



Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl



Late Miocene climate and time scale reconciliation: Accurate orbital calibration from a deep-sea perspective

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ARTICLE INFO

Article history:

Received 8 March 2017

Received in revised form 22 June 2017

Accepted 23 July 2017

Available online xxxx

Editor: H. Stoll

Keywords:

late Miocene

palaeoclimate

stable isotope stratigraphy

astrochronology

magnetostratigraphy

geological time scale

ABSTRACT

Accurate age control of the late Tortonian to early Messinian (8.3–6.0 Ma) is essential to ascertain the origin of benthic foraminiferal $\delta^{18}\text{O}$ trends and the late Miocene carbon isotope shift (LMCIS), and to examine temporal relationships between the deep-sea, terrisphere and cryosphere. The current Tortonian–Messinian Geological Time Scale (GTS2012) is based on astronomically calibrated Mediterranean sections; however, no comparable non-Mediterranean stratigraphies exist for 8–6 Ma suitable for testing the GTS2012. Here, we present the first high-resolution, astronomically tuned benthic stable isotope stratigraphy (1.5 kyr resolution) and magnetostratigraphy from a single deep-sea location (IODP Site U1337, equatorial Pacific Ocean), which provides unprecedented insight into climate evolution from 8.3–6.0 Ma. The astronomically calibrated magnetostratigraphy provides robust ages, which differ by 2–50 kyr relative to the GTS2012 for polarity Chrons C3An.1n to C4r.1r, and eliminates the exceptionally high South Atlantic spreading rates based on the GTS2012 during Chron C3Bn. We show that the LMCIS was globally synchronous within 2 kyr, and provide astronomically calibrated ages anchored to the GPTS for its onset (7.537 Ma; 50% from base Chron C4n.1n) and termination (6.727 Ma; 11% from base Chron C3An.2n), confirming that the terrestrial C3:C4 shift could not have driven the LMCIS. The benthic records show that the transition into the 41-kyr world, when obliquity strongly influenced climate variability, already occurred at 7.7 Ma and further strengthened at 6.4 Ma. Previously unseen, distinctive, asymmetric saw-tooth patterns in benthic $\delta^{18}\text{O}$ imply that high-latitude forcing played an important role in late Miocene climate dynamics from 7.7–6.9 Ma. This new integrated deep-sea stratigraphy from Site U1337 can act as a new stable isotope and magnetic polarity reference section for the 8.3–6.0 Ma interval.

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1. Introduction

The late Tortonian to early Messinian (8.3–6.0 Ma) is characterised by long-term reduction in benthic foraminiferal $\delta^{18}\text{O}$ values and by distinctive short-term $\delta^{18}\text{O}$ cycles (Hodell et al., 2001; Drury et al., 2016). Coevally, a permanent -1% change in oceanic $\delta^{13}\text{C}_{\text{DIC}}$, referred to as the late Miocene carbon isotope shift (LMCIS), marks the last major global carbon cycle shift expressed in all oceanic basins, after which near-modern inter-oceanic $\delta^{13}\text{C}$ gra-

dients are established at ~ 6.7 Ma (Keigwin, 1979; Hodell and Venz-Curtis, 2006). Furthermore, this time period marks the development of strong equator to pole SST gradients with major cooling at high latitudes but little change in the tropics (Herbert et al., 2016). Accurate age control is crucial to ascertain the origin of the $\delta^{18}\text{O}$ cyclicity and the LMCIS, as constraining the precise timing of such events can allow accurate determination of temporal and causal relationships between deep-sea, terrestrial and cryosphere records.

The late Tortonian–early Messinian Geological Time Scale (GTS2012) is constructed using astronomically tuned sedimentary cycles in Mediterranean successions (Hilgen et al., 1995; Krijgsman et al., 1999). However, recent studies utilising astronom-

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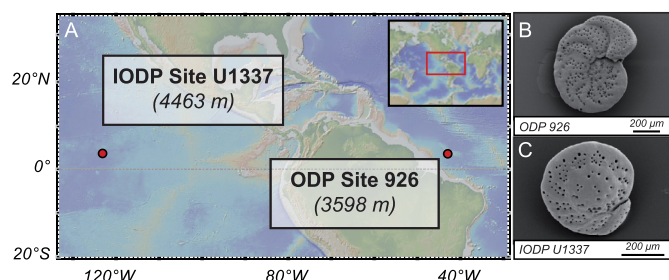


Fig. 1. A) Location and water depth of IODP Site U1337 in the equatorial Pacific and ODP Site 926 on Ceara Rise in the equatorial Atlantic (<http://www.geomapapp.org>); B) SEM image of a *Cibicoides wuellerstorfi* from Site 926; C) SEM image of a *Cibicoides mundulus* from Site U1337. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ically tuned deep-sea sedimentary successions have challenged the Mediterranean tuning (Channell et al., 2010; Westerhold et al., 2012, 2015). Discrepancies in the Mediterranean tuning could originate because road-cut outcrops are often more difficult to integrate and interpret than deep-sea sedimentary successions, which benefit from multiple hole sedimentary splices and integration between multiple sites. To test the Tortonian–Messinian GTS, independent astronomical calibration of Chrons C3An.1n to C4r.1r is required in suitable successions outside the Mediterranean.

Up to now, no stand-alone integrated high-resolution chemo-, magneto-, and cyclostratigraphy exist for 8–6 Ma from a single non-Mediterranean deep-sea site. The absence of appropriate records was overcome with the retrieval of equatorial Pacific Integrated Ocean Drilling Program (IODP) Site U1337 (Fig. 1A). Site U1337 is an ideal location at which to generate the required stratigraphy, as it is characterised by relatively high pelagic sedimentation rates (~ 2 cm/kyr) and high biogenic carbonate content. Crucially, a rudimentary shipboard magnetic polarity stratigraphy was recovered at Site U1337 with great potential for improvement (Expedition 320/321 Scientists, 2010b).

