller et al., 1991; Wright and Miller, 1992). These $\delta^{18}O$ maxima are often referred to as Oi and Mi "events". As higher resolution records have become available it has become clear that, similar to the Plio-Pleistocene, climate change during the Oligo-Miocene is strongly paced by variations of Earth's eccentricity-modulated precession and obliquity cycles. The influence of long-period eccentricity and obliquity cycles (~2.4- and ~1.2-Myr, respectively) on the pacing of the cryosphere, and carbon cycle is less well understood, although the prolonged absence of seasonal extremes (i.e. summer warming) may have played an important role in pacing global or high-latitude cooling and glacial expansion on Antarctica (Beaufort, 1994; Billups et al., 2004; Lourens, 1994; Lourens and Hilgen, 1997; Pälike et al., 2006a; Pälike et al., 2006b; Tian et al., 2008; Turco et al., 2001; Zachos et al., 2001). Records proximal to the Antarctic ice sheet provide support for astronomically controlled changes in seasonality significantly affected high-latitude climate and cryosphere (Naish et al., 2001).

Here, we present new high-resolution Oligo-Miocene (30.1–17.1 mega-annum, Ma) X-ray fluorescence (XRF) core scanning results and benthic $\delta^{13}C$ and $\delta^{18}O$ records from Ocean Drilling Program (ODP) Site 1264 on the Walvis Ridge, located in the southeastern Atlantic Ocean. This study builds on a previously published early Miocene stratigraphy from the same site (Liebrand et al., 2011). Time-series analysis, using an initial untuned magnetobiostratigraphic age model, indicates that eccentricity is most strongly expressed (Liebrand et al., 2011). We calibrate the records solely to the ~110-kyr component of the nominal (La2011_ecc3L) eccentricity solution and thereby avoid tuning complications arising from unknown phase relations and poorly constrained values for tidal dissipation and dynamical ellipticity that has affected tuning attempts based on obliquity and precession (Laskar et al., 2011; Zeeden et al., 2014). We construct a tuned age model by identifying the interference patterns resulting from different eccentricity periods (of mainly 95, 99, 124, 131 kyr/cycle and 405 kyr/cycle, here referred to as "~110-kyr" and "405-kyr" cycles) in signal and target curves and their subsequent alignment. We then use the eccentricity tuned astrochronology from Site 1264 to evaluate existing interpretations of astronomical pacing of Oligo-Miocene records (Abels et al., 2007; Billups et al., 2004; Pälike et al., 2006a; Pälike et al., 2006b; Tian et al., 2008; Zachos et al., 2001) and compare the results to those for the Miocene (Abels et al., 2005; Holbourn et al., 2013; Holbourn et al., 2015) and the Palaeocene-Eocene (Lourens et al., 2005). We specifically assessed the influence of the very long period eccentricity (~2.4-Myr) and the long period obliquity (~1.2-Myr) cycles on the climate/cryosphere of the early phase of Earth's Cenozoic Icehouse.

2. MATERIAL AND METHODS

2.1. Site descriptions

The records presented here are derived from two ODP Leg 208 sites drilled on the Walvis Ridge in the subtropical southeastern Atlantic Ocean (Fig. 1): Site 1264 (28°31.955'S, 2°50.730'E, 2505 m water depth) and Site 1265 (28°50.101'S, 2°38.354'E, 3059 m water depth) (Zachos et al., 2004). At Site 1264, two holes were drilled to ~280 meters below sea floor (mbsf) that yielded relatively expanded Oligocene and Miocene strata. No clear primary palaeomagnetic signal was discerned in shipboard analysis (Bowles, 2006; Zachos et al., 2004), but we have transposed magnetostratigraphies to Site 1264 through detailed cross-site correlations with Sites 1265 and 1266 (28°32.550'S, 2°20.610'E, 3798 m water depth). Through these correlations four small recovery gaps in the Oligocene of

Site 1264 are identified and filled with samples from Site 1265. Through comparison of integrated magnetobiostratigraphies, we compare stable isotope records and astrochronologies from the Walvis Ridge composite (primarily derived from Site 1264) to those from Ceara Rise Sites 926 and 929 (western equatorial Atlantic) (Pälike et al., 2006a), Agulhas Ridge Site 1090 (Atlantic sector of Southern Ocean) (Billups et al., 2004), Equatorial Pacific Sites 1218, U1334 and U1337 (Beddow et al., 2016; Holbourn et al., 2015; Pälike et al., 2006b) and South China Sea Site 1148 (Tian et al., 2008) (Fig. 1). Detailed site-to-site correlations of stable isotope records across the Oligocene-Miocene (Climatic) Transition (OMT) are presented in *Beddow et al*., (2016).

2.2. X-ray fluorescence core scanning

At Site 1264 the Oligo-Miocene study section is composed of $CaCO_3$-rich foraminifer-bearing nannofossil oozes (Zachos et al., 2004). XRF core scanning data were generated at the MARUM XRF-laboratory, University of Bremen. For Site 1264 the entire study interval was scanned along the shipboard splice with sufficient overlap between holes to enable independent splice review. Four splice gaps and/or uncertain tie-points were confirmed in the Oligocene part of the shipboard splice of Site 1264 (Fig. 2). To cover these intervals and check for stratigraphic continuity, we also scanned the lower Oligocene through lower Miocene of Site 1265. The XRF data were collected using an AVAATECH core scanner (Serial No. 12), fitted with an Oxford Instruments 100W Neptune Rh X-ray tube and a Canberra X-PIPS Silicon Drift X-ray Detector (SDD; Model SXD 15C-150-500). A step size of 20 mm, down-core slit size of 10 mm and a cross-core slit size of 12 mm were applied. The X-ray tube was operated at 10kV with

0.15mA current setting, and the measuring time for each step interval was 20 seconds with a dead time of >20 seconds. A processing model tailored to the 10kV scans was applied. Outliers resulting from section-ends and cracks were identified by eye and removed. We use calibrations ($r^2_{(1264)}$ = 0.84, $r^2_{(1265)}$ = 0.95) between ln(Ca/Fe) and shipboard coulometric $CaCO_3$ measurements from Sites 1264 and 1265 (Zachos et al., 2004) to estimate $CaCO_3$ content continuously throughout the study interval (Supp. Fig. 1). "$CaCO_3$ est." is used throughout the text to refer to carbonate content estimated by ln(Ca/Fe). Gaps in the $CaCO_3$ est. record from Site 1264 were supplemented with data from Site 1265. The use of a log-ratio record is preferred over integrated elemental area or "count" records to avoid biases related to, for example, the closed sum effect (inherent to XRF core scanning) and variable grain-size and water content; the use of log ratios also aids the comparability between XRF data obtained from the different drill-sites and/or scanners (Weltje and Tjallingii, 2008).

2.3. Depth models and site-to-site correlations

The shipboard splices of Sites 1264 (between 206–316 mcd), 1265 (between 117–163 mcd) and 1266 (133–198 mcd) are revised here using shipboard magnetic susceptibility and colour reflectance data (Zachos et al., 2004) and new XRF data. For several splice tie-points, small corrections are made. The new composite depth scales are referred to as "revised meters composite depth" (rmcd). For all sites, we also present an adjusted-rmcd (armcd) scale to correlate intervals that fall outside the splice to the splice and hence, armcd is equivalent to rmcd in the intervals within the splice.

The spliced records are correlated in the depth domain between Walvis Ridge Sites 1264, 1265 and 1266 using visually selected multi-sensor track magnetic susceptibility, colour reflectance or XRF tie-points and subsequent automated correlation using the Match script (Lisiecki and Lisiecki, 2002). No significant changes are made for the early Miocene correlation between Sites 1264 and 1265 previously published (Liebrand et al., 2011). We estimate the maximum uncertainty in the depth correlations to be of the order of 10–20 cm, depending on the structure of the data in a particular interval.

2.4. Sample processing and stable isotope analyses

For this study, the previously published early Miocene record from Site 1264 (1919 samples spanning ~44 m between ~216 and 260 armcd, or ~5 Myr, (Liebrand et al., 2011)), was extended downwards into the Oligocene and upwards into the Miocene (2689 new samples, spanning ~67 m between ~207 and 216 armcd, and between ~260 and 318 armcd, or ~8 Myr in total). All new samples were taken at 2.5-cm resolution along the splice at a volume of 10–15 cm^3. Weights were recorded after each step of sample processing. Discrete sample magnetic susceptibility was measured on freeze-dried bulk samples at Utrecht University on a Kappabridge KLY-2 and at the University of Southampton on a Kappabridge KLY-4 magnetic susceptibility system. Samples were washed over 38, 63 and 150 μm sieves with tap water and dried overnight at 50°C. For all samples, the epifaunal benthic foraminifer species *Cibicides mundulus* was picked from the >150 μm fraction. Stable isotope measurements were performed on single tests (i.e. the visually best specimen available per sample); however, two to four specimens were measured simultaneously in ca. 50% of the samples to reach the minimum (~20 μg) or ideal (30–50 μg) sample weight for the Kiel carbonate device. For the Site 1264 sample set (n = 2536), the foraminiferal calcite was reacted with phosphoric acid in a Thermo Finnigan Kiel-III automated preparation system at Utrecht University. Purified CO_2 was analysed on a Thermo Finnigan MAT 253 mass spectrometer. The results were compared to an internal gas standard and isotopic ratios were drift-corrected to nine individual NBS-19 values measured along each sample run. To cover the four gaps in the Oligocene part of the Site 1264 records, 153 samples of Site 1265 measured using a Thermo Finnigan GasBench-II carbonate preparation device coupled to a Thermo Finnigan Delta-V mass spectrometer at Utrecht University. A small (0.2‰) correction was applied for the oxygen isotope results obtained on the Delta-V to match duplicate runs (n = 27) of the same sample set measured on the Thermo Finnigan MAT 253. Outliers defined in either the oxygen or carbon stable isotope records from Sites 1264 and 1265 were removed from both records and, if possible, remeasured. We also redefined outliers in the previously published early Miocene part of the records, which were measured at both Utrecht University and the University of Florida (Liebrand et al., 2011).

2.5. Time series analysis

Power spectra of the depth and time series were calculated using Blackman-Tukey Fast-Fourier Transforms (Paillard et al., 1996). Wavelet analyses were applied to track cyclicities and to quantify their changing amplitudes through depth or time (Grinsted et al., 2004) and to calculate their mean spectral power (Torrence and Compo, 1998). The wavelet-script of *Grinsted et al.* (2004) was adapted to enable three-dimensional (3D) viewing, which enhanced the resolvability of the time-period transforms also when depicted in two dimensions (2D). To further assess the amplitude evolution of specific frequency bandwidths, broad bandwidth Gaussian filters (Paillard et al., 1996) and their Hilbert-transforms were computed. These results were compared in the age-domain to those of the astronomical calculations (Laskar et al., 2011). Blackman-Tukey cross-spectra were calculated between the data records and eccentricity to obtain coherency and phase estimates (Paillard et al., 1996).

3. RESULTS

3.1. Description of the records

3.1.1 Size-fraction, XRF, and stable isotope records

The dry weights of the three sample fractions, combined with the dry weights of the washed samples, were used to calculate weight percent (wt%) records of the 0–38, 38–63, 63–150 and >150 μm size fractions (Fig. 2). At Site 1264, a steady increase in the percentage of the 63–150 μm fraction is observed between 305–250 armcd (late Oligocene), briefly interrupted by a small decrease between 260–255 armcd, followed a steady decrease between 250–220 armcd and another increase between 220–207 armcd (early Miocene). Peaks in the >150 μm size fraction are observed near 253 armcd (OMT interval) and 210 armcd. Higher wt% values in the >150 μm size fraction are recorded in the upper part of the study section between 253–207 armcd (early Miocene) compared to the lower study interval (317–253 armcd; mid to late Oligocene) (Fig. 2).

Variability in the XRF-derived $CaCO_3$ est. record ranges between 88 and 100 wt% $CaCO_3$ and is largest between 252–216 armcd (early Miocene) and 279–318 armcd (mid

Oligocene) (Fig. 2). These intervals also record the highest and lowest $CaCO_3$ values in the study interval. Reduced variability is recorded between 252–279 armcd (late Oligocene).

Benthic foraminiferal stable oxygen isotope ratios ($\delta^{18}O$) vary between 1.25 and 2.45‰, resulting in a total range of 1.2‰ across the study interval (Fig. 2). The highest $\delta^{18}O$ values of ~2.4‰ are reached at ~253 armcd (Oligocene-Miocene Transition) Low $\delta^{18}O$ values of ~1.2‰ are recorded in several intervals between ~263–220 armcd (latest Oligocene and early Miocene). After detrending, the $\delta^{18}O$ record has a standard deviation of ~0.15‰ and a maximum variability of ~1.0‰. Similar to the $CaCO_3$ est. record, an interval with particularly reduced amplitude variability in $\delta^{18}O$ is recorded between 260–280 armcd (late Oligocene).

