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 (δ18O) 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 δ18O from Ocean Drilling Project (ODP) Site 1209 in the northern tropical Pacific Ocean. The new seawater δ18O record for Site 1209 indicates two major glacial episodes occurred at ~44.8 and 42.7Ma. We also evaluate the seawater δ18O-sea-level calibration accounting for potential biases arising from carbonate ion concentration, Cenozoic ice δ18O composition and additional ice storage as a result of glacio-eustatic sea level fall.


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 δ18O (δ18Osw) 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 δ18O 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 δ18O 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 δ18O 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 δ18O 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 Mg/Ca-based paleotemperature record for ~2.4 Ma.

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-$] for C. wuellerstorfi (Elderfield et al., 2006), a 30µmol/kg change in [CO$_3$$^2-$] associated with the 1km deepening of the CCD observed across Eocene-Oligocene boundary may produce a temperature bias of up to 0.9ºC, resulting in a 0.10 to 0.15‰ uncertainty in $\delta^{18}O$ 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 $\delta^{18}O$ record, a minimum error estimate that only partly takes into account potential sources of error.

The $\delta^{18}O$ 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
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 δ¹⁸O record highlights at least two transient phases of bipolar glaciation ca. 44.6 Ma and 42.7 Ma.

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References