We present a high-resolution astronomically tuned benthic stable isotope stratigraphy (1.5–2 kyr resolution) and magnetostratigraphy (2.5 kyr resolution across reversals) for 8.3–6.0 Ma to provide accurate age control and constrain late Miocene climate evolution at an unprecedented resolution from a deep-sea perspective. We verify the Site U1337 astrochronology by comparison to an extended benthic stable isotope stratigraphy from equatorial Atlantic Ocean Drilling Program (ODP) Site 926 (Fig. 1A), which has an independent astrochronology (Zeeden et al., 2013). The new U1337 astrochronology is used to independently calibrate the high-resolution magnetostratigraphy and improve the GPTS for 8.3–6.0 Ma and to establish a key reference stratigraphy for the late Miocene. We finally investigate the origin of the LMCIS and the late Tortonian–early Messinian patterns in benthic $\delta^{18}\text{O}$.

2. Materials and methods

All datasets are archived as supplementary tables in the open access Pangaea database (<https://doi.pangaea.de/10.1594/PANGAEA.872722>).

2.1. Site locations and sampling strategy

This study utilises late Miocene sediments recovered from IODP Site U1337 (Fig. 1A; $3^{\circ}50.009'\text{N}$, $123^{\circ}12.352'\text{W}$; 4463 m water depth; 4190–4260 m palaeowater depth between 8.3–6.0 Ma; Expedition 320/321 Scientists, 2010b; Pälike et al., 2012) in the eastern equatorial Pacific, retrieved during Pacific Equatorial Age Transect (PEAT) Expedition 321 (Expedition 320/321 Scientists,

2010b). A total of 1186 samples were taken for isotope analysis between 110 and 168.03 revised m composite depth (rmcd = CCSF-A from Wilkens et al., 2013) to increase the resolution of existing 10-cm resolution isotopic record produced at IODP Site U1337 by Jun Tian (Tongji University; Tian et al., 2017), in order to obtain a final resolution of ~ 3 –4 cm (~ 1.5 –2 kyr). For discrete palaeomagnetic analysis, 597 cube samples (standard ODP $2 \times 2 \times 2$ cm = 8 cc) were taken between 92.76 and 167.88 m rmcd from parallel holes U1337A, U1337B and U1337D, at a minimum sampling resolution of 50 cm (100 kyr). Across reversals, sampling resolution was increased to 5 cm (2.5 kyr) and completed in at least two parallel holes. All off splice data were adjusted to the revised Wilkens et al. (2013) splice using mapping pairs (Supplementary Table 1).

This study additionally uses sediments from ODP Site 926 (Fig. 1A; $3^{\circ}43.141'\text{N}$, $42^{\circ}54.501'\text{W}$; 3598 m water depth) in the equatorial Atlantic, retrieved during Ceara Rise ODP Leg 154 (Shipboard Scientific Party, 1995). A total of 449 samples were taken at 5–10 cm resolution (3–6 kyr) between 165.86 and 208.03 rmcd (Wilkens et al., 2017) to increase the resolution of published isotope data between 7.3–5.5 Ma (Shackleton and Hall, 1997) and to extend the record to 8.0 Ma.

2.2. Site U1337 palaeomagnetic data

To reconstruct the magnetic reversal stratigraphy between C3An.1n and C4r.1r at Site U1337, all discrete cube samples were analysed for natural remanent magnetisation (NRM). Palaeomagnetic directions and magnetisation intensities were measured on a cryogenic magnetometer (2G Enterprises model 755 HR) at the Faculty of Geosciences, University of Bremen (Germany). NRM was measured on each sample before applying alternating field demagnetisation using peak-field steps of 5, 7.5 and 10 mT. After each demagnetisation step, magnetisation directions and intensities were measured (Supplementary Table 2).

To determine the characteristic remanent magnetisation (ChRM; Supplementary Tables 3 and 4), magnetisation components were determined from AF demagnetisation of the NRM using the method of Kirschvink (1980), anchoring components to the origin of orthogonal projections. The peak fields for determination of ChRM are generally in the 5–10 mT range. A stable direction (ChRM) could not be found for 2% of the samples. The maximum angular deviation (MAD) was calculated to quantify the quality of the individual magnetic component directions. MAD values above 15° are excluded from further interpretation (9%). MAD values are generally below 10° , with 10% falling between 10° and 15° . Approximately 11% of the measurements have no MAD value, as they are based on fewer than three demagnetisation steps. To azimuthally orient the data, the FLEXIT orientation (Expedition 320/321 Scientists, 2010a) was added to the sample declination values. All FLEXIT corrected declinations larger than 270° were plotted between -90° and 0° .

2.3. Stable isotope analyses

SEM images show that the benthic foraminiferal preservation is generally good at both sites, and that the foraminifera are suitable for isotopic analysis (Fig. 1B and C). From Site U1337, 1–6 translucent *C. mundulus* specimens (250–500 µm) and for Site 926, 2–6 translucent *C. mundulus* or *C. wuellerstorfi* (250–500 µm) were analysed for carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) isotopes using a Kiel I carbonate preparation device attached to a Finnigan MAT 251 at MARUM (University of Bremen, Germany), with an analytical precision of 0.03‰ for $\delta^{13}\text{C}$ and 0.04‰ for $\delta^{18}\text{O}$. All results are reported against Vienna Pee Dee Belemnite (VPDB) using the standard δ notation (per mille ‰), determined using calibrated

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