Stable carbon isotope ratios ($\delta^{13}C$) of *C. mundulus* range between ~0.2 and ~1.9‰ throughout the record (Fig. 2). A long-term increase in $\delta^{13}C$ is observed up to 240 armcd, which is interrupted by a step-wise decrease at 240 armcd corresponding to the Oligocene-Miocene Carbon Maximum (Hodell and Woodruff, 1994). Several $\delta^{13}C$ minima of ~0.2‰ are recorded between 290–318 armcd. The $\delta^{13}C$ record peaks with values of ~1.9‰ at ~253 armcd. After the long-term trend is removed the $\delta^{13}C$ record has a standard deviation of ~0.15‰ and shows ~1.0 ‰ amplitude variability.

3.1.2. Magnetostratigraphy

Despite recognition of clear polarity zones at nearby Deep-Sea Drilling Project (DSDP) Leg 73 sites (e.g. (Tauxe and Hartl, 1997)), it was not possible to generate a magnetostratigraphic record of similar quality at Site 1264 (Bowles, 2006; Zachos et al., 2004). To obtain a magnetostratigraphic age constrain we instead transposed the palaeomagnetic records from Site 1265 (C5En(o)–C7n(y)) and Site 1266 (C6Cn.1n(y)–C11n.2n(o)) to Site 1264 (see section 2.3). The chron labelling of Sites 1265 and 1266 are reinterpreted after comparison with the Oligocene and Miocene GPTS (Hilgen et al., 2012; Vandenberghe et al., 2012); the published magnetostratigraphies of these sites, however, have not been revised.

4. CYCLOSTRATIGRAPHY AND TUNED AGE MODEL

4.1. Cyclostratigraphy

4.1.1. Spectral analysis in the depth-domain

Wavelet and mean spectral-power analyses were initially carried out on the proxy records in the depth domain. All depth series ($CaCO_3$ est., $\delta^{13}C$, $\delta^{18}O$) show at least two (broad) spectral peaks: the first peak centred at ~3.4 m/cycle and a second peak at ~0.9 m/cycles, of which the former is most strongly recorded in $\delta^{13}C$ and the latter in $CaCO_3$ est. and $\delta^{18}O$ (Fig. 3). We recognise clear bundling of three to four ~0.9 m cycles into ~3.4 m cycles in the best-preserved intervals of the $CaCO_3$ est. record (e.g. between 220–250 mcd, Fig. 2). In general, the spectral power of the shorter (<1 m/cycle) periods is much reduced compared to that of the longer (>1 m/cycle) periods. The ~3.4 m cycle in $\delta^{13}C$ can be tracked nearly continuously in the depth domain, suggesting that sedimentation rates for the largest part of the record had been relative stable and that spectral peaks in the depth domain are indicative of certain periodicities in the age domain. This period is split in two components between 285 and 315 armcd, indicating that two closely spaced periods are present. The strongest responses of both stable isotope records on the ~3.4 m/cycle period are present at ~255 armcd.

4.1.2. Application of initial magneto-biostratigraphic age model

An initial age model based on a polynomial fitting through selected bio- and magnetostratigraphic age control points was applied to the Site 1264 record (Bowles, 2006; Zachos et al., 2004) (Supp. Fig. 2). This polynomial age model is not affected by transient changes in sedimentation rates or assumptions about astronomical climate forcing. Based on the initial age model, the bundling recognised in the $CaCO_3$ est. depth-series represents three to four ~110-kyr cycles (~0.9 m/cycle) into 405-kyr cycles (~3.4 m/cycle). Consequently, we confidently link the ~3.4 m and ~0.9 m cycles present throughout nearly all depth-series to 405- and ~110-kyr eccentricity periods, respectively. Wavelet depth-period conversions show that we can track the ~3.4 m and ~0.9 m (weaker) cycles and that these cycles vary moderately in thickness throughout the records (between 5–2 m and 1.5–0.5, respectively; Fig. 3).

4.1.3. Proxy for tuning and phase relationships

The $CaCO_3$ est. record is the most continuous recorder of the ~110-kyr eccentricity cycle throughout the study interval and is selected as tuning signal. We favour tuning to $CaCO_3$ est. over tuning to the isotope records, as the former likely represents a more direct regional response to insolation forcing, whereas the latter are most likely affected by the slow response times of the global cryosphere and carbon systems introducing phase lags. It is uncertain whether carbonate production or water column/seafloor dissolution was a more important control on carbonate accumulation at Site 1264, but identification of the dominant process is important because it determined the phase relation of the $CaCO_3$ est. record to eccentricity. The phase relationship between benthic foraminiferal $\delta^{18}O$ and eccentricity, however, is clear at Site 1264 and also at other drill sites (Pälike et al., 2006a; Pälike et al., 2006b), with maxima in $\delta^{18}O$ (indicative of cooler more glacial conditions) associated with ~110-kyr eccentricity minima and *vice versa*. $\delta^{18}O$ and $CaCO_3$ est. are positively correlated throughout the Site 1264 record on the ~110-kyr period, and hence we infer a phase relationship in which maxima in $CaCO_3$ correspond to minima in eccentricity (and *vice versa*). Additional indication of an inverse relationship between $CaCO_3$ est. and eccentricity is the cycle-shape of early Miocene ~110-kyr $CaCO_3$ cycles that show narrow peaks and broad troughs between 19.5 and 22.5 Ma (Fig. 4), thereby mimicking the inverse of the eccentricity solution, despite the fact that (post-) depositional processes can distort cycle shapes (Herbert, 1994). The increase in absolute $CaCO_3$ values and the change in ~110-kyr cycle shapes during the early Miocene now suggest that carbonate production is the most important control on this part of the records. If dissolution was the main control on $CaCO_3$ est., the opposite phase relationship would be expected (Herbert, 1994) with peak dissolution (and hence low $CaCO_3$ content) during glacial maxima in response to, for example, the intrusion of more corrosive bottom waters into the Atlantic Ocean (e.g. (Pälike et al., 2006a)) or comparable processes. During the Oligocene, dissolution may have had a somewhat stronger control on the record. However, $CaCO_3$ values remain high at Site 1264 throughout the study interval, and there is no evidence of similarly strong ~110-kyr cyclicity in the size fraction records data that would indicate major dissolution. With the sign of the phase relationship between $CaCO_3$ and eccentricity determined at the ~110-kyr period, we assumed that this relationship is completely inverse because of the striking similarity in the shape of the excursions between signal and target after this phase-shift has been applied. This allows $CaCO_3$ est. maxima to be tied to eccentricity minima without introducing a lag for the entire span of the record.

4.2. Tuned age model

4.2.1. Tuning to stable eccentricity

The choice of the eccentricity solution as target curve for tuning was primarily driven by the exceptionally strong expression of eccentricity in the $CaCO_3$ est. and benthic stable isotope records in combination with the lack of strong obliquity and precession-controlled variability. A broad Gaussian filter of the detrended data plotted on the initial magnetobiostratigraphic age model, centred around the 405-kyr period, identified 32 cycles, indicating that the total duration of the time-series is ~13 Myr. Initial tuning tie points in the data filters were selected at every 405-kyr maximum, corresponding to 405-kyr eccentricity minima. Next, all data sets ($CaCO_3$, $\delta^{18}O$, $\delta^{13}C$) were considered to visually identify the individual ~110-kyr cycles. Fine-tuning of the entire record to the (nominal) La2011_ecc3L eccentricity solution was, however, solely based on a synchronisation (i.e. final depth-to-age tie point selection) of $CaCO_3$ est. maxima to ~110-kyr eccentricity minima (hereafter referred to as the "tuned age model"). Eccentricity minima correspond to periods when Earth orbit around the sun was near circular and form relatively short lasting "events" in the eccentricity solution (compared to the maxima), which makes them precise age-calibration points. The latest numerical eccentricity solution (La2011_ecc3L) is considered to be reliable back to ~50 Ma (Laskar et al., 2011). Application of the tuned age model across the Site 1264 study interval indicates that sedimentation rates range between ~0.5 and 1.5 cm/kyr (Supp. Fig. 3)

4.2.2. Spectral analysis in the tuned time-domain

On the astronomically tuned age model, the Site 1264 records span the interval between 30.1 and 17.1 Ma (Fig. 4). This comprises a Rupelian–Burdigalian interval contemporaneous with 405-kyr eccentricity Cycles 43–74 and Chrons C5–C11. It further encompasses ~2.4-Myr eccentricity Cycles 8–13 and ~1.2-Myr obliquity Cycles 16–26. Power-spectral and wavelet analyses of the eccentricity tuned time-series of $CaCO_3$ est., $\delta^{13}C$, and $\delta^{18}O$ display high spectral power at the ~110- and 405-kyr eccentricity frequencies and low (or even absent) spectral power at the higher obliquity and precession frequencies (Fig. 5). Intervals with high-amplitude ~110-kyr power reoccur in the wavelet of $\delta^{18}O$ at ~29.4, ~27.4, ~22.8 and ~19.6 Ma. An additional low frequency spectral peak is recorded in $\delta^{18}O$ and $\delta^{13}C$ that corresponds to periods of ~160- and ~200-kyr, respectively; during eccentricity Cycle 53 a very high-amplitude response on this period can be observed in the $\delta^{18}O$ record. The 405-kyr cycles can be most easily tracked in the stable isotope records, despite the lack of a strong 405-kyr signal in some intervals. This shows time periods, particularly during ~2.4-Myr eccentricity maxima, where the relative response of the proxy records to 405-kyr eccentricity was much attenuated, for example, during the late Oligocene and (briefly) post-OMT (Fig. 5). The $CaCO_3$ est.

record shows split ~125-kyr and ~95-kyr responses during ~2.4-Myr eccentricity maxima in the early Miocene, similar to the eccentricity solution.

4.2.3. Filtering and amplitude modulation

Detrended and normalised time-series were filtered using broad Gaussian band-pass filters centred on the 1/405 and 1/110 (combined 1/125 and 1/95) eccentricity frequencies (*Paillard et al.*, 1996). Additionally, amplitude modulations of the filters were calculated using a Hilbert-transform (e.g. (Shackleton et al., 1999)). The amplitude of the 405-kyr cycle in $\delta^{13}C$ is largest during ~2.4-Myr minima, thereby mimicking the amplitude modulation of the 405-kyr filtered eccentricity solution, albeit slightly amplified and lagged in certain intervals (Fig. 6, Supp. Fig. 4). A similar strong response is not observed in $\delta^{18}O$, but a weaker ~2.4-Myr modulation of 405-kyr cycles is still apparent, especially in the Oligocene interval. The $CaCO_3$ est. record does not show a clear 405-kyr amplitude response to ~2.4-Myr eccentricity. The amplitude modulation of the ~110-kyr cycle in $CaCO_3$ est., however, shows large responses during 405-kyr eccentricity Cycles 72, 69–68, 56–54, 50, 49 and 44 (Fig. 7). Similar analyses on $\delta^{18}O$ show strong ~110-kyr cycles concurrent with 405-kyr eccentricity Cycles 73, 69–68, 57 and 49. An attenuated amplitude response of $\delta^{18}O$ to the ~110-kyr eccentricity cycle corresponds to 405-kyr eccentricity Cycles 64–59. The $\delta^{13}C$ record shows strong ~110-kyr responses contemporaneous with 405-kyr eccentricity Cycles 69 and 43.

4.2.4. Coherency and phase

All time series are coherent with eccentricity at the 405-, ~125- and ~95-kyr periods and $CaCO_3$ est. is also coherent on the (weak) ~50 kyr eccentricity period (Fig. 8). Spectral power and coherency are variable throughout the records in close relation to amplitude modulation by the ~2.4-Myr eccentricity cycle. Blackman-Tukey cross-spectral phase estimates indicate an unstable phase of $CaCO_3$ est., a ~7 kyr lead of $\delta^{18}O$, and a ~18 kyr lag of $\delta^{13}C$ relative to eccentricity at the 405-kyr period (Fig. 8). At the ~125-kyr period lags of ~2 kyr, ~6 kyr and ~7 (i.e. 4–10) kyr relative to eccentricity are calculated, for $CaCO_3$ est., $\delta^{18}O$, and $\delta^{13}C$, respectively. An in-phase relationship is identified at the ~95-kyr eccentricity period for $CaCO_3$ est., while for $\delta^{18}O$ and $\delta^{13}C$ this is a lag of ~6 kyr (4–8 and. 3–9 kyr, respectively). The in-phase relations found for $CaCO_3$ est. to eccentricity at the ~110-kyr period (i.e. the combined ~95- and ~125-kyr periods) are imposed on the record by the tuning assumptions. We note that these phase estimates are sensitive to relatively small changes in the tuned age model and represent averages of the entire time-series, and not all are stable throughout this time interval. Phase relationships to obliquity and precession are not calculated as they are excluded from the tuning target curve.

