Earth and Planetary Science Letters 401 (2014) 18–30

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

A high-resolution benthic stable-isotope record for the South Atlantic: Implications for orbital-scale changes in Late Paleocene–Early Eocene climate and carbon cycling

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ARTICLE INFO

Article history:
Received 10 October 2013
Received in revised form 13 May 2014
Accepted 27 May 2014
Available online 16 June 2014
Editor: G.M. Henderson

Keywords:
Paleogene
stable isotopes
benthic foraminifera
cyclostratigraphy
hyperthermals
Ocean Drilling Program

ABSTRACT

The Late Paleocene and Early Eocene were characterized by warm greenhouse climates, punctuated by a series of rapid warming and ocean acidification events known as "hyperthermals", thought to have been paced or triggered by orbital cycles. While these hyperthermals, such as the Paleocene Eocene Thermal Maximum (PETM), have been studied in great detail, the background low-amplitude cycles seen in carbon and oxygen-isotope records throughout the Paleocene–Eocene have hitherto not been resolved. Here we present a 7.7 million year (myr) long, high-resolution, orbitally-tuned, benthic foraminiferal stable-isotope record spanning the late Paleocene and early Eocene interval (∼52.5–60.5 Ma) from Ocean Drilling Program (ODP) Site 1262, South Atlantic. This high resolution (∼2–4 kyr) record allows the changing character and phasing of orbitally-modulated cycles to be studied in unprecedented detail as it reflects the long-term trend in carbon cycle and climate over this interval. The main pacemaker in the benthic oxygen-isotope ($\delta^{18}O$) and carbon-isotope ($\delta^{13}C$) records from ODP Site 1262, are the long (405 kyr) and short (100 kyr) eccentricity cycles, and precession (21 kyr). Obliquity (41 kyr) is almost absent throughout the section except for a few brief intervals where it has a relatively weak influence. During the course of the Early Paleogene record, and particularly in the latest Paleocene, eccentricity-paced negative carbon-isotope excursions ($\delta^{13}C$, CIEs) and coeval negative oxygen-isotope ($\delta^{18}O$) excursions correspond to low carbonate ($CaCO_3$) and coarse fraction (%CF) values due to increased carbonate dissolution, suggesting shoaling of the lysocline and accompanied changes in the global exogenic carbon cycle. These negative CIEs and $\delta^{18}O$ events coincide with maxima in eccentricity, with changes in $\delta^{18}O$ leading changes in $\delta^{13}C$ by ∼6 (±5) kyr in the 405-kyr band and by ∼3 (±1) kyr in the higher frequency 100-kyr band on average. However, these phase lags are not constant, with the lag in the 405-kyr band extending from ∼4 (±5) kyr to ∼21 (±2) kyr from the late Paleocene to the early Eocene, suggesting a progressively weaker coupling of climate and the carbon-cycle with time. The higher amplitude 405-kyr cycles in the latest Paleocene are associated with changes in bottom water temperature of 2–4 °C, while the most prominent 100 kyr-paced cycles can be accompanied by changes of up to 1.5 °C. Comparison of the 1262 record with a lower resolution, but orbitally-tuned benthic record for Site 1209 in the Pacific allows for verification of key features of the benthic isotope records which are global in scale including a key warming step at 57.7 Ma.

1. Introduction

The Early Paleogene was climatically dynamic, with both sustained and transient episodes of elevated global temperatures and pCO_2 levels, as well as periodic carbon-cycle and climatic perturbations of varying magnitude. This period, therefore, provides a diversity of case studies for investigating the links between orbital forcing, climate and the carbon-cycle under a range of greenhouse conditions, and for determining the role of threshold events in the climate system in response to gradual changes in boundary conditions. This period is marked by long-term warming from the mid Paleocene (∼58 Ma) to the Early Eocene, culminating in the Early Eocene Climatic Optimum (EECO, ∼51 Ma) when global temperatures were the warmest of the past 90 myr (Zachos et al., 2001;

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http://dx.doi.org/10.1016/j.epsl.2014.05.054
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Friedrich et al., 2012). This change from a relatively cool Paleocene to a very warm Early Eocene is expressed in a decrease of global benthic δ^{18}O values of >1‰ over ~9 myr, representing a change in bottom water temperatures on the order of ~6 °C (Zachos et al., 2001). The early Paleogene carbon-cycle was also very dynamic, with long-term swings in the benthic carbon-isotope record (δ^{13}C) on the order of ±2.5‰ (Zachos et al., 2008).

