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Eastern equatorial Pacific benthic foraminiferal distribution and deep water temperature changes during the early to middle Miocene

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ABSTRACT

We investigate changes in benthic foraminiferal assemblages and estimate bottom water temperatures (BWT), based on Mg/Ca ratios of *Oridorsalis umbonatus*, over three selected intervals of major climate change during the late early to middle Miocene at Integrated Ocean Drilling Program (IODP) Sites U1337 (4463 m water depth) and U1338 (4200 m water depth), eastern equatorial Pacific Ocean. The targeted intervals are: (1) the onset of the Miocene Climatic Optimum (MCO; at ~16.9 Ma) and associated carbon cycle perturbation (Site U1337); (2) the episode of peak warmth within the MCO centered at 15.6 Ma (Site U1338); (3) the major cooling step at ~13.8 Ma related to east Antarctic ice-sheet expansion (Site U1338). Assemblages from these three intervals are mainly composed of cosmopolitan, long ranging (e.g., Paleogene to recent), lower bathyal to abyssal species, including calcareous elongated forms that became extinct during the middle Pleistocene. The onset of the MCO and interval of peak warmth had little impact on benthic foraminiferal accumulation rates (BFAR), abundances and assemblage composition. A transient BWT warming of 2.6 °C at the onset of the interval of peak warmth concurred with a benthic stable oxygen isotope ($\delta^{18}O$) decrease of 1‰, suggesting that the $\delta^{18}O$ decrease was largely controlled by BWT changes. A substantial increase in BFAR and in the abundances of *Epistominella exigua* and epifaunal taxa after ~13.83 Ma coincides with increased opal accumulation rates, reflecting enhanced and seasonally pulsed organic carbon (C_{org}) flux to the seafloor during the global cooling step. During this interval, BWT decrease by 1.7 °C concurrent with a 1.0‰ increase in the stable oxygen isotope composition of seawater ($\delta^{18}O_{sw}$). Comparable trends at Ocean Drilling Program (ODP) Site 1146 in the South China Sea, with a 2.2 °C cooling and 0.9‰ increase in $\delta^{18}O_{sw}$ at ~13.8 Ma, further support that the benthic $\delta^{18}O$ increase during the major cooling step was largely controlled by ice volume changes.

1. Introduction

The response of deep sea benthic foraminifera to Miocene intervals of major climate change, such as the Miocene Climatic Optimum (MCO, ~16.9 to ~14.7 Ma; e.g., Holbourn et al., 2014, 2015) and the global cooling linked to east Antarctica ice-sheet expansion at ~13.8 Ma (Woodruff et al., 1981; Woodruff and Savin, 1991; Flower and Kennett, 1994; Shevenell et al., 2004, 2008; Holbourn et al., 2005, 2014), remains an open question. Previous studies do not all agree on the timing and magnitude of major Neogene deep sea foraminiferal turnovers and their linkages to paleoclimatic and paleoceanographic events. For instance, benthic foraminiferal turnovers in the western Pacific (Woodruff and Douglas, 1981) and North Atlantic (Thomas, 1987) Oceans, representing either migratory or evolutionary events, were associated with middle Miocene global cooling and Antarctic ice sheet expansion. Woodruff and Douglas (1981) reported 16 benthic foraminiferal first/last occurrences between 16 and 12 Ma at Deep Sea Drilling Project (DSDP) Site 289 (2206 m water depth, western equatorial Pacific) and Thomas (1987) recorded six first/last occurrences between 15.5 and 13.5 Ma at DSDP Sites 608 and 610 (~3500 m water depth, northeastern North Atlantic Ocean). Protracted intervals of faunal reorganization also appear to have occurred through the early to middle Miocene that were not linked to short-lived climatic events in the deep eastern equatorial Pacific Ocean (Thomas, 1985; Thomas and Vincent, 1987) and deep North Atlantic Ocean (Berggren, 1972; Miller and Katz, 1987). Fundamental limitations for some of these early studies, however, were the incomplete recovery of Miocene sediment successions and the lack of well constrained chronologies. Moreover, these studies focused mainly on evolutionary turnovers rather than on transient changes in assemblage composition during intervals of profound climate reorganizations, such as the intensification of equatorial Pacific upwelling and changes in deep water circulation associated with the

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middle Miocene cooling phase (Holbourn et al., 2013b, 2014).