5. IMPLICATIONS OF ECCENTRICITY TUNED AGE MODEL

5.1. Eccentricity prevalence

Despite the lack of strong precession and obliquity signals at Site 1264, eccentricity-paced variability is strong in comparison to previously published Oligo-Miocene stable isotope and $CaCO_3$ est. records. Even in intervals with the highest sedimentation rates (~1.5 cm/kyr, e.g. between 29.5 and 28.5 Ma, and 24.8 and 22.0 Ma; Fig. 5), where higher frequencies have a greater likelihood of being preserved, eccentricity is still prevalent over precession and obliquity. This suggests that the dominance of eccentricity does not result from diagenesis, bioturbation or other post-depositional biases.

There is a striking similarity between $CaCO_3$ est. and eccentricity patterns at Site 1264, especially during the early Miocene part of the record (Fig. 4). Eccentricity pattern recognition in the $CaCO_3$ est. record becomes more difficult across intervals that correspond to strong ~2.4-Myr eccentricity minima, characterised by a weaker expression of the ~110-kyr beat for the duration of one or two 405-kyr cycles. Within the ~2.4-Myr minima, fewer tie-points were selected for tuning and only those that are certain on either side of the ~2.4-Myr eccentricity minimum were used.

On the tuned age model, eccentricity is strongly expressed in the mean power spectra and wavelet analyses. Only a weak obliquity component can be identified in certain intervals – an important result considering the exclusion of obliquity from the tuning target curve. The relative weakness of the obliquity signal at Site 1264 is probably the result of the moderate-to-low sedimentation rates and contrasts markedly with the records from Ceara Rise Sites 926 and 929, which are characterised by high sedimentation rates of ~2.5 cm/kyr and show a very strong imprint of obliquity (Pälike et al., 2006a). The phase-relations of the $CaCO_3$ est. and stable isotope records to the 405-kyr and ~110-kyr eccentricity periods at Site 1264, however, are in general agreement with those described for records from the Ceara Rise (Pälike et al., 2006a; Zachos et al., 2001) and equatorial Pacific (Pälike et al., 2006b), with the exception of the apparent ~7-kyr lead of the Site

1264 $\delta^{18}O$ record to the 405-kyr eccentricity cycle, and the ~20- and ~30-kyr lags of the Ceara Rise $\delta^{18}O$ and $\delta^{13}C$ isotope chronologies, respectively, to the ~110-kyr eccentricity periods (Pälike et al., 2006a).

The 160–200 kyr period found in the time series and power spectra of the isotope records (especially in $\delta^{18}O$) from Site 1264 may reflect (i) a response to the ~180-kyr modulation of the 40-kyr obliquity cycle, (ii) a harmonic response to two ~110-kyr eccentricity cycles, or (iii) a harmonic to half of the 405-kyr eccentricity cycle. Whichever mechanism is responsible for this cyclicity, all possible mechanisms would require a nonlinear climatic response, as no equally strong direct responses to obliquity or climatic precession are found in the power-spectra and wavelet analyses of Site 1264. The ~180-kyr period is also recognised in the amplitude modulation of spliced magnetic susceptibility records from Ceara Rise (Shackleton et al., 1999) and in power spectra of an (obliquity-tuned) early Miocene benthic stable isotope records from Site 1148 (Tian et al., 2008), suggesting that it may represent a global signal.

5.2. Exclusion of precession and obliquity

Precession and obliquity were excluded from the Site 1264 tuning approach mainly due to the lack of a clear expression of these high-frequency signals. In addition, there are currently no constraints for tidal dissipation and dynamical ellipticity, which in turn affect the exact ages of individual obliquity and precession cycles (though not their modulations) beyond ~10 Ma (Zeeden et al., 2014). The eccentricity-based tuning approach applied in this study is unaffected by these problems but compromises age precision at the obliquity/precession level (~20–40 kyr). We argue, however, that previously published Oligo-Miocene age-calibration studies that incorporated obliquity and/or precession in their tuning-targets cannot guarantee age precision at this level either. The accuracy of any tuned ages >10 Ma is primarily constrained by the stable eccentricity solution (Zeeden et al., 2014), which modulates precession, or by tuning to the stable modulation of obliquity (Shackleton et al., 1999).

The weak imprints of precession and obliquity on the $CaCO_3$ est. and stable isotope records at Site 1264 could be the result of under-sampling, but only within the intervals with the lowest sedimentation rates. Technically, though, the sampling resolution of 2.0–2.5 cm (≤3.0 kyr) is above the Nyquist frequencies of precession and obliquity even in intervals with lower sedimentation rates. We propose several alternative mechanisms that may have affected the strength of precession and obliquity in the data. First, bioturbation and physical processes could have resulted in severe sediment mixing over time, which would have operated as a low-pass filter. Second, diagenesis resulting from partial $CaCO_3$ dissolution and recrystallization could have disturbed the higher frequency signals. 'Frosty' preservation of foraminifera at Site 1264 indicates some degree of diagenesis. Third, a precession signal could have been cancelled out in globally integrated proxy records if an equal and out-of-phase northern hemisphere and southern hemisphere ice-sheet response to precession forcing operated during the Oligo-Miocene interval, similar to what has been proposed for the 40-kyr obliquity-paced early Pleistocene (Raymo et al., 2006). Fourth, transient two-to-three fold changes in LSRs (0.5–1.5 cm/kyr) across the study interval (Supp. Fig. 3) may have distorted the higher frequencies in the depth domain, so that the precession, obliquity and eccentricity components overlap in mean spectral power (Fig. 2, bottom panel) and especially the precession frequencies become harder to register (Herbert, 1994). Fifth, the strength of the eccentricity signal may have been enhanced relative to those of precession and obliquity, as the latter are not included in the tuning target curve. Sixth, there was a general lack of cyclicity in bottom-water temperature, carbonate production, etc. on obliquity/precessional time scales at Site 1264. It is likely that some combination of these mechanisms explains the weak imprint of precession and obliquity at Site 1264, with the exception of an out-of-phase precession control on Oligo-Miocene global land-ice since there is no evidence for an extensive NH ice sheet until the Plio-Pleistocene.

5.3. Sedimentation rates and size fractions

Linear sedimentation rates (LSR) documented at Site 1264 (~0.5–1.5 cm/kyr) are typical for $CaCO_3$ dominated pelagic sites (Supp. Fig. 3). Peak LSRs (~1.0–1.5 cm/kyr) are recorded across the OMT, contemporaneous with an increase in %coarse fraction (mainly within size fractions 63–150 μm and >150 μm; Fig. 2). The 63–150 μm size fraction increases between 27.5 and 23.0 Ma and then declines between 23.0 and 21.5 Ma. We link these trends to changing climatic and ecological conditions associated with the late Oligocene warming trend (~26.5–23.5 Ma; Fig. 4) and OMT (~23.5–22.5 Ma) that enhanced planktic foraminiferal production/accumulation. However, we cannot rule out a possible control of secular changes in carbonate saturation state and transient lysocline migrations on preservation of planktic foraminifera. We note that the size fractions are selected based on the mesh size of the sieves and that they may also have been affected by changes in the production/accumulation of the fine-fraction (nannofossil) carbonate.. The increase in LSR across the OMT is synchronous with increased benthic foraminiferal accumulation rates at Site 1265 (Diester-Haass et al., 2011) and may indicate (temporarily) increased export productivity at Walvis Ridge during the OMT, perhaps associated with increased carbon burial in the deep sea acting as a contributing positive feedback to the transient OMT glaciation (Diester-Haass et al., 2011; Mawbey and Lear, 2013).

5.4. Age model comparison through magneto-biostratigraphy

The magnetostratigraphic records compiled here (Bowles, 2006) on an astronomically tuned age model are not sufficiently resolved to further constrain the GPTS ages for polarity reversals (Table 1, Supp. Fig. 5). The tuned ages from Walvis Ridge generally support the ages of Billups et al. (2004), Pälike et al. (2006b) and the GTS2012 (Hilgen et al., 2012; Vandenberghe et al., 2012) for the chrons between 30.1 and 17.1 Ma (chrons C5D through C11) within the uncertainties resulting from site-to-site correlations, astronomical tuning and the exact position of the reversals in depth. However, the ages for Chron 7 (with the exception of C7n.2n(o)), marked as "uncertain" by Bowles (2006), appear anomalously young compared to the ages of the GTS2012 and Cande and Kent (1995). Additionally, the tuned early Miocene ages between 23.5 and 20.5 Ma (chrons C6An.2n (o) through C7n.2n (y)) are consistently older than the GTS2012 ages by ~33 kyr, suggesting that the linear interpolation between the mid Miocene and the OMT age points used to calibrate the magnetostratigraphic reversal ages for the early Miocene underestimates the ages of these chrons (Table 1, Supp. Fig. 5) (Hilgen et al., 2012;

Lourens et al., 2004). A detailed description of the nannofossil biostratigraphy and age constraints is presented in the supplementary information (see also Supp. Fig. 6).

6. A revised astronomical-pacing theory for the Oligo-Miocene

6.1. Long-period eccentricity-pacing of benthic $\delta^{18}O$ and $\delta^{13}C$

We identify four recurrent, 405-kyr long intervals at Site 1264 that are characterised by strong oscillations in benthic foraminiferal $\delta^{18}O$. These intervals occur in response to high-amplitude ~110-kyr eccentricity forcing and are contemporaneous with ~2.4-Myr eccentricity maxima (Cycles 13, 12, 10 and 9) and with relatively lower amplitude 405-kyr eccentricity maxima (Cycles 73, 68, 57 and 49, Figs. 4 and 9). These $\delta^{18}O$ events stand apart by their very large magnitude of oscillation (~1.0‰) occurring on timescales as short as ~110 kyr. For instance, during 405-kyr eccentricity Cycle 68, there is a very prominent interglacial-glacial cycle with a magnitude of ~1.0‰ – almost encompassing the range of $\delta^{18}O$ variability in the entire record in one ~110-kyr cycle. This range of variability may also have been present at higher frequencies during the Oligo-Miocene, however, the relatively low sedimentation rates at Site 1264 would likely prevent their detection in the isotope records.

There is no consistent relationship through the Oligo-Miocene between the $\delta^{18}O$ events (hereafter identified by their corresponding 405-kyr cycle number) and the ~1.2-Myr amplitude modulation of obliquity. Episodes 73 and 68 correspond (broadly) to ~1.2-Myr obliquity maxima, while Episodes 57 and 49 correspond to nodes in the ~1.2-Myr amplitude modulation of obliquity (Figs. 4 and 7). The $\delta^{18}O$ record from Site 1264 therefore only partially supports the view that the power of ~110-kyr cycles increases during nodes in the amplitude modulation of obliquity (Abels et al., 2005; Holbourn et al., 2013; Pälike et al., 2006a; Pälike et al., 2006b), which also has implications for the transient glaciation across the OMT. The long-term early Oligocene–early Miocene context that Site 1264 provides for the OMT, combined with reconstructions of atmospheric CO_2 levels (Beerling and Royer, 2011; Zhang et al., 2013), suggests that tectonic events and the long-term trends in CO_2 contributed significantly to the severity of the transient glaciation across OMT. Additional evidence of nonlinearity and secular changes within the climate/cryosphere system comes from the observation that certain intervals with similar eccentricity configurations (weak 405-kyr maxima during ~2.4-Myr maxima) did not result in high-amplitude ~110-kyr cycles in benthic $\delta^{18}O$, for example during ~2.4-Myr eccentricity Cycle 11 in the late Oligocene (Figs. 4 and 7).

The ~2.4-Myr cycle is also pronounced in the modulation of the 405-kyr filtered $\delta^{13}C$ record (Fig. 6, Supp. Fig. 4). Comparison with other high-resolution stratigraphies from the Meso- and Cenozoic shows that 405-kyr carbon cycle variability is persistently controlled by the ~2.4-Myr eccentricity pacing from the Cretaceous (Sprovieri et al., 2013), through Palaeo-Eocene (Littler et al., 2014; Lourens et al., 2005) to (at least) the Oligo-Miocene ((Boulila et al., 2012; Pälike et al., 2006b), this study). A ~2.4-Myr pacing in the Oligo-Miocene is also reported in lacustrine sediments of the Ebro basin (Valero et al., 2014) and in land mammal turnover rates (Van Dam et al., 2006).