Superimposed on these long-term climate and carbon-cycle trends were a series of high-amplitude, transient perturbations to the climate and carbon-cycle known as "hyperthermals", the largest and best-studied of which is the Paleocene Eocene Thermal Maximum (PETM; ETM-1; ~55.5 Ma) (e.g., Kennett and Stott, 1991; Zachos et al., 2005; Lourens et al., 2005; Röhl et al., 2007; Tripati and Elderfield, 2005; Sluijs et al., 2006, 2007; Nicolo et al., 2007; McInerney and Wing, 2011). At least three such hyperthermals are recognized in the Early Eocene (ETM-1 to 3), which all share similar characteristics of rapid and large increases in global temperature accompanied by transient changes to the global carbon-cycle, as recorded by negative excursions in δ^{18}O and δ^{13}C records, and evidence for massive dissolution of deep-sea marine carbonates (e.g., Zachos et al., 2005; Lourens et al., 2005; Sluijs et al., 2009; Agnini et al., 2009; Stap et al., 2009, 2010a, 2010b; McInerney and Wing, 2011; Komar et al., 2013). Similar events, of smaller magnitude have also been recorded from the Paleocene (e.g., Top C27n event, aka the LDE (Latest Danian Event), Dan C2 event, the Early Late Paleocene Event (ELPE) etc.; Röhl et al., 2004; Westerhold et al., 2011; Coccioni et al., 2010; Quillévéré et al., 2008), as well as lower amplitude cyclic perturbations, particularly in the latest Paleocene (Cramer et al., 2003; Zachos et al., 2010). Construction of orbitally-tuned age models for the Early Paleogene events suggests that many if not all of the hyperthermals, and many of the other smaller perturbations during this interval, were paced by variations in Earth's orbit, with particular power in the long (405 kyr) and short (100 kyr) eccentricity bands (e.g., Lourens et al., 2005; Westerhold et al., 2007; 2008; Zachos et al., 2010; Hilgen et al., 2010; Galeotti et al., 2010).

The causal mechanism for the initiation of the large hyperthermals such as the PETM remains contentious, with the leading hypothesis involving the release of large quantities of reduced carbon from methane clathrate reservoirs (Dickens et al., 1995, 1997; Zeebe et al., 2009). A mechanism to initiate release of this methane is still a matter of debate (e.g., Sluijs et al., 2007), but several triggers have been suggested, including: the crossing of a climatic threshold associated with the long-term warming trend (Lourens et al., 2005; Lunt et al., 2010; DeConto et al., 2012), or a pulse of NAIP volcanism that caused warming above the background values or release of thermogenic methane (Svensen et al., 2004; Storey et al., 2007; Wieczorek et al., 2013; Rampino, 2013). Other theories put forward to explain the origin of the hyperthermals include the large-scale release of Antarctic permafrost carbon due to favorable orbital configurations (DeConto et al., 2012), desiccation of a large marine basin (Higgins and Schrag, 2006), or even a cometary impact (Kent et al., 2003), of which the latter two seem unlikely due to a lack of evidence or a mechanism linking orbital cyclicity with these phenomenon.