The evolution of bottom water temperatures (BWT) over the early to middle Miocene interval is not well understood either. Low-resolution benthic Mg/Ca-based BWT reconstructions coupled with benthic stable oxygen isotopes ($\delta^{18}O$) measurements over the entire Cenozoic enabled the recognition of several episodes of bottom water cooling related to major ice-sheet expansion phases, such as at the Eocene/Oligocene boundary, middle Miocene and Plio-Pleistocene (Lear et al., 2000; Billups and Schrag, 2002, 2003). High-resolution paired benthic Mg/Ca and $\delta^{18}O$ records for the Miocene mainly focused on the climatic transition leading to global cooling and east Antarctica ice-sheet growth at ~13.8 Ma (Billups and Schrag, 2002; Shevenell et al., 2008; Lear et al., 2010, 2015). The scarcity of high-resolution Miocene BWT reconstructions is largely due to the fact that generating Mg/Ca records remains challenging, mainly due to the preservation of foraminiferal tests and the unresolved Mg/Ca composition of Miocene seawater.

In this study, we investigated changes in benthic foraminiferal assemblages and generated Mg/Ca-based BWT reconstructions over three selected intervals of major climate change at Integrated Ocean Drilling Program (IODP) Sites U1337 (4463 m water depth) and U1338 (4200 m water depth), eastern equatorial Pacific Ocean. The targeted intervals are: (1) the onset of the MCO and subsequent carbon cycle perturbation (16.93 to 16.65 Ma), (2) a prominent episode of peak warmth within the MCO (centered at 15.6 Ma) identified in high resolution stable isotope records from the Pacific (Holbourn et al., 2007) and Atlantic (Raffi et al., 2006) Oceans, (3) the major cooling step at ~13.8 Ma associated with east Antarctic ice-sheet expansion. By investigating these continuous and well dated sedimentary archives, our main objectives are: (1) to assess the response of deep sea benthic foraminiferal assemblages to late early to middle Miocene episodes of major climate change and (2) to evaluate whether the high-amplitude orbital scale variability imprinted in the benthic $\delta^{18}O$ records is coupled to changes in BWT.

2. Material and methods

2.1. Location of sites and sampling strategy

Sites U1337 and U1338, drilled during IODP Expedition 321 in the eastern equatorial Pacific Ocean, recovered continuous, well preserved lower to middle Miocene successions, which are mainly composed of nannofossil oozes with intervals of increased biogenic silica (Pälike et al., 2010; Holbourn et al., 2014; Lyle and Baldauf, 2015). Site U1337 was drilled between the Galapagos and Clipperton fracture zones (3°50.009′N, 123°12.352′W) in 4463 m water depth (Fig. 1). The site was located close (~1°) to the paleo-Equator between 19 and 11 Ma and was backtracked to a water depth of ~3800 m at ~17 Ma (Pälike et al., 2012). Site U1338 is situated just north of the Galapagos Fracture Zone (2°30.469′N, 117°58.178′W) in 4200 m water depth (Fig. 1). The site was located close (~1°) to the paleo-Equator between ~14.5 and 6 Ma (Pälike et al., 2012) and was backtracked to a water depth of ~3200 m at ~17 Ma (Pälike et al., 2012). According to Pälike et al. (2012), uncertainties of the estimated paleo-depths are in the range of a few hundred meters (~250 m).

We selected three intervals of major climate change (Fig. 2): (1) the onset of the MCO and subsequent carbon cycle perturbation, from 375.96 to 370.30 m composite depth (mcd) equivalent to 16.96–16.65 Ma at Site U1337 (Holbourn et al., 2015); (2) the interval of peak warmth within the MCO, from 426.34 to 424.19 mcd equivalent to 15.64–15.56 Ma at Site U1338 (Holbourn et al., 2014); and (3) the major cooling step related to extensive ice growth over Antarctica, from 374.94 to 368.73 mcd equivalent to 13.93–13.75 Ma at Site U1338 (Holbourn et al., 2014). The average temporal resolution is ~10 kyr for foraminiferal counts, ~20 kyr for Mg/Ca measurements and ~5 kyr for stable isotope measurements over the onset of the MCO at Site U1337; ~3 kyr for foraminiferal counts, ~7 kyr for Mg/Ca measurements, and ~2 kyr for stable isotope measurements over the interval of peak warmth at Site U1338; ~9 kyr for foraminiferal counts and Mg/Ca measurements and ~1.5 kyr for stable isotope measurements over the major cooling step at Site U1338. Original age models and sedimentation rates for Sites U1337 and U1338 are from Holbourn et al. (2015) and Holbourn et al. (2014), respectively, following splice revisions by Wilkens et al. (2013), as detailed in Kochhann et al. (2016).