6.2. Recurring episodes of high-amplitude, ~110-kyr cyclicity in benthic $\delta^{18}O$

The high-resolution record from Site 1264 demonstrates that high-amplitude, ~110-kyr-paced benthic $\delta^{18}O$ cycles are associated with ~2.4-Myr eccentricity maxima and provides a new picture of global climate change during the Oligo-Miocene. Previous studies have shown that high-amplitude ~110-kyr cycles are present throughout the Oligocene and Miocene (Holbourn et al., 2013; Holbourn et al., 2015; Pälike et al., 2006b; Zachos et al., 2001), but the 13-Myr long record presented here gives a unique perspective on the recurrence of these high-amplitude cycles. We view the intervals of enhanced glacial/interglacial cyclicity (Episodes 73, 68, 57 and 49; Fig. 9) to be the most characteristic episodes of the Oligo-Miocene, in a similar way that hyperthermal events have come to define the key responses of interest of Cenozoic Greenhouse climate to eccentricity-paced carbon cycle perturbations (Lourens et al., 2005). This new view, based on a unique continuous high-resolution stratigraphy from one location spanning 13 Myr, conflicts with the prevailing paradigm and its accompanying chemostratigraphic Oi and Mi zonation scheme originally defined based on low-resolution benthic $\delta^{18}O$ records (Miller et al., 1991; Wright and Miller, 1992). In this scheme, oxygen isotope zones were defined as 1.0 to 4.5 Myr long intervals with a positive $\delta^{18}O$ excursion at their base and were numbered, like biozones, in a chronological order. Later studies used these zonations to refer to the most prominent positive $\delta^{18}O$ excursions of the Oligocene and Miocene (e.g. (Zachos et al., 1997)). These positive $\delta^{18}O$ excursions have been previously postulated to occur at ~1.2-Myr intervals in conjunction with nodes in the amplitude modulation of obliquity (Lourens, 1994; Lourens and Hilgen, 1997; Pälike et al., 2006b; Turco et al., 2001; Zachos et al., 2001). The extended $\delta^{18}O$ record from Site 1264, with clear variability in the amplitude modulation of the ~110-kyr cycle, now shows that these recurrent episodes resulted from a nonlinear response of Earth's climate and cryosphere to ~2.4-Myr eccentricity pacing. This contrasts an earlier interpretation of the untuned early Miocene interval of the same site, which proposed a pacing of glacial expansions in Antarctica and subsequent high-amplitude ~110-kyr variability in $\delta^{18}O$ as resulting from a nonlinear response to multiples of 405-kyr eccentricity cycles (Liebrand et al., 2011).

7. CONCLUSIONS

We present high-resolution XRF- and coulometry-based $CaCO_3$ and benthic foraminiferal $\delta^{18}O$ and $\delta^{13}C$ records from South Atlantic Ocean Site 1264 (Walvis Ridge) that span a 13-Myr interval through the early Oligocene to early Miocene (30.1 to 17.1 Ma). All time series record a very strong imprint of eccentricity, particularly short (~110-kyr) eccentricity. The dampened expression of obliquity and climatic precession may be regarded as atypical for Oligo-Miocene high-resolution climate proxy records but allows development of an age model solely based on the alignment with the eccentricity solution. This age calibration approach is further strengthened by the unknown phase relationship of the global climatic response to precession forcing and by the poorly constrained values for tidal dissipation and dynamical ellipticity during the Oligo-Miocene, which affects both the stability of obliquity and precession in the astronomical solutions. The eccentricity-based tuning of ODP Site 1264 is broadly in agreement with earlier astronomical age calibration studies and within error of GPTS2012 age calibrations of palaeomagnetic reversals.

The Site 1264 records show variable amplitudes of response to eccentricity forcing. The ~110 and 405-kyr responses are especially amplified and paced by the ~2.4-Myr eccentricity cycle. This view of pacing of the global climate system and the Antarctic ice sheet, controlled mainly by eccentricity modulation of precession during the mid Cenozoic, revises previous Oligo-Miocene astronomical pacing and forcing theories that attributed stronger and almost singular linear control of obliquity (and precession) on global change. The $\delta^{18}O$ data show that the global (high-latitude) Oligo-Miocene ocean–atmosphere–cryosphere system was modulated by the ~2.4-Myr very long period eccentricity cycle and remarkably sensitive on a timescale of ~110-kyr.

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FIGURE CAPTIONS

Figure 1: Site locations. a) Palaeogeography (~23 Ma) showing approximate locations of the drill-sites discussed (www.odsn.de). The existence of a significant northern hemisphere Oligo-Miocene ice sheet is currently unknown. WALV stands for Walvis Ridge. **b)** Modern day bathymetry of the Walvis Ridge with selected ODP Leg 208 sites used in this study ((Zachos et al., 2004) and references therein).

Figure 2: Stratigraphic records from Sites 1264, 1265 and 1266. XRF and stable isotope depth-series predominantly from Site 1264, complemented by data from Site 1265, which cover four small recovery gaps at Site 1264 (see red crosses and grey horizontal lines). Magnetostratigraphy is transposed from Sites 1265 and 1266 (Bowles, 2006). Grey indicates uncertain polarity, narrow grey bars indicate uncertain reversal positions. Core-photographs (Zachos et al., 2004) show apparent cyclicity resulting from uneven lighting conditions. We have therefore depicted colour-extracts of the well-lit parts from each core-section to graphically represent the general homogeneity of the mud.

Figure 3: Wavelet analyses in the stratigraphic domain. 2D views of 3D-wavelets (after (Grinsted et al., 2004; Torrence and Compo, 1998)). Continuous black lines on the wavelets represent the 95% significance levels. E, O, P stands for an arbitrary mix of

eccentricity, obliquity, and precession (Laskar et al., 2011; Laskar et al., 2004), which here is rescaled to depth using the tuning tie-points.

Figure 4: Astrochronology from Walvis Ridge (predominantly Site 1264). Eccentricity-tuned records plotted against the stable components (i.e. modulations in case of obliquity) of the La2004 obliquity and La2011_ecc3L eccentricity solutions (Laskar et al., 2011; Laskar et al., 2004). Green, black, and grey numbers represent the ~2.4-Myr eccentricity, ~1.2-Myr obliquity, and 405-kyr eccentricity cycles, respectively, counted back from the present. Note that obliquity is only depicted for comparison; it did not serve as tuning-target. The transposed (to Site 1264) and tuned magnetostratigraphies from Sites 1265 and 1266 (Bowles, 2006) are combined and compared to the GTS2012 (Hilgen et al., 2012; Vandenberghe et al., 2012). Grey means uncertain polarity, narrow grey bars represent uncertain reversal position.

Figure 5: Wavelet analyses in the tuned age domain. See Fig. 3 for explanation.

Figure 6: ~2.4-Myr eccentricity amplitude modulation of 405-kyr eccentricity cycle. 3D-wavelets show that the amplitude of the 405-kyr eccentricity cycle is largest during ~2.4-Myr eccentricity minima (Laskar et al., 2011). This is mimicked and amplified in the benthic $\delta^{13}C$ record. Green numbers corresponds to the ~2.4-Myr eccentricity cycles. Note that long-period cycles (>1 Myr) have been removed from both records.

Figure 7: 405-kyr eccentricity amplitude modulation of ~110-kyr eccentricity cycle. Hilbert-transforms of detrended, normalised, and Gaussian filtered data (coloured) and eccentricity (grey; (Laskar et al., 2011)). The ~2.4-Myr and 405-kyr eccentricity cycle numbers are given in green and grey respectively. Red dotted line represents arbitrary threshold value at half of the maximum eccentricity amplitude variability, selected to aid the eye in identifying 405-kyr cycles with particularly high-amplitude ~110-kyr responses. The episodes of high-amplitude ~110-kyr cyclicity in the $\delta^{18}O$ record are compared to the amplitude modulation of obliquity (Laskar et al., 2004).

Figure 8: Phase relationships with respect to eccentricity. Blackman-Tukey power-spectra, of the data records (coloured) versus eccentricity (grey; (Laskar et al., 2011)) and their combined cross-spectral coherency and phase estimates (Paillard et al., 1996). bw stands for bandwidth. ATANH stands for hyperbolic arctangent. Error bars and red dotted lines indicate the 95% confidence levels and coherency significance thresholds, respectively. The in-phase relation (~0 kyr) between $CaCO_3$ est. and eccentricity is resultant from the tuning assumption. Negative phases correspond to a lead of the data with respect to eccentricity; positive phases represent a lag of the data to eccentricity.

Table 1: Tuned chron ages from Walvis Ridge compared to the GTS2012. Uncertainty intervals between top and bottom reflect the uncertain stratigraphic position at Sites 1265 and 1266. Uncertainties resulting from site-to-site correlation and astronomical tuning are not incorporated.

Figure 9: Recurrent episodes of high-amplitude ~110-kyr cycles in $\delta^{18}O$. "History doesn't repeat itself, but it rhymes" (attributed to Mark Twain); "rhyming" climate/cryosphere histories, or natural experiments of Antarctic glaciation, of the Oligo-Miocene are shown. Grey numbers corresponds to 405-kyr eccentricity cycles.