While the highest amplitude hyperthermals have been studied in great detail and with various multi-proxy and modeling approaches, the preceding and intervening millions of years have thus far largely been constrained by lower-resolution, often composite, datasets, which provide insufficient resolution to ascertain the forcing behind the high-frequency variations in climate and the carbon-cycle, at least of the extent that they have been resolved (e.g., Zachos et al., 2001; Cramer et al., 2003; Zachos et al., 2010). In particular, the existing benthic stable-isotope record for the early Paleogene is composed of stacked records from many different deep-sea sites, and from various ocean basins (e.g. Zachos et al., 2001, and references therein). While useful for some applications, the stacked records lack the fidelity required to resolve climate and carbon cycle variations on orbital frequencies, and therefore to ascertain the true nature of the hyperthermals and other transient climate phenomena of the Paleogene. Arguably, resolution of the higher frequency patterns of paleoceanographic variability is also essential to resolving the origin of the long-term trends.

Here we present a stratigraphically continuous, high-resolution benthic foraminiferal stable-isotope record from ODP Site 1262 in the South Atlantic, which encompasses almost 8 myr of astronomically-tuned time spanning the Late Paleocene to Early Eocene (C24.2r to C26r). This complements and extends a shorter, high-resolution bulk stable-isotope record from Site 1262 (Zachos et al., 2010). Comparison of the new Atlantic isotopic record to a corresponding benthic stable-isotope record from the Pacific allows for isolation of the global from local signals (Westerhold et al., 2011). We then explore the implications of these records for the long-term evolution of the climate and marine carbon cycle response to orbital forcing over the late Paleocene-early Eocene as the planet slowly warmed.

2. Materials and methods

2.1. Site location, lithology and sampling

ODP Site 1262 is located in the eastern South Atlantic (27°S) at a water depth of 4759 m, and is the deepest site drilled as part of the Leg 208 Walvis Ridge depth transect (Zachos et al., 2004). This site was located at a paleolatitude of ~34°S in the Paleogene (Fig. 1). Three offset holes (A, B, C) were cored using advanced piston coring (APC) system ensuring complete recovery of the section with minimal coring disturbance. Shipboard splices of the holes was achieved using magnetic susceptibility data (Zachos et al., 2004) and later confirmed using high resolution XRF scanning Fe data (Westerhold et al., 2007, 2008). Early Paleogene sediments at Site 1262 predominantly consist of nannofossil oozes with fluctuating proportions of clay and variable preservation of carbonate microfossils, indicative of deposition above, but close to, a dynamic lysocline, at a paleodepth of ~3600 m (Zachos et al., 2004). Samples were taken from both Holes 1262A and 1262B. Samples were taken every 3 cm of the splice from Holes 1262A and 1262B between 109 and 185 mcd. According to the adopted chronology (see below), this implies a temporal resolution of ~2.5 kyr for much of the Latest Paleocene–Earliest Eocene (114–165 mcd), and a slightly lower resolution ~3–4.5 kyr in the mid Late Paleocene (165–185 mcd), and the post-ETM-2 Early Eocene interval (109–114 mcd). Freeze-dried samples were soaked in distilled water to disaggregate, then washed through a 38 μm mesh sieve and rinsed with ethanol before being dried. Benthic stable-isotope data was generated from 2433 samples of the cosmopolitan deep-water benthic foraminifera *Nuttalides truempyi* picked from the >150 μm fraction (1621 at Santa Cruz and 812 at MARUM, Bremen).

2.2. Stable isotopes

On average, 11 specimens of *N. truempyi* were used for each isotopic analysis. Isotopic measurements were carried out on a Thermo-Finnigan MAT253 mass spectrometer interfaced with a Kiel Device (UCSC), and a Thermo-Finnigan MAT251 mass spectrometer interfaced with a Kiel Device (MARUM, Bremen). At UCSC, analytical precision (1σ) is based on repeat analysis of an in-house standard (Carrara marble), calibrated to the international standards NBS18 and NBS19, and averages ±0.05‰ for δ^{13}C and ±0.08‰ for δ^{18}O. At Bremen, analytical precision (1σ) is based on the in-house