Early Cenozoic glaciation: Exploring the paradigm of an 'ice-free' middle Eocene

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Summary The onset of the Cenozoic 'greenhouse-icehouse' transition is poorly constrained, with the Middle Eocene often considered the intermediary 'doubthouse' phase. Most benthic foraminiferal oxygen isotope ($\delta^{18}O$) reconstructions typically assume 'ice-free' conditions during this period. However, the occurrence of high-frequency sea-level change of tens of meters in the sequence stratigraphic record, is best explained by glacio-eustacy (e.g. Browning et al., 1996). To explore the paradigm of an 'ice-free' Middle Eocene, we discuss a high-resolution record of seawater $\delta^{18}O$ from Ocean Drilling Project (ODP) Site 1209 in the northern tropical Pacific Ocean. The new seawater $\delta^{18}O$ record for Site 1209 indicates two major glacial episodes occurred at ~44.8 and 42.7Ma. We also evaluate the seawater $\delta^{18}O$-sea-level calibration accounting for potential biases arising from carbonate ion concentration, Cenozoic ice $\delta^{18}O$ composition and additional ice storage as a result of glacio-eustatic sea level fall.

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Introduction

A fundamental shift in Earth's ocean-climate system occurred during the late Paleogene. The transition from the Early Cenozoic 'greenhouse' world into the Oligocene 'icehouse' is marked by an abrupt 1‰ shift in benthic and seawater $\delta^{18}O$ ($\delta^{18}O_{sw}$) values close to the Eocene-Oligocene boundary (E/O), reflecting the appearance of substantial continental ice-sheets on Antarctica (e.g., Coxall et al., 2005). A sharp transition has also been observed in records of ice-rafted debris (IRD) and clay mineralogy, consistent with a major episode of glacial expansion at the Eocene-Oligocene boundary (Ehrmann & Mackensen, 1992). The occurrence of high-frequency sea level variations on the order of tens of meters (Browning et al., 1996) and Southern Ocean IRD during the Eocene (Ehrman & Mackensen, 1992) indicates the greenhouse-icehouse transition may have more gradual, with variable ice volume possibly as early as the Middle Eocene, and hence this interval has been termed the 'doubthouse'.

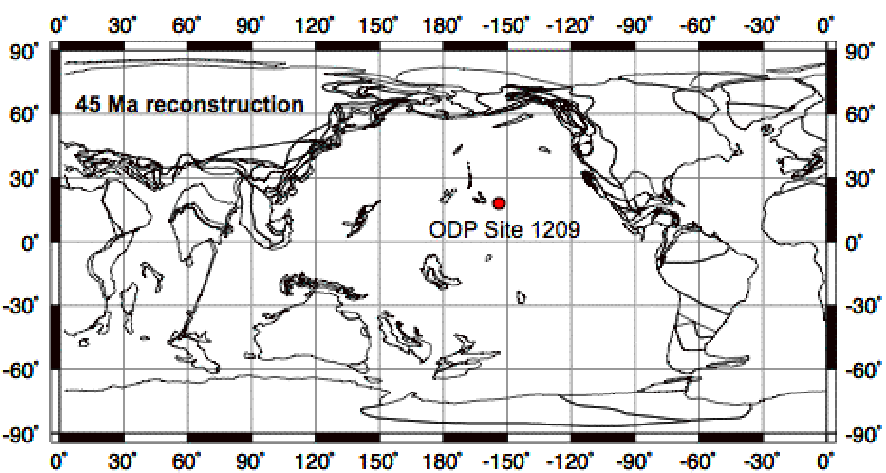

Figure 1. Paleogeographic reconstruction for the Middle Eocene showing the position of ODP Site 1209. The site is situated on the northern flank of Shatsky Rise in the Pacific Ocean (32°39.108´N, 158°30.3564´E). Shatsky Rise was located in the Northern sub-tropical belt throughout the Middle and Late Eocene (paleolatitude 15-20ºN, Figure 1.), having an intermediate paleodepth of ~2.5 km (Bralower et al., 2002). This site was located 1.0 to 1.5 km above the Pacific calcite compensation depth for the entire duration of the study interval (Tripati et al., 2005). The age model for this interval is constrained by 3 nannofossil datums (Bralower et al., 2005).