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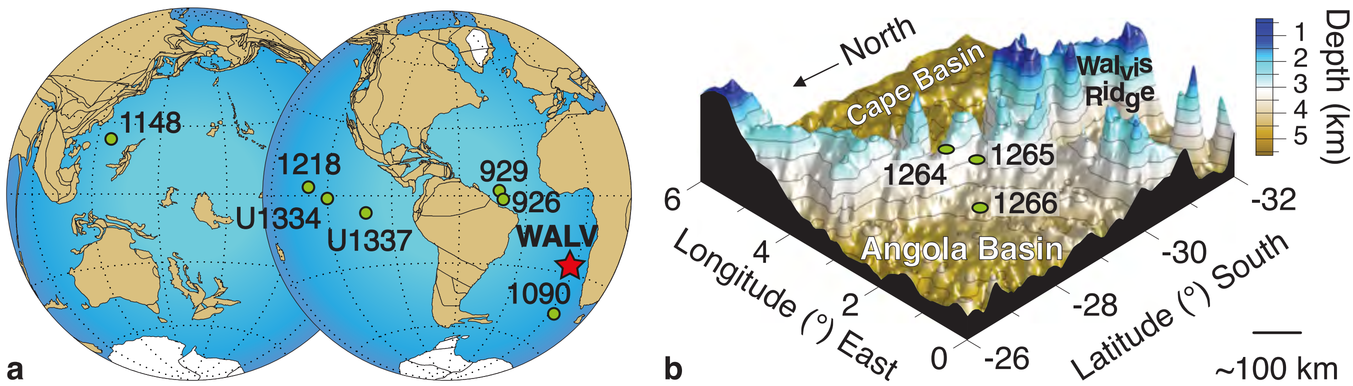
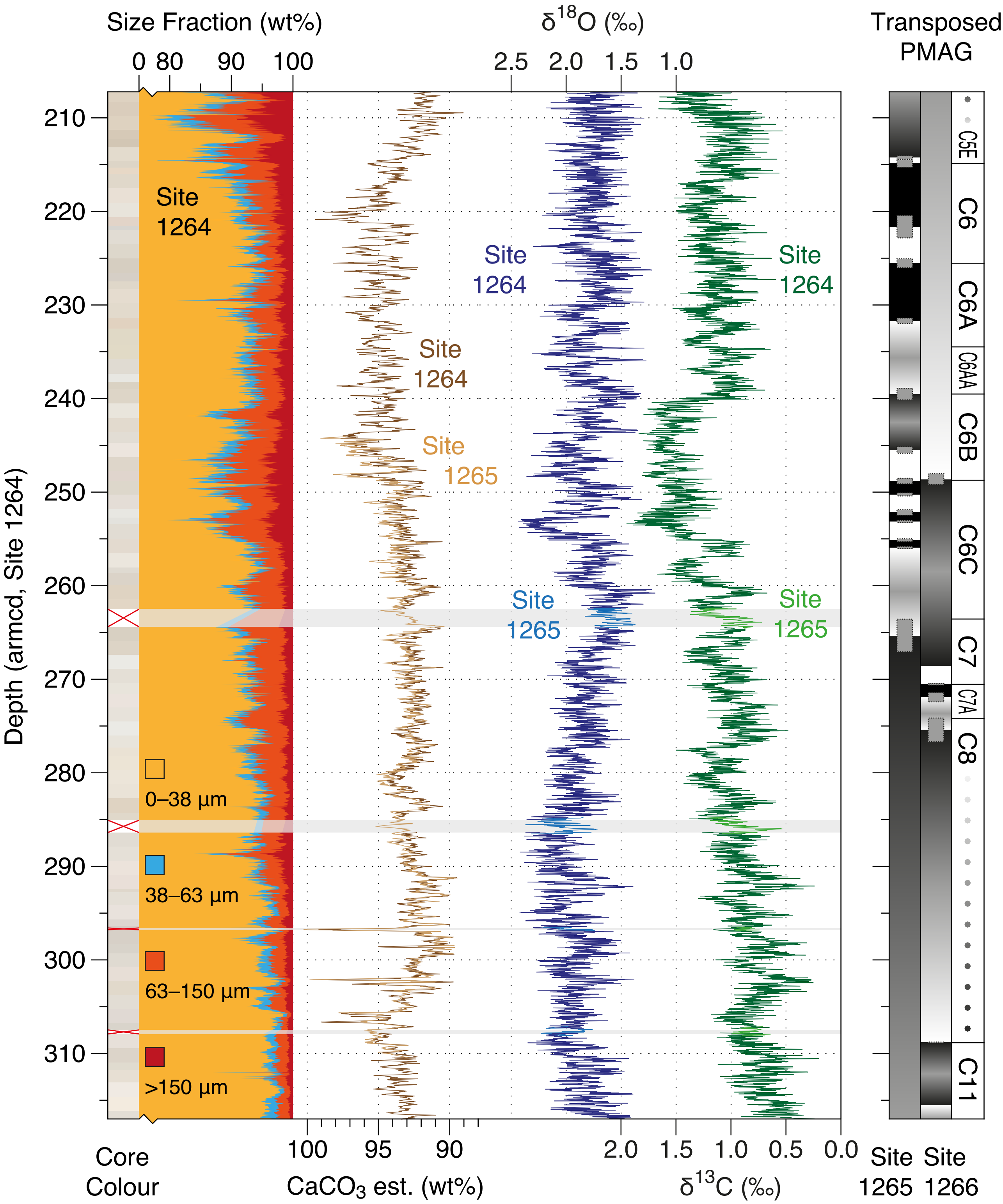
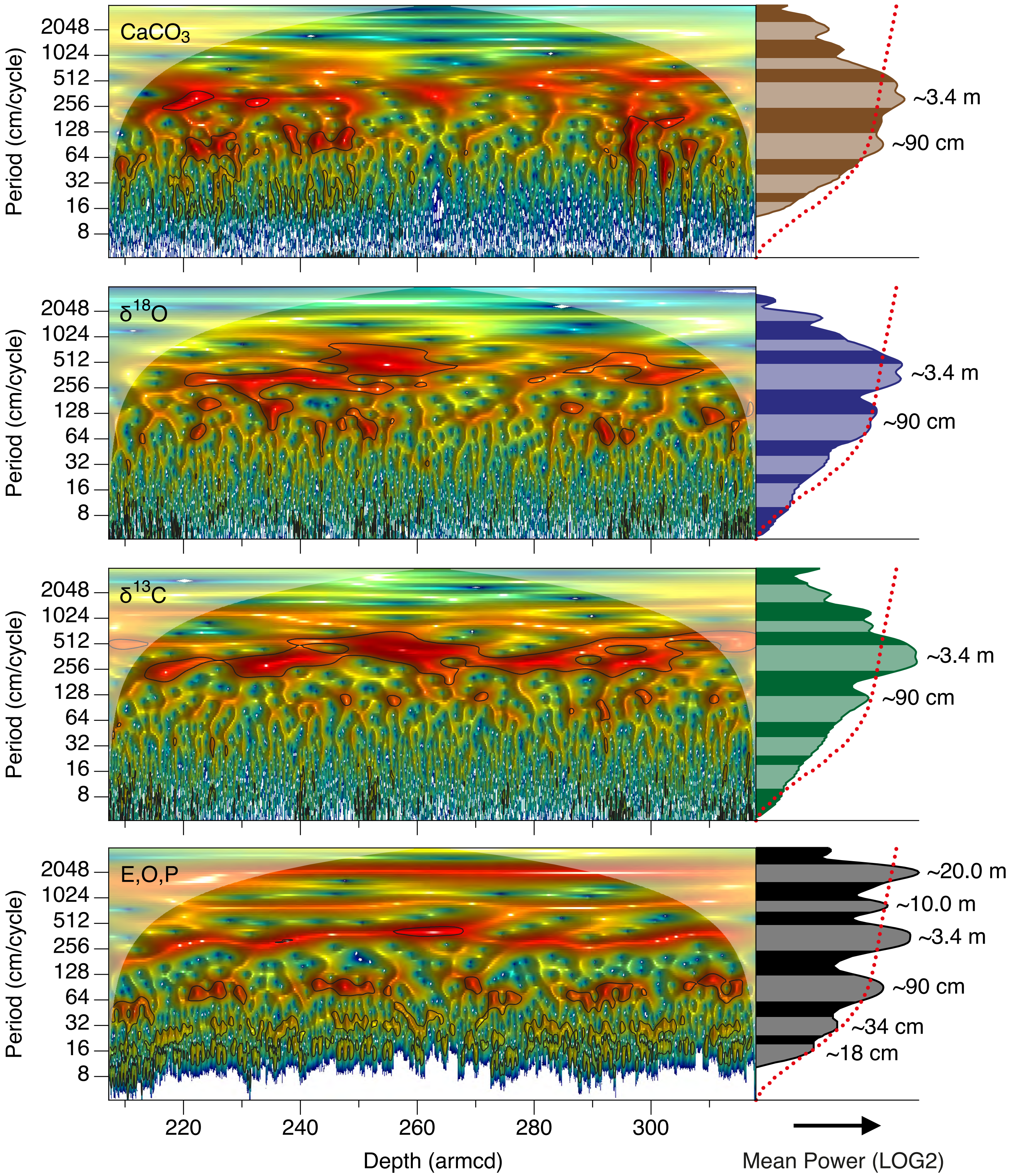


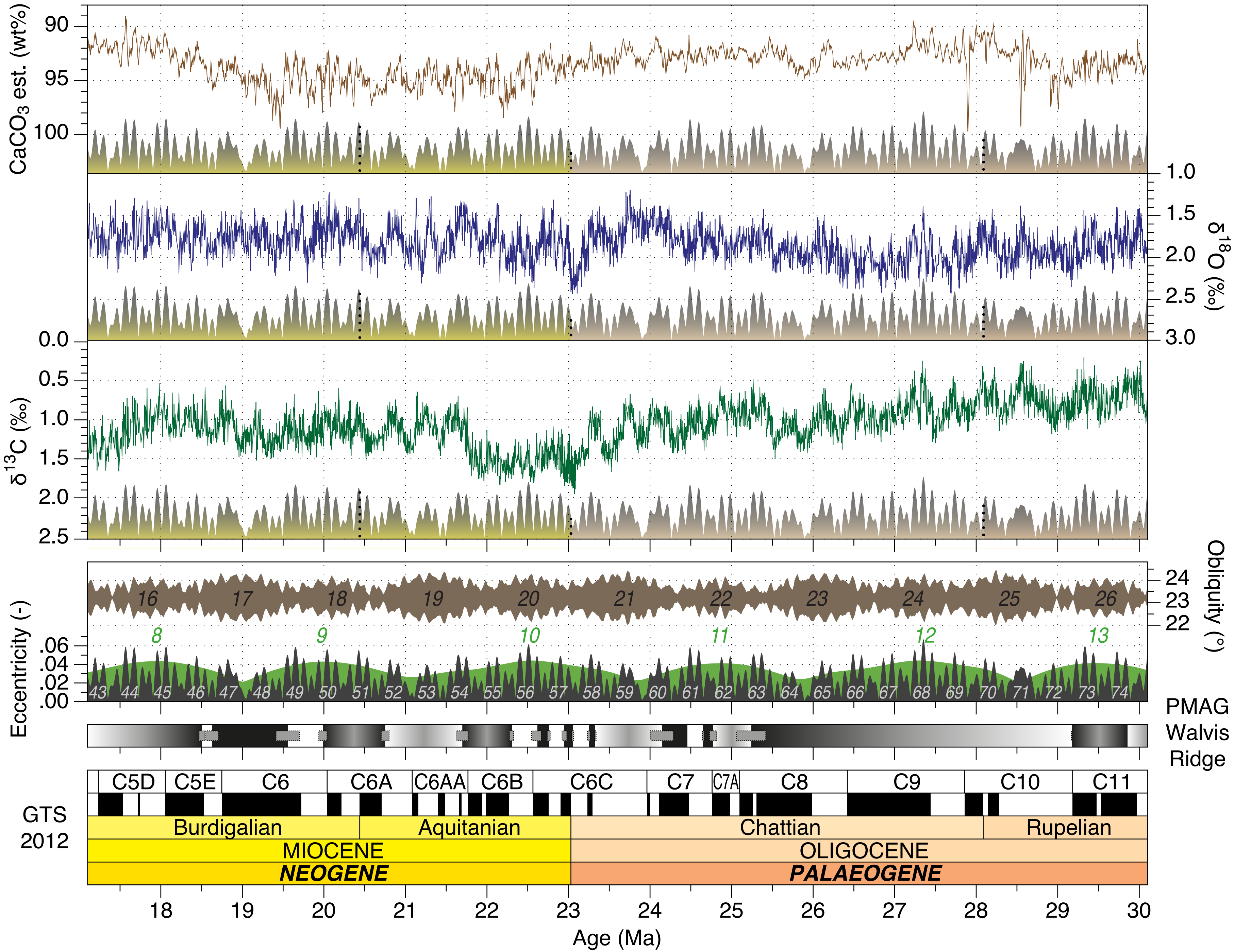
1148
1218
U1334
U1337
929
926
WALV
1090
a
North
Cape Basin
Walvis Ridge
1264
1265
1266
Angola Basin
6
4
2
0
Longitude (°) East
-26
-28
-30
-32
Latitude (°) South
Depth (km)
1
2
3
4
5
~100 km
b



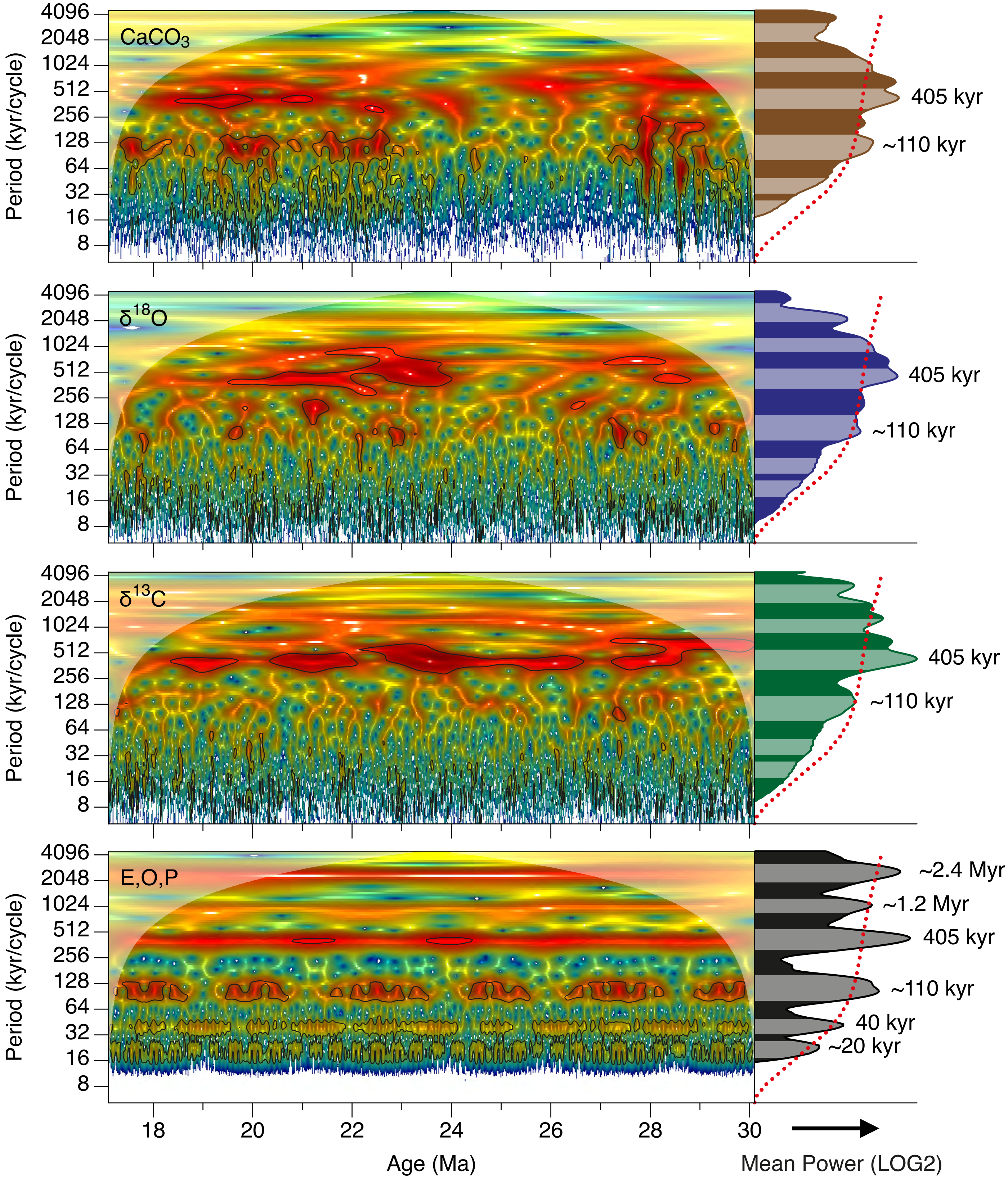
Size Fraction (wt%)
0 80 90 100
δ18O (‰)
2.5 2.0 1.5 1.0
Transposed PMAG
210
220
230
240
250
260
270
280
290
300
310
Depth (armcd, Site 1264)
Site 1264
Site 1264
Site 1264
Site 1264
Site 1265
Site 1265
Site 1265
0–38 µm
38–63 µm
63–150 µm
>150 µm
C5E
C6
C6A
C6AA
C6B
C6C
C7
C7A
C8
C11
Core Colour
100 95 90
CaCO3 est. (wt%)
2.0 1.5 1.0 0.5 0.0
δ13C (‰)
Site 1265
Site 1266



