Evidence for synchronous glaciation of Antarctica and the Northern Hemisphere during the Eocene and Oligocene: Insights from Pacific records of the oxygen isotopic composition of seawater

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Summary Constraints on Earth's glacial history come from the deep-sea oxygen isotope ($\delta^{18}O$) record. The growth of Antarctic ice during the early Cenozoic is modelled to have driven changes in seawater $\delta^{18}O$ of up to 0.5‰ (DeConto & Pollard, 2003). Larger shifts in the mean $\delta^{18}O$ of seawater therefore require some storage of ice in both hemispheres. In order to study the evolution of the cryosphere, we developed high-resolution records of seawater $\delta^{18}O$ for three Pacific sites. The seawater $\delta^{18}O$ reconstructions show that several large (>0.65‰) shifts in seawater $\delta^{18}O$ occurred throughout the middle Eocene to early Oligocene. Our records of seawater $\delta^{18}O$ indicate there was ice stored on Antarctica and in the Northern Hemisphere at about 44.5 Ma, 42 Ma, 38 Ma, and after 34 Ma.

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Introduction

A change in the state of Earth's ocean-climate system occurred at the end of the Eocene epoch (55-34 Ma), when the "greenhouse" climate that had been sustained since the Cretaceous evolved to the "icehouse" conditions that characterized the Oligocene through present (Matthews & Poore, 1980; Miller et al., 1987; Zachos et al., 2001). The transition from extreme global warmth to glacial conditions is one of the most prominent in Earth's climatic evolution, yet one of the most poorly understood. Long-term high-latitude cooling began in the early Eocene (~51 Ma), as seen by an increase in low-resolution $\delta^{18}O$ records from benthic foraminifera (Miller et al., 1987, Zachos et al., 2001) and Southern Ocean planktic foraminifera (Zachos et al., 1994) and a decrease in benthic foraminiferal Mg/Ca ratios (Lear et al., 2000). Although some studies have concluded tropical sea-surface temperatures also cooled gradually during the Eocene (Zachos et al., 1994), most climate proxy records support warm and stable tropical sea-surface temperatures throughout the Eocene (Adams et al., 1990, Pearson et al., 2001, Tripati & Zachos, 2002, Tripati et al., 2003), with evidence for small cooling steps at 48, 45 and 42 Ma from planktic foraminiferal Mg/Ca data (Tripati et al., 2003).

The earliest Oligocene (ca. 34 Ma) is widely accepted as the interval associated with the onset of "icehouse" conditions. High-resolution reconstructions of seawater $\delta^{18}O$ show a +1‰ shift that is interpreted to record a sudden and massive expansion of ice volume (Zachos et al., 1992; Lear et al., 2000; Coxall et al., 2005), along with the occurrence of ice-rafted debris in the Southern Ocean (Ehrmann & Mackensen, 1992) and a change in clay mineralogy consistent with increased glacial erosion on Antarctica (Robert & Kennett, 1992; Ehrmann, 1998). There is stable isotope and lithological evidence for small-scale ice sheets in the Northern Hemisphere during the late Miocene (~10-6 Ma) and the build-up of ice in the Pliocene, beginning around 3 Ma (summarised in Zachos et al., 2001). Others have argued for significantly earlier initiation of ice sheet development using low-resolution proxy records (Robert & Kennett, 1992; Billups & Schrag, 2003), with some studies concluding substantial Antarctic ice volume from the late Cretaceous or Eocene (Browning et al., 1996; Miller, 1998; Miller et al., 2004), and continental ice in the Northern Hemisphere since 38 Ma (Eldrett et al., 2007).

There are few constraints on climate stability and cryospheric development during the greenhouse-icehouse transition because of the poor resolution of the few existing datasets, particularly for the middle and late Eocene (49-34 Ma). Until recently, detailed Eocene paleoceanographic records have been limited to two studies because of diagenetic alteration, hiatuses, coring gaps, and lack of stratigraphic constraints, and these studies have inferred large changes in surface water hydrography from planktic foraminiferal oxygen isotope records in the Western Atlantic (Wade & Kroon, 2002) and Southern Ocean (Bohaty & Zachos, 2003). Recent Ocean Drilling Program (ODP) cruises, ODP Legs 198 and 199, successfully recovered continuous middle Eocene through Oligocene sedimentary sequences spanning the greenhouse icehouse-transition from the tropical Pacific Ocean (Bralower et al., 2002; Lyle et al., 2002). This region is a major locus for production and burial of biogenic carbonate in the modern and glacial ocean. Volumetrically it represents a significant portion of the global ocean, and therefore is used often as a "dipstick" for changes in whole ocean carbon chemistry during the Pleistocene. In the Eocene the tropical Pacific would have comprised about 2/3 of all the tropical oceans (van Andel et al., 1973; Lyle et al., 2002), and would have been of even greater importance than during the Pleistocene. This region was dominated by siliceous deposition until the Eocene-Oligocene boundary at 34 Ma, when calcium carbonate nannofossil ooze and chalk replaced radiolarian ooze and radiolarite in less than 300,000 years (Tripati et al., 2005), associated with a deepening of the calcite compensation depth (CCD, the water depth at which calcium carbonate rain rate is balanced by the dissolution rate) of over 1 km.