Until recently, benthic foraminiferal $\delta^{18}O$ records of the Eocene 'doubthouse' have been limited. Deep-sea sites spanning this critical transition are scarce, and much of the available core material is plagued by hiatuses and/or contains poorly preserved carbonates. Several benthic $\delta^{18}O$ records for this interval have been published over the past four years, and have produced contrasting interpretations. A period of transient deep ocean warming, termed the Middle Eocene Climatic Optimum, was inferred from the benthic $\delta^{18}O$ record for the Southern Ocean at ~42.7 Ma assuming ice-free conditions (Bohaty & Zachos, 2003). Warming at this time was corroborated by a short-lived reversal towards lighter $\delta^{18}O$ values at Demerara Rise (tropical Atlantic) between 44 and 42 Ma. (Sexton et al., 2006).

In contrast, recently published carbonate content and seawater $\delta^{18}O$ records from the deep equatorial Pacific exhibit a positive excursion similar in magnitude to that observed across the Eocene-Oligocene boundary (Tripati et al., 2005, 2007). The amplitude of $\delta^{18}O$ changes in the middle Eocene to early Oligocene require some ice storage in both hemispheres, consistent with recent reports of IRD in Eocene and Oligocene sediments in the Northern Hemisphere (Moran et al., 2006; Eldrett et al., 2007). These records imply that the Middle Eocene was not exclusively 'ice-free' and support a glacioeustatic origin for sea-level variations recorded in the sequence stratigraphic record at ~44.5 Ma, 42.7 Ma, and 40.2 Ma (Pekar et al., 2005, Miller et al., 1998). The rapid termination of the major Middle Eocene excursion which begins at 42.7 Ma and ends at 40.5 Ma coincides, within error of the age models, to a sequence boundary in the New Jersey passive margin sequence (Browning et al., 1996). Yet the magnitude of the inferred sea-level change differs significantly: using a conservative Quaternary seawater $\delta^{18}O$ sea-level calibrations of ~ 0.0084‰ per 1m (Shackleton, 2000; Waelbroeck et al., 2002); the late Middle Eocene seawater $\delta^{18}O$ excursion requires ~ 165 m of sea level change, over 140 m more than the minimum estimates of sea level change estimated from the New Jersey margin (Miller et al., 2006). The 1.5‰ excursion in seawater $\delta^{18}O$ at the Eocene-Oligocene transition implies a similarly large change in sea level, yet sequence stratigraphic estimates are on the order of tens to 70 metres (Coxall et al., 2005; Gale et al., 2006).

Additional benthic $\delta^{18}O$ records are needed to resolve the onset and magnitude of early Cenozoic glaciation. This type of data is also critical to the development of more accurate seawater $\delta^{18}O$-sea level calibrations. Here we explore the paradigm that the Middle Eocene was 'ice-free' using high-resolution coupled benthic foraminiferal $\delta^{18}O$ and Mg/Ca-based paleotemperature records for Site 1209 in the northern tropical Pacific Ocean. Throughout the Cenozoic, the Pacific basin has been the largest oceanic reservoir. Consequently Pacific records of seawater $\delta^{18}O$ are a better approximation for mean seawater $\delta^{18}O$ than those from smaller basins and shallow passive margins.

Results and Discussion

The benthic $\delta^{18}O$ record for Site 1209 exhibits a long-term trend towards heavier values with superimposed large amplitude oscillations of 0.5 to 0.7‰. The range of $\delta^{18}O$ values observed is consistent with those previously recorded for this site (Dutton et al., 2005). Rapid positive shifts occur at ~44.6 Ma, 43.2 Ma and 42.6 Ma, and do not return to pre-excursion values. The Mg/Ca-based temperature record indicates only 2ºC variations from a baseline value of ~9-10ºC throughout the Middle Eocene.