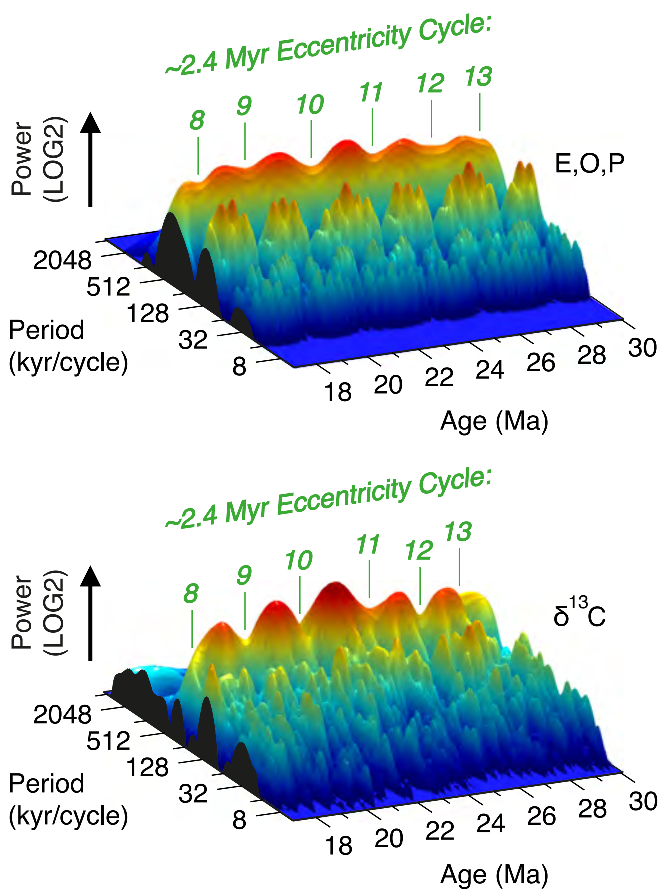
CaCO3
δ18O
δ13C
E,O,P
Period (cm/cycle)
2048
1024
512
256
128
64
32
16
8
~3.4 m
~90 cm
~20.0 m
~10.0 m
~34 cm
~18 cm
220
240
260
280
300
Depth (armcd)
Mean Power (LOG2)



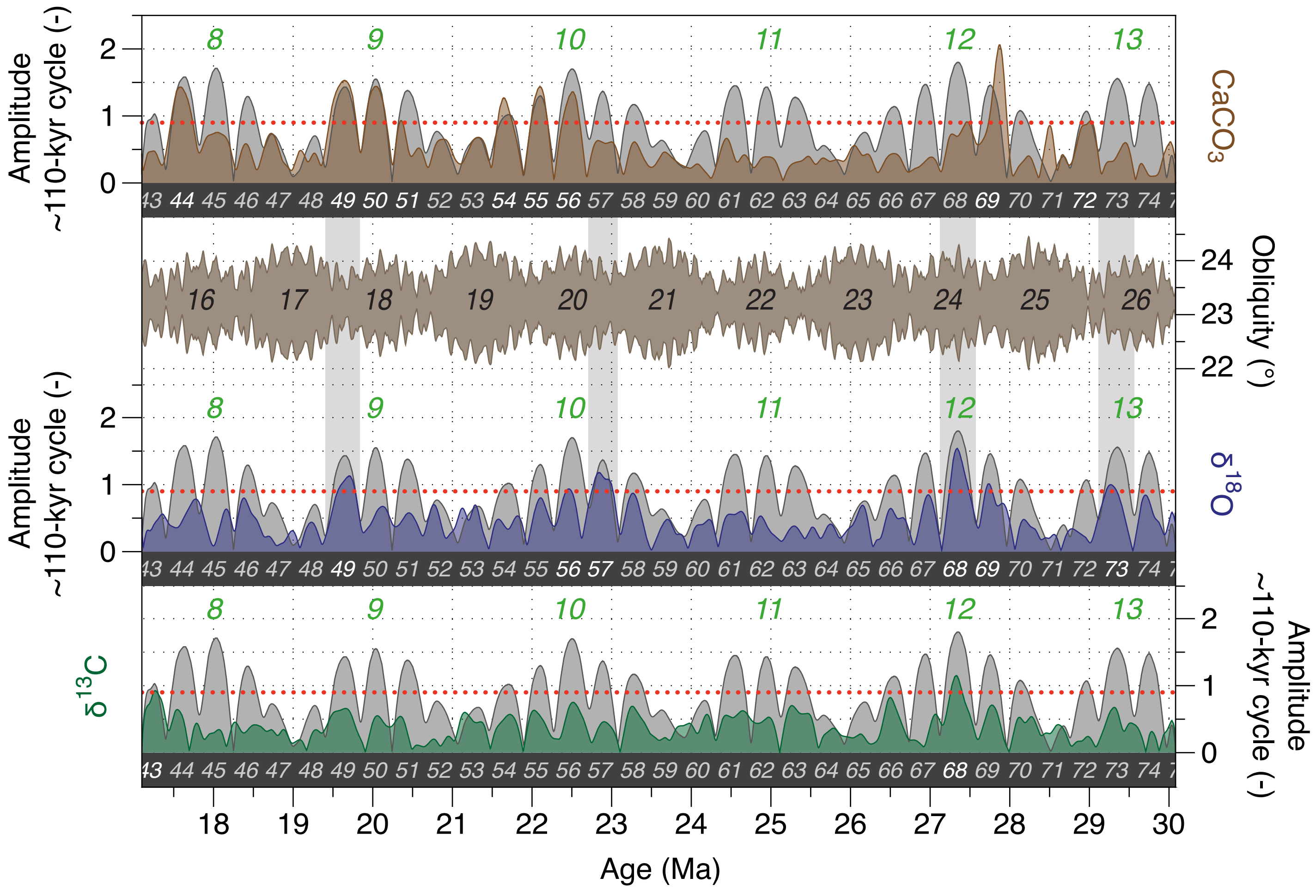
CaCO3 est. (wt%)
δ18O (‰)
δ13C (‰)
Obliquity (°)
Eccentricity (-)
PMAG Walvis Ridge
GTS 2012
Age (Ma)
Burdigalian
Aquitanian
Chattian
Rupelian
MIOCENE
OLIGOCENE
NEOGENE
PALAEOGENE
C5D
C5E
C6
C6A
C6AA
C6B
C6C
C7
C7A
C8
C9
C10
C11



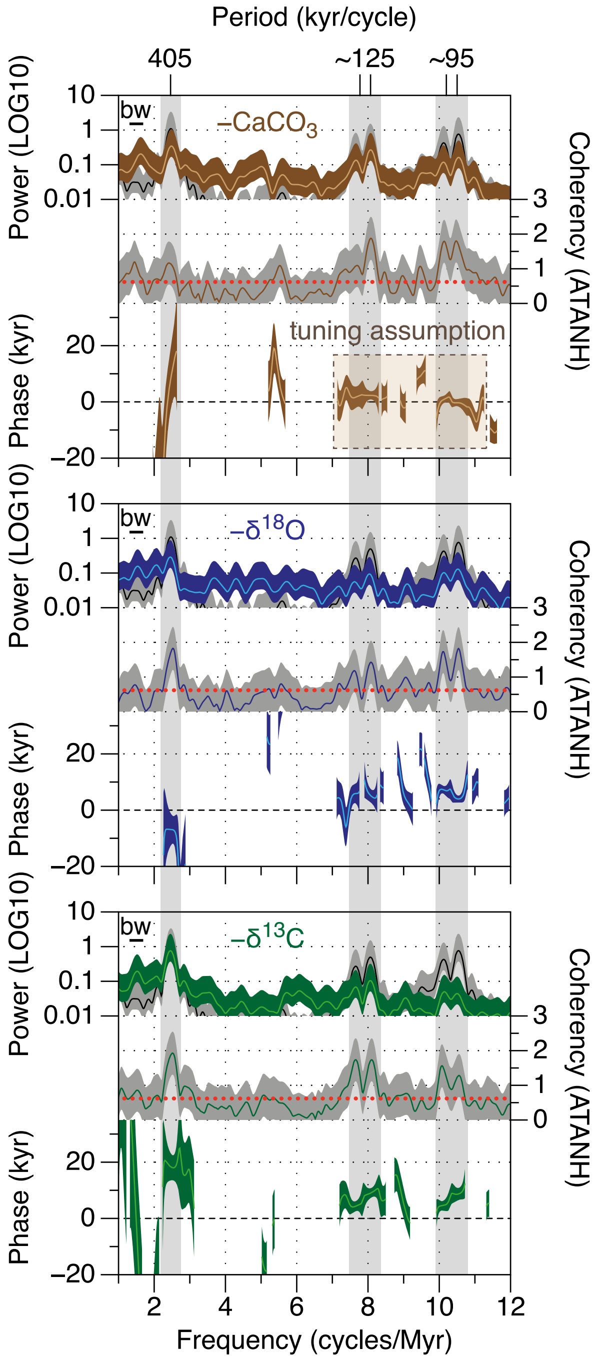
CaCO3
δ18O
δ13C
E,O,P
Period (kyr/cycle)
4096
2048
1024
512
256
128
64
32
16
8
405 kyr
~110 kyr
~2.4 Myr
~1.2 Myr
40 kyr
~20 kyr
18
20
22
24
26
28
30
Age (Ma)
Mean Power (LOG2)



~2.4 Myr Eccentricity Cycle:
8
9
10
11
12
13
Power (LOG2)
E,O,P
2048
512
128
32
8
Period (kyr/cycle)
18
20
22
24
26
28
30
Age (Ma)
~2.4 Myr Eccentricity Cycle:
8
9
10
11
12
13
Power (LOG2)
δ13C
2048
512
128
32
8
Period (kyr/cycle)
18
20
22
24
26
28
30
Age (Ma)