The carbonate compensation depth

The marked CCD deepening has been linked to a rapid growth of the Antarctic ice sheet based on the coincident 1‰ transient increase in records of surface and deep water δ18O (termed Oi-1) and occurrence of ice-rafted debris in the Southern Ocean at 34 Ma (Zachos et al., 1992; Coxall et al., 2005). We used the presence/absence of calcium carbonate (0% isopleth) at ODP sites with different paleodepths to approximate the basinal CCD in the central equatorial Pacific Ocean and the subtropical South Atlantic Ocean (Tripati et al., 2005). Our records show evidence for large, basinally synchronous shifts in the CCD beginning at ~42 Ma, which is 8 Ma before the Eocene-Oligocene transition. The largest Eocene changes in CCD occurred between about 42 and 38 Ma, when the equatorial Pacific and South Atlantic CCD deepened and shoaled in unison. The equatorial Pacific CCD was shallow during the late Eocene and underwent a large deepening ~34 Ma, whereas the South Atlantic CCD was relatively deep during the late Eocene, and appears to have deepened by only a few hundred meters at ~34 Ma. Because calcium has an oceanic residence time of 10^6 years (Broecker & Peng, 1982), the middle and late Eocene global CCD variations must record large swings in deep water carbonate saturation.

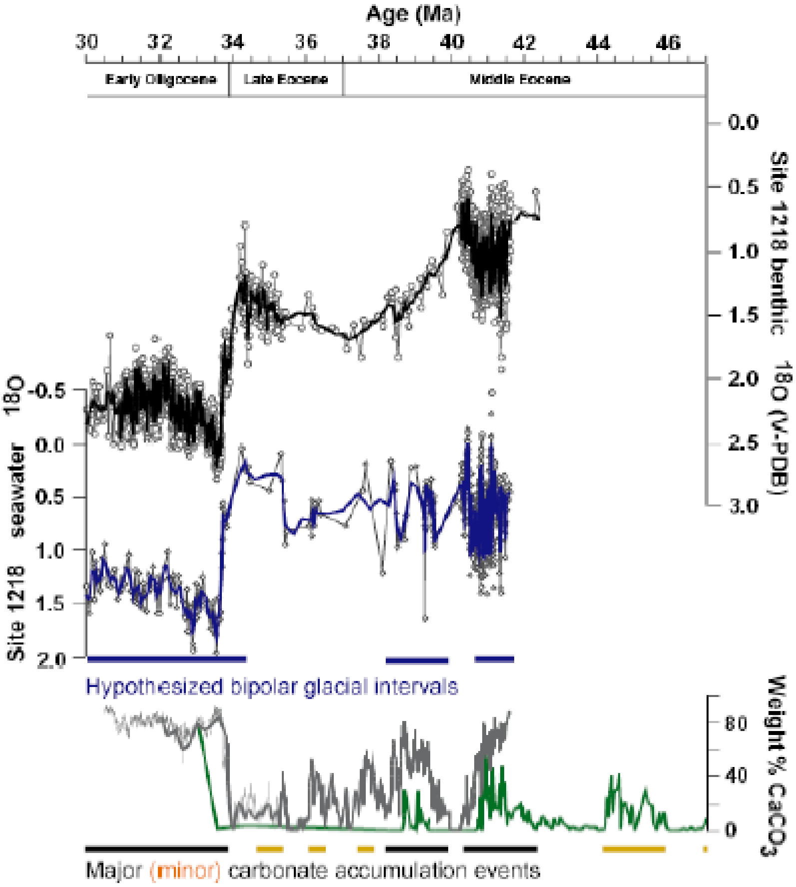

Figure 1. A composite of published (Tripati et al., 2005; Coxall et al., 2005; Lear et al., 2004) and unpublished records for the deep Pacific spanning the late middle Eocene to early Oligocene. Top panel shows benthic foraminiferal d18O. The black line is a 5 point running mean through the data. Middle panel shows seawater d18O based on combining Mg/Ca temperatures with the benthic d18O record. Third panel shows carbonate content for deep Pacific sites 1218 (grey) and 1219 (green), and position of carbonate accumulation events.

In order to more accurately resolve the timing and amplitude of CCD changes across the greenhouse-icehouse transition, we developed high-resolution records of calcium carbonate content and mass accumulation rate (MAR) for complete and well-preserved middle and late Eocene sedimentary sequences from equatorial Pacific Sites 1218 and 1219 (Figure 1). As with the 0% isopleth (calcium carbonate absence) data, these detailed records show that extended intervals of calcium carbonate deposition in the equatorial Pacific Ocean occurred prior to Oi-1, during the middle and late Eocene. Additionally, the data show rapid, large-amplitude changes, with carbonate values ranging from 0 to 90%, and multiple peaks of carbonate deposition, at 40,000 and 100,000 years intervals.