The seawater $\delta^{18}O$ record exhibits large positive excursions of ~1.3 and ~1.1‰ at 44.8 Ma and 42.7 Ma, respectively. The magnitude of the excursions indicates two major glacial episodes during the Middle Eocene. The 44.8 Ma glacial has not yet been reported in other benthic foraminiferal or seawater $\delta^{18}O$ records. However, the second glaciation is correlative with the glacial previously reported at ODP Site 1218 (Tripati et al., 2005). At Site 1209, both glaciations show a similar structure, commencing with a rapid 1-1.2‰ shift that become progressively heavier before terminating with an equally rapid negative shift. Intriguingly the duration of the glacial episodes are variable. Based on the current age model, it appears that the earliest glaciation terminates after ~400 ka whilst the later glacial is sustained for ~2.4 Ma.

An 'ice-free' paradigm

The fidelity of the seawater $\delta^{18}O$ record is partly dependent on the accuracy of seawater temperatures reconstructed using benthic foraminiferal Mg/Ca ratios. Analytical precision based on replicates of Cenozoic foraminiferal standards is 3%; consequently it is possible to resolve changes in seawater temperature of <±1ºC. However, the estimated error associated with the species-specific Mg/Ca paleotemperature calibrations (e.g. 8.6% for combined pre-exponent and exponent errors for *Cibicidoides sp.* Lear et al., 2002), decreases such precision to ~±1ºC. Potential bias in foraminiferal Mg/Ca ratios may also result from the effects of carbonate ion concentration ($[CO_3^{2-}]$). Using the sensitivity of Mg/Ca to $\Delta[CO_3^{2-}]$ for C. *wuellerstofi* (Elderfield et al., 2006), a 30µmol/kg change in $[CO_3^{2-}]$ associated with the 1km deepening of the CCD observed across Eocene-Oligocene boundary may produce a temperature bias of up to 0.9°C, resulting in a 0.10 to 0.15‰ uncertainty in $\delta^{18}O_{sw}$ reconstructions (Tripati & Elderfield, 2005). The errors quantified above are to be taken as minimum estimates of the propagated error. Additional uncertainty is associated with the temporal variations in seawater Mg/Ca ratios and the heterogeneous distribution of Mg in foraminiferal tests. However, to date, these factors are poorly constrained and therefore it is not possible to quantify the associated errors. Accounting for errors associated with foraminiferal Mg/Ca, we apply a 0.15‰ error-envelope to our benthic $\delta^{18}O_{sw}$ record, a minimum error estimate that only partly takes into account potential sources of error.

The $\delta^{18}O_{sw}$ record for Site 1209 highlights significant variability in ice volume as far back as 45.5 Ma, and supports the presence of large and dynamic Antarctic ice sheets during the Middle Eocene. Previous studies have highlighted the correlation between fluctuations in the CCD and glacioeustatic sea level fall (Tripati et al., 2005; Coxall et al., 2005). There is evidence for large deepenings of the tropical Pacific CCD (Tripati et al., 2005) that roughly correlate with positive excursions in seawater $\delta^{18}O$ at Site 1209. Additional support comes from changes in planktonic foraminiferal fragmentation records for Site 1209 (Hancock & Dickens, 2002), which reflect variations in dissolution and indirectly can be used to infer changes in seawater carbonate saturation. Decreases in fragmentation (and therefore dissolution) are observed at 42.7 Ma and 44.9 Ma (Hancock & Dickens, 2002), coincident with changes in the $\delta^{18}O_{sw}$ record, likely reflecting a deepening of the saturation horizon due to changing basin-to-shelf fractionation of carbonate deposition during the Middle Eocene (Tripati et al., 2005).