For comparison, we additionally measured benthic foraminiferal Mg/Ca ratios at Ocean Drilling Program (ODP) Site 1146 (19°27.40′N, 116°16.37′E), drilled during ODP Leg 184 at the northern margin of the South China Sea in a water depth of 2091 m (Wang et al., 2000). The Site 1146 record only extends back to ~16.5 Ma; thus, the selected intervals are: (1) the episode of peak warmth from 539.88 to 536.91 m below seafloor (mbsf) equivalent to 15.62–15.54 Ma and (2) the major cooling step from 491.76 to 488.15 mbsf equivalent to 13.93–13.75 Ma. Average temporal resolution is ~7 kyr for Mg/Ca measurements and 2.5 kyr for stable isotope measurements across the episode of peak warmth and ~14 kyr for Mg/Ca measurements and 4 kyr for stable isotope measurements across the major cooling step. The major cooling step falls within lithologic Unit IIB that is characterized by abundant biogenic calcite (Wang et al., 2000). Clay content increases during the interval of peak warmth within lithologic Unit III. The age model for Site 1146 follows Holbourn et al. (2007).

2.2. Sample preparation and benthic foraminiferal counts

Sediment samples were oven dried at 40 °C and weighed before being washed over a 63 μm-mesh sieve. Residues were then oven-dried at 40 °C and weighed prior to sieving for ~10 min into the following grain-size fractions: 63–150 μm, 150–250 μm, 250–315 μm and > 315 μm. All benthic foraminifera were picked from the > 315 and 250–315 μm fractions for each sample. Depending on abundance, the 150–250 μm fractions were split in aliquots and the number of picked benthic foraminifera converted to the whole fraction and added to the > 315 and 250–315 μm counts (Supplementary table C1). We additionally counted specimens of *Epistominella exigua*, an indicator of pulsed organic flux to the sea floor (e.g., Gooday, 1988; Smart et al., 1994), in a split of the 63–150 μm fractions, since this small species occurs predominantly within this grain-size fraction (Supplementary table C2).

Shannon-Wiener diversity (*H′*) was calculated with the software PAST – Paleontological statistics (Hammer et al., 2001). We also used PAST to perform a principal component analysis (PCA) on benthic foraminiferal counts from the > 150 μm grain size fractions (Supplementary table C1). Percentages of planktic (P) against benthic (B) foraminifera [$P(\%) = 100 * (P / (P + B))$] were estimated for each sample from the > 315, 250–315 and 150–250 μm fractions, based on counts of ~200 specimens.

To calculate benthic foraminiferal accumulation rates (BFAR), expressed as specimens $cm^{-2}\ kyr^{-1}$, we used linear sedimentation rates (LSRs; $cm\ kyr^{-1}$), dry bulk densities ($g\ cm^{-3}$) and dry bulk sample weights (g). LSRs were linearly interpolated from age control tie points given in Kochhann et al. (2016). Dry bulk densities were linearly interpolated from gamma ray attenuation (GRA) bulk densities, after converting GRA bulk densities to dry bulk densities according the linear relationships presented in Pälike et al. (2010) for Sites U1337 and U1338. We multiplied LSRs by the sediment dry bulk densities ($g\ cm^{-3}$) and then by the number of benthic foraminifera per gram of bulk sample weight (specimens g^{-1}). Data sets are available as supplementary information (Appendix B; Supplementary tables C1 and C2). Slides containing the benthic foraminiferal assemblages are archived in the collections of the Marine Micropaleontology Unit at the University of Kiel.

2.3. Mg/Ca analysis

Mg/Ca ratios were measured on *Oridorsalis umbonatus*