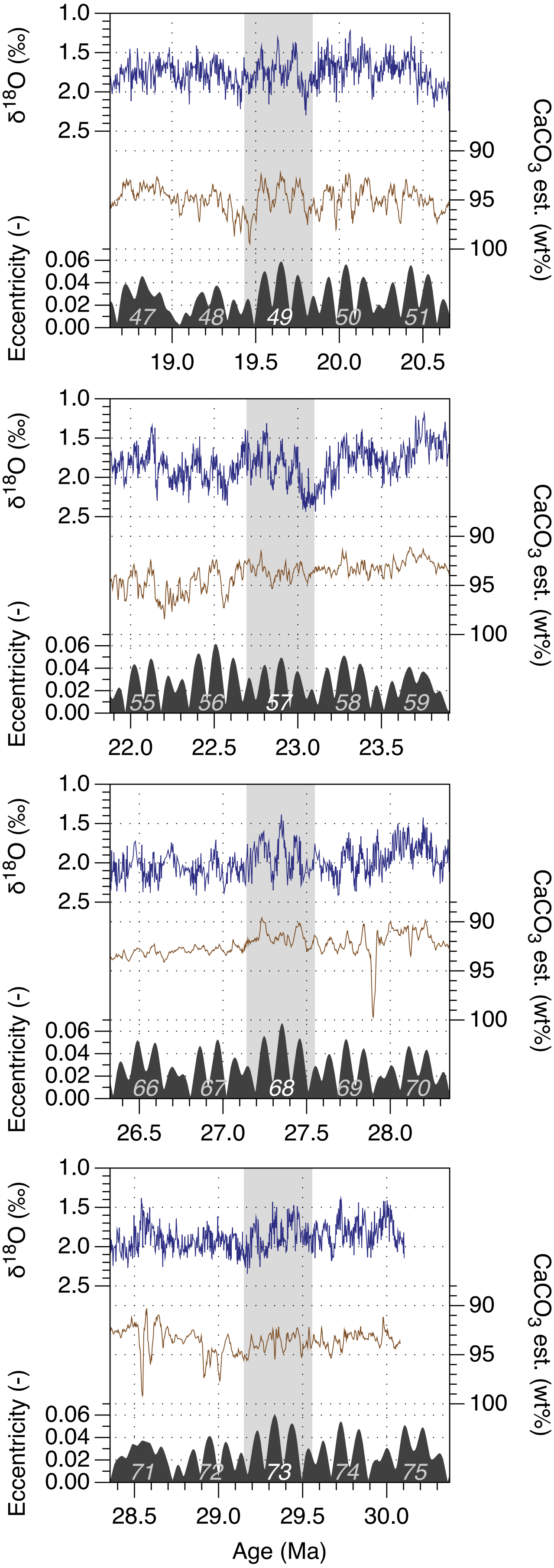
Amplitude ~110-kyr cycle (-)
CaCO3
Obliquity (°)
δ18O
δ13C
8
9
10
11
12
13
16
17
18
19
20
21
22
23
24
25
26
43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74
Age (Ma)
18 19 20 21 22 23 24 25 26 27 28 29 30



Period (kyr/cycle)
405
~125
~95
bw
−CaCO3
tuning assumption
−δ18O
−δ13C
Power (LOG10)
Coherency (ATANH)
Phase (kyr)
Frequency (cycles/Myr)

Chron	GTS2012 age (Ma)	WALV. Top tuned age (Ma)	WALV. Mid tuned age (Ma)	WALV. Bottom tuned age (Ma)	GTS2012 – WALV. Mid tuned Δ (kyr)
C5En (o)	18.524	18.469	18.505	18.541	19
C6n (y)	18.748	18.551	18.629	18.707	119
C6n (o)	19.722	19.413	19.557	19.700	165
C6An.1n (y)	20.040	19.937	19.988	20.038	52
C6An.2n (o)	20.709	20.705	20.752	20.800	-43
C6AAr.2n (y)	21.659	21.629	21.698	21.768	-39
C6Bn.2n (o)	22.268	22.276	22.302	22.328	-34
C6Cn.1n (y)	22.564	22.547	22.617	22.665	-53
C6Cn.1n (o)	22.754	22.741	22.758	22.776	-4
C6Cn.2n (y)	22.902	22.920	22.950	22.979	-48
C6Cn.2n (o)	23.030	23.041	23.051	23.061	-21
C6Cn.3n (y)	23.233	23.231	23.248	23.264	-15
C6Cn.3n (o)	23.295	23.323	23.331	23.338	-36
C7n.2n (y)	24.109	24.007	24.147	24.287	-38
C7n.2n (o)	24.474	24.459	24.459	-	15
C7An (y)	24.761	24.643	24.653	24.662	108
C7An (o)	24.984	24.729	24.772	24.815	212
C8n.2n (y)	25.304	25.063	25.241	25.419	63
C11n.1n (y)	29.183	29.167	29.171	29.175	12
C11n.2n (o)	29.970	29.857	29.857	-	113

Liebrand et al. Table 1.


δ18O (‰)
CaCO3 est. (wt%)
Eccentricity (-)
1.0
1.5
2.0
2.5
90
95
100
0.06
0.04
0.02
0.00
47
48
49
50
51
19.0
19.5
20.0
20.5
55
56
57
58
59
22.0
22.5
23.0
23.5
66
67
68
69
70
26.5
27.0
27.5
28.0
71
72
73
74
75
28.5
29.0
29.5
30.0
Age (Ma)

Appendix A. Supplementary information to: "Cyclostratigraphy and eccentricity tuning of the early Oligocene through early Miocene (30.1–17.1 Ma): *Cibicides mundulus* stable oxygen and carbon isotope records from Walvis Ridge Site 1264"

Liebrand et al.

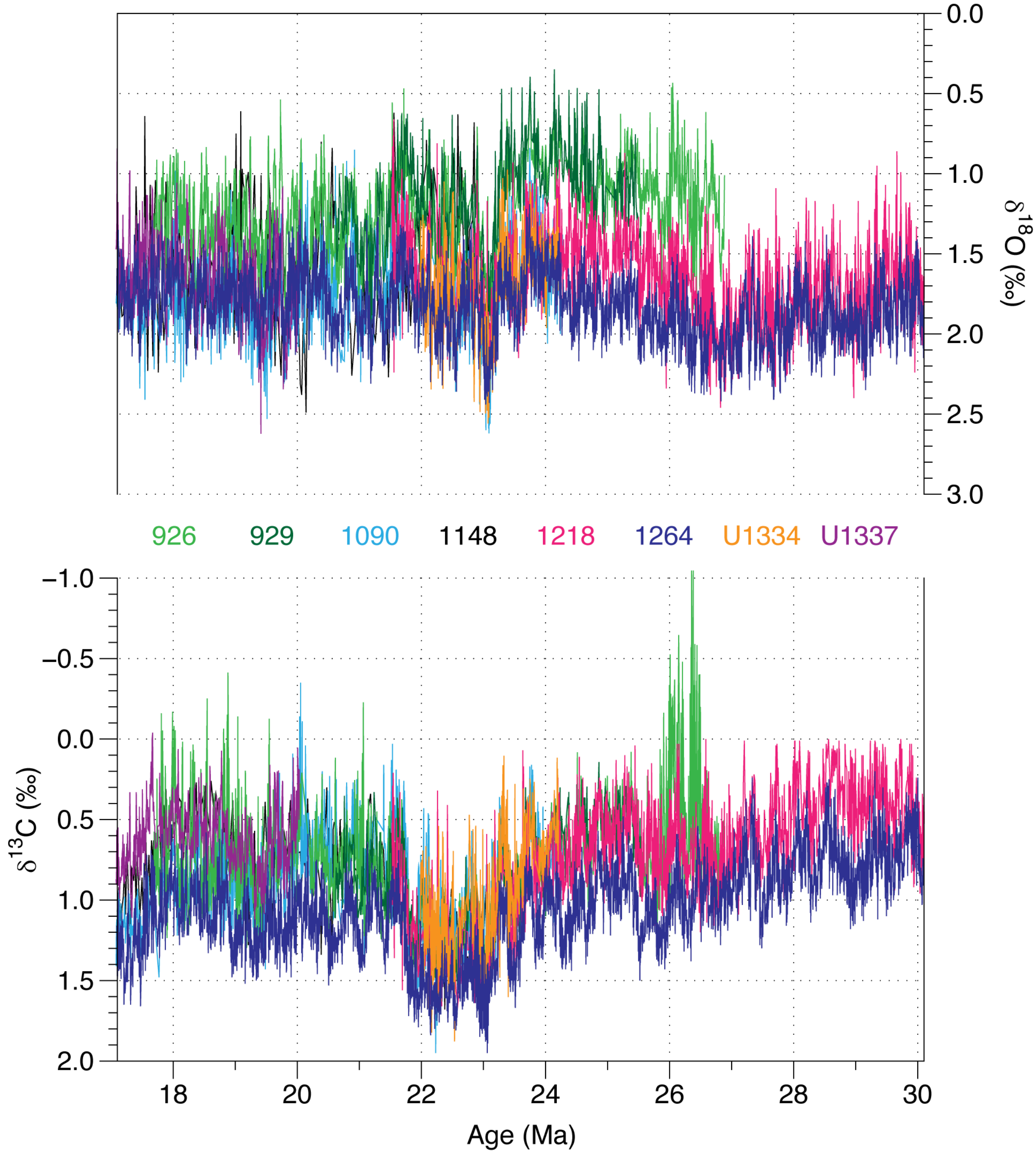


Fig. S1. Comparison of high resolution Oligo-Miocene benthic stable isotope stratigraphies. Benthic foraminiferal records from ODP Sites 926 & 929 (Flower et al., 1997; Pälike et al., 2006a; Paul et al., 2000; Zachos et al., 1997; Zachos et al., 2001), 1090 (Billups et al., 2004), 1146 (Tian et al., 2008), 1218 (Coxall et al., 2005; Lear et al., 2004; Pälike et al., 2006b; Tripati et al., 2006; Wade and Pälike, 2004), 1264 (this study, (Liebrand et al., 2011)), and from IODP Sites U1334 (Beddow et al., 2016) and U1337 (Holbourn et al., 2015).

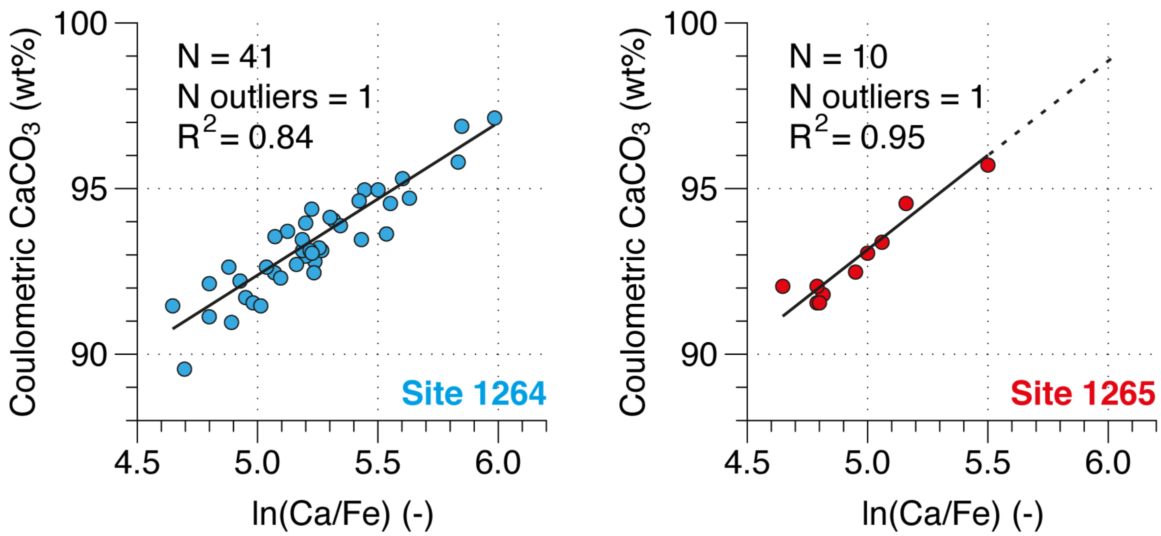


Fig. S2. Estimating $CaCO_3$ content. XRF data (ln(Ca/Fe)) from ODP Sites 1264 and 1265 (Fig. 1 of main document) are calibrated to shipboard coulometric $CaCO_3$ measurements (Zachos et al., 2004) to obtain $CaCO_3$ est. records.

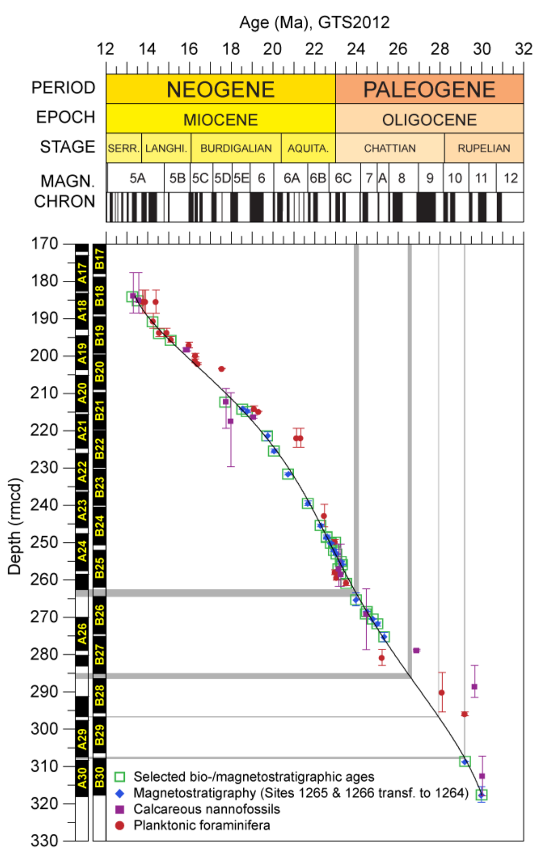


Fig. S3. Initial age-model for ODP Site 1264. A polynomial function describes the initial depth-age relation used to aid assessing the duration of the main oscillations in the depth-domain. Shipboard biostratigraphic and magnetostratigraphic data were used to construct the initial age-model (Bowles, 2006; Zachos et al., 2004).