The carbonate and accumulation rate data constrain shifts in the middle and late Eocene CCD of 500 meters to within 100,000 years, and of 800 meters to less than 200,000 years, demonstrating that they are comparable in rate, magnitude, and structure to those observed across the Eocene-Oligocene boundary. We hypothesised these CCD fluctuations were related to glaciations. To test this hypothesis and study the evolution of ice volume during the early Cenozoic, we developed high-resolution records of seawater $\delta^{18}O$ for sites in the tropical Pacific by combining new and published (Lear et al., 2004; Coxall et al., 2005; Tripati et al., 2005) records of benthic foraminiferal $\delta^{18}O$ with Mg/Ca-based paleotemperatures.

Seawater $\delta^{18}O$

Deep Pacific $\delta^{18}O$ records are the most representative of mean $\delta^{18}O$ due to the size of the ocean basin. Changes in the mean $\delta^{18}O$ of seawater reflect the growth or melting of continental ice. We calculated seawater $\delta^{18}O$ by combining records of benthic foraminiferal $\delta^{18}O$ with Mg/Ca-based paleotemperatures for sites in the deep tropical Pacific. In addition to using published data for Site 1218 (Lear et al., 2004; Coxall et al., 2005; Tripati et al., 2005), we have made new measurements of foraminifera from Sites 1209, 1218 and 1219, including a section that spans a previously reported isotopic event.

Large shifts in seawater $\delta^{18}O$ require some storage of ice in the Northern Hemisphere, as the growth of Antarctic ice would have driven changes in seawater $\delta^{18}O$ of up to 0.5‰ (DeConto and Pollard, 2003). Fluctuations in carbonate ion concentrations during the time interval studied (Tripati et al., 2005) may have resulted in estimates of seawater $\delta^{18}O$ that are biased by 0.1‰ (Elderfield et al., 2006). Due to this and other possible artefacts (described in Dawber & Tripati, 2007), we chose to use 0.65‰ as a threshold value for Northern Hemisphere ice storage.

The seawater $\delta^{18}O$ reconstructions for Sites 1218 and 1219 show that several large (>0.65‰) shifts in seawater $\delta^{18}O$ occurred throughout the late middle Eocene to early Oligocene. The magnitude of variations in seawater $\delta^{18}O$ necessitate the storage of ice in both the Northern and Southern Hemisphere between 42-40 Ma, 39-37 Ma, and after 34 Ma. Similar amplitude shifts are observed at Site 1209 in the North Pacific during these three intervals (Dawber & Tripati, 2007). Periods of widespread carbonate deposition (or carbonate accumulation events) and lowstands of the carbonate compensation depth (CCD) have also been linked to glaciations during the late middle Eocene to early Oligocene (Coxall et al., 2005; Lyle et al., 2005; Tripati et al., 2005). The largest seawater $\delta^{18}O$ increases are associated with prominent CCD deepenings, as indicated by deep Pacific records of carbonate content.

Increases in deep Pacific seawater $\delta^{18}O$ of ~1.5‰ are observed at ~42 and 34 Ma. A number of seawater $\delta^{18}O$-sea level relationships have been proposed, and even with a conservative estimate (i.e., the Quaternary relationship of 0.12‰/10 metres of sea level), a 1.5‰ change in seawater $\delta^{18}O$ supports 125 metres of sea level variation. If we assume the isotopic composition of ice was lower during the Eocene and Oligocene (and use a relationship of 0.08‰/10 metres of sea level), the seawater $\delta^{18}O$ record indicates 190 metres of sea level change. Similarly, the shared bulk and benthic $\delta^{18}O$ shifts support a sea level change of between 100 and 150 metres.

Summary

Deep Pacific records of seawater $\delta^{18}O$ support the occurrence of bipolar glaciation as early as the middle Eocene to early Oligocene. We suggest that glacial onset in the two hemispheres was relatively synchronous rather than initiating some 20-30 Ma later in the North, possibly supporting a role for declining atmospheric carbon dioxide levels as a driver for the development of the cryosphere. Our findings support earlier suggestions that the fluctuations in sea level reconstructed for this time interval reflect changes in ice storage in both the Northern and Southern Hemisphere (Coxall et al., 2005; Tripati et al., 2005). Climate model simulations have shown that the rapid glaciation of Antarctica can be explained by declining atmospheric carbon dioxide levels and changing seasonality (DeConto and Pollard, 2003), although tectonic forcing may also be an important factor (Scher and Martin, 2006). A similar study focused on the northern high latitudes may shed light on what processes played significant roles in inducing Northern Hemisphere glaciation.

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