δ^{18}O – sea level calibration

To assess the scale of Middle Eocene glaciation, an appropriate sea-level calibration must be applied. Modern sea level calibrations typically utilise benthic foraminiferal δ^{18}O ratios and assume 1) temperature scales linearly with ice volume, and 2) local $\delta^{18}O_{sw}$ effects are negligible. While these assumptions may be somewhat reasonable for Quaternary studies, they need to be closely examined for application to earlier periods because the style of glaciation may have been different. Assuming paleotemperatures are accurate, a more appropriate approach to sea level reconstruction is the use of calibrations derived from the $\delta^{18}O_{sw}$ record, as this is principally a function of ice volume. Modelling studies show that fully glaciating an early Cenozoic Antarctic continent would have yielded a maximum shift in seawater δ^{18}O of 0.5‰ (DeConto & Pollard, 2003). Several excursions observed in the $\delta^{18}O_{sw}$ record at Site 1209 greatly exceed this threshold value, yet there is no evidence in the sequence stratigraphic record that substantiate such large sea level changes (~130 m) (e.g. Miller et al., 2006). A crucial caveat is that sea-level estimates derived from the sequence stratigraphic record represent minimum estimates only, and it is therefore impossible to quantify the discrepancy between the records. However, owing to the magnitude of the excursions observed in the $\delta^{18}O_{sw}$ record, it is necessary to revaluate the change in mean seawater δ^{18}O that could have occurred by fully glaciating the Antarctic continent.

The assumed δ^{18}O composition of Cenozoic ice is crucial to the choice of sea level calibration and for determining this threshold value. Modern Antarctic δ^{18}O ice compositions range from -30‰ in coastal areas to -50‰ in the interior (Mix & Ruddiman, 1984) and are influenced by several factors, including precipitation temperature, precipitation trajectories and elevation. Evidence for the establishment of the Antarctic circum-polar current during the Middle through Late Eocene (Scher & Martin, 2006) and continental aridification (e.g. Dupont-Nivet et al., 2007) imply significant changes in atmospheric heat transport and precipitation patterns. Thus the δ^{18}O composition of early Cenozoic ice is difficult to constrain. The assumption of an early Cenozoic ice δ^{18}O composition similar to the modern average value is unfounded, as Cenozoic temperatures have been shown to be much warmer than present (e.g. Lear et al., 2000; Pearson et al., 2001; Tripati et al., 2003, 2005).

We suggest a reasonable calibration to use is 0.091‰ per 10m sea level, a relationship derived from a modelling study (DeConto & Pollard, 2003) that assumes a Cenozoic ice δ^{18}O composition of ~-30‰, a value consistent with warm Cenozoic seawater temperatures. A caveat to consider with this calibration is that additional ice storage that may be facilitated on Antarctic as a result of glacioeustatic sea-level fall and the exposure of shelf area. However, this is unlikely to have been important in the Cenozoic, assuming the bathymetry was broadly similar to the modern, as a sea level fall of hundreds of meters is required to expose significant shelf area. Using the calibration of DeConto & Pollard (2003), and taking into account the biases described above in calculations of seawater δ^{18}O, we estimate that fully ice covered Antarctica would drive a change in $\delta^{18}O_{sw}$ of 0.65‰. The seawater δ^{18}O reconstruction for Site 1209 indicates multiple, large amplitude (>0.65‰) shifts occurred during the Middle Eocene, in excess of the threshold value for glaciating Antarctica. As such, the magnitude of these excursions is consistent with the storage of ice in both hemispheres.

Summary

Foraminiferal oxygen isotope and Mg/Ca paleotemperature records for Site 1209 indicate that the Middle Eocene was a period of large fluctuations in ice volume. There is evidence from Site 1209 for significant continental ice volume as early as 44.6 Ma, ~ 10 million years prior to the Eocene–Oligocene boundary. The $\delta^{18}O_{sw}$ record highlights at least two transient phases of bipolar glaciation *ca.* 44.6 Ma and 42.7 Ma.

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