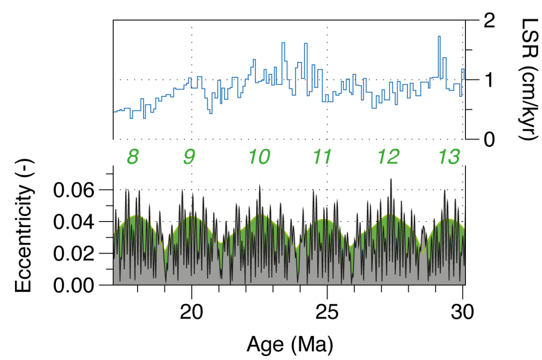


Fig. S4. Linear sedimentation rates (LSR) at ODP Site 1264. LSRs are calculated between tuning tie-points (i.e. ~110-kyr eccentricity minima (Laskar et al., 2011)) and vary between 1.7 and 0.4 cm/kyr, or between 17 and 4 m/Myr.

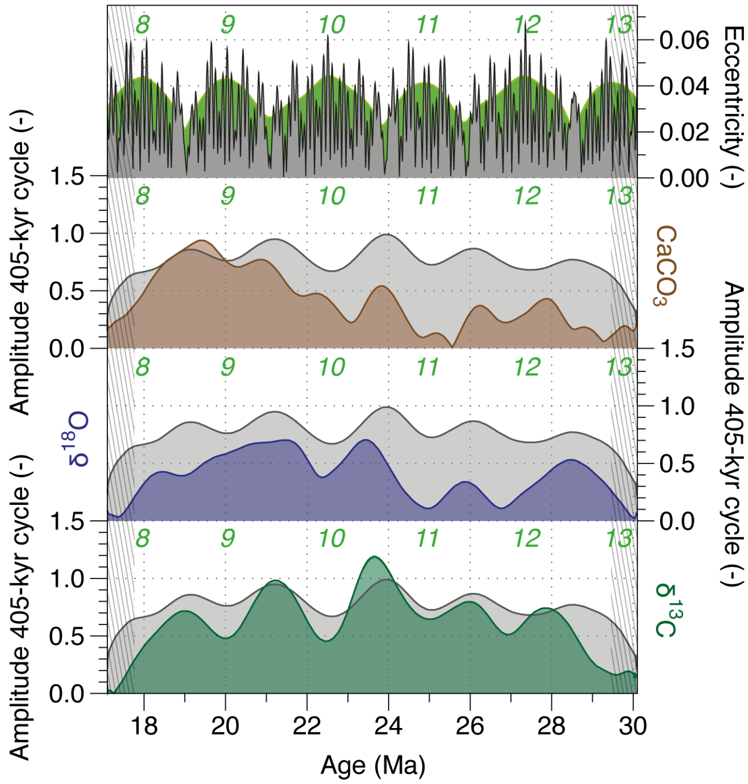


Fig. S5. ~2.4-Myr-eccentricity amplitude modulation of the 405-kyr-eccentricity cycle. The top panel depicts the La2011_ecc3L eccentricity solution (grey) (Laskar et al., 2011) and the amplitude modulation of its ~2.4-Myr component (green). The bottom three panels show the Hilbert-transforms of normalised, detrended, and Gaussian filtered data (coloured) and eccentricity (grey). The ~2.4-Myr eccentricity cycle numbers are given in green.

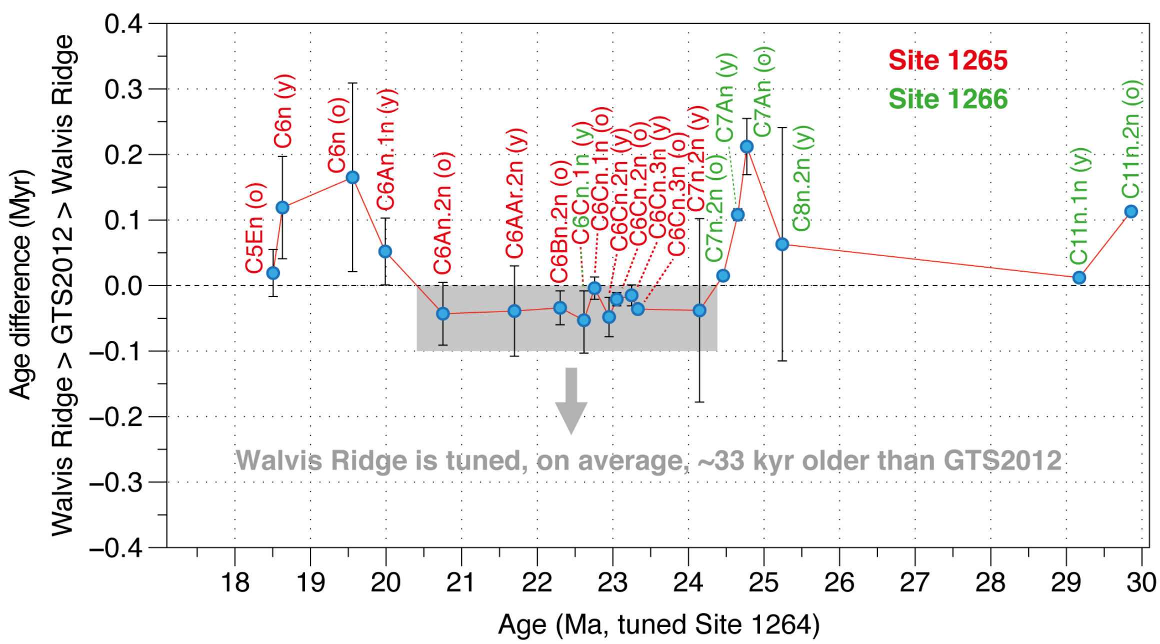


Fig. S6. Palaeomagnetic data from Walvis Ridge. Age differences between the tuned magnetostratigraphies from ODP Sites 1265 and 1266 and the GTS2012 are depicted. This figure is a visual representation of Table 1 in the main document.

1. BIOSTRATIGRAPHY

1.1. Rationale and methods

Comparison of the shipboard biostratigraphic results from Site 1264 (Zachos et al., 2004) with published data from Sites 926 and 929 (Pälike et al., 2006a; Shackleton et al., 2000) suggested that the ranges of calcareous nannofossil *Sphenolithus delphix* did not (fully) overlap. We wanted to test the robustness of this apparent and unexpected diachrony because *S. delphix* is one of the key OMT marker species that has generally proved to be a reliable datum (Raffi, 1999). Therefore, we have generated records of *Sphenolithus* counts (N/mm^2) based on selected samples across the OMT interval, which record the abundances of *S. delphix*, and other OMT marker species, namely *Sphenolithus calyculus*, *Sphenolithus capricornutus* and *Sphenolithus disbelemnos* in detail. At Chieti University, smear-slides of bulk sediment were made using standard preparation techniques, and were analysed with a polarizing microscope at 1250× magnification. In addition to the quantitative Sphenolith stratigraphies, the abundance of *Triquetrorhabdulus carinatus* was qualitatively evaluated.

1.2. Results

The preservation of calcareous nannofossils at Site 1264 is moderately affected by dissolution. Despite this suboptimal signal we have been able to evaluate the relative abundances and constrain the ranges of those *Sphenolithus* species related to the OMT (Raffi, 1999). *S. delphix* and *S. capricornutus* show the typical variability in their distribution ranges, comparable to other locations. During a δ^{18}O maximum, about 405 kyr prior to the OMT (at ~260 armcd, ~23.7 Ma, during 405-kyr eccentricity Cycle 59, Supp. Fig. S7), the lowermost occurrence of *S. delphix* (peaking at 7 per mm^2) is concomitant with more abundant *S. calyculus* specimens (22 per mm^2). *S. delphix* re-enters (peak 19 per mm^2) the stratigraphic record contemporaneously with the onset of the transient glaciation across the OMT (between 255–254 armcd, 23.2–23.1 Ma, 405-kyr eccentricity Cycle 58, Supp. Fig. S7). At this time, also *S. capricornutus* shows a peak in abundance (57 per mm^2). In the interval below the main peak in *S. capricornutus* (~256 armcd, ~23.3 Ma), rare specimens of *S. disbelemnos* are recorded (8 per mm^2). The gradual decrease in the abundance of *T. carinatus* across the Oligocene-Miocene Transition from Site 1264 is characteristic of the younger part of its distribution range, and is in agreement with observations from other marine locations (Backman et al., 2012).

1.3 New age calibrations for selected Oligo-Miocene nannofossil markers

These new results show that the apparent diachrony between the shipboard range of *S. delphix* at Site 1264 with the one from Site 926 is no longer present. However, the updated range of *S. delphix* at Site 1264, presented here, is twice as long compared to those of Sites 926 and 1218. A similar, longer distribution range for *S. delphix* has also been observed in the North Atlantic at Site U1405 (Agnini, 2016; Norris et al., 2012). Recent age-calibration of *S. delphix* at Site 1218 indicated that it ranged from 23.38 to 23.06 Ma (Backman et al., 2012). The longer range of *S. delphix* found at Site 1264 has age limits of 23.73 to 23.11 Ma, thereby extending the bottom age by ~350 kyr. The restricted occurrence of *S. disbelemnos* at Site 1264 precedes the known earliest occurrence of this biostratigraphic marker, which is calibrated elsewhere at 22.41 Ma (Backman et al., 2012), by ~980 kyr. We find an earliest occurrence of *S. disbelemnos* at 23.39 Ma.

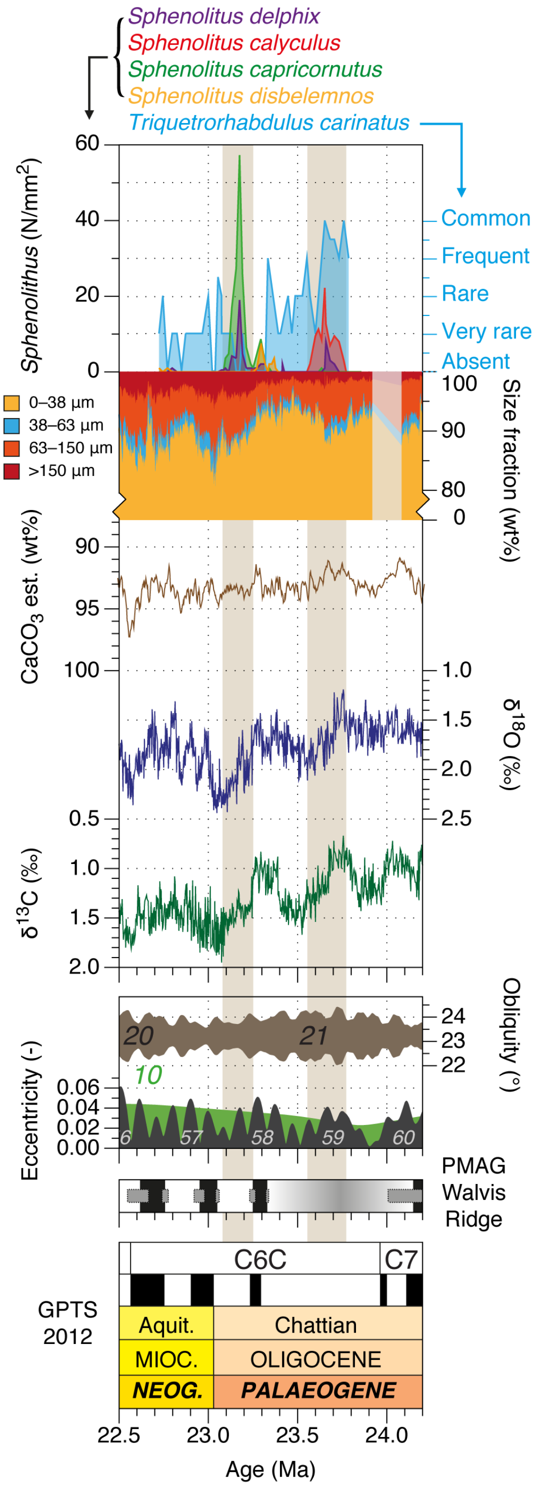


Fig. S7. Calcareous nannofossil stratigraphy across the Oligocene-Miocene Transition. Quantitative and qualitative nannofossil abundances are compared to proxy records and the GTS2012 (Hilgen et al., 2012; Vandenberghe et al., 2012). See Fig. 4 in the main document for a further explanation.

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