Showing a strong link between climatic and pCO_2 changes: resolving discrepancies between oceanographic and Antarctic climate records for the Oligocene and early Miocene (34-16 Ma)

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Summary An apparent mismatch between published oxygen isotope data and other paleoclimate proxies for the span from 26-16 Ma is resolved by calibration against eustatic estimates obtained from backstripped continental margin stratigraphy. Ice-volume estimates from calibrated oxygen isotope data compare favorably with stratigraphic and palynological data from Antarctica, and with estimates of atmospheric carbon dioxide for the early Oligocene through early Miocene (34-16 Ma). These isotopic data suggest that the East Antarctic Ice Sheet grew to as much as 30% greater than the present-day ice volume at glacial maxima. This conclusion is corroborated by seismic reflection and stratigraphic data from the Antarctic margin that suggest that the ice sheet may have covered much of the continental shelf at Oligocene and early Miocene glacial maxima. Palynological data suggest long-term cooling during the Oligocene, with near tundra environments developing along the coast at glacial minima by the late Oligocene.

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Introduction

The history and mechanisms of late Paleogene and early Neogene (34-16 Ma) climate and ice-volume changes continue to be controversial, despite a plethora of new data, owing to apparent inconsistencies between available proxies. For example, distal proxies for Antarctic climate and ice volume, which include deep-sea oxygen isotopic data (Zachos et al., 2001; Coxall et al., 2005) and stratigraphic records of sea-level change at mid- to low-latitude continental margins (e.g., Kominz and Pekar, 2001; Miller et al., 2005) provide estimates for the size of the early Oligocene ice sheet that vary greatly, from as small as ~50% of the volume of the present-day East Antarctic Ice Sheet (EAIS; e.g., Zachos et al., 2001) to as large as twice that volume (Coxall et al., 2005).

Stratigraphic and palynological data acquired close to Antarctica (e.g., Cooper et al., 1991; Raine and Askin, 2001) suggest a heavily glaciated continent at Oligocene-early Miocene glacial maxima and gradual cooling between successive glacial minima, from cool temperate conditions in the early Oligocene to tundra-like conditions in the latest Oligocene to early Miocene. They are, however, puzzlingly inconsistent with $\delta^{18}O$ evidence (an abrupt decrease in $\delta^{18}O$ values) for global warming and a significant decrease in EAIS volume during the late Oligocene, persisting into the early Miocene (Zachos et al. 2001). The latter data have been taken to indicate a decoupling during that interval between climate change and atmospheric pCO_2 estimates based on $\delta^{13}C$ data from alkenones (Pagani et al., 2005), with pCO_2 values gradually decreasing during the Eocene to Miocene, and reaching near modern levels by the latest Oligocene.

Calibrations of isotopic data against stratigraphically constrained sea-level changes allow apparent conflicts between proxies to be resolved, with all proxies brought into alignment with alkenone $\delta^{13}C$ evidence for a secular decrease in atmospheric pCO_2 for the entire interval between 34 and 16 Ma (Pagani et al., 2005).

Calibration of isotopic records to glacioeustasy

Ice-volume and their associated sea-level changes were determined by calibrating detrended amplitudes of apparent sea level (ASL, defined as eustasy plus water loading effects) based on 2-D flexural backstripping of the stratigraphy recovered from boreholes (Kominz and Pekar, 2001; Pekar et al., 2002) drilled as part of the New Jersey Coastal Plain Drilling Program (e.g., Miller et al., 1998) to $\delta^{18}O$ amplitudes for Oi-events identified by Miller et al. (1991) and Pekar and Miller (1996) in deep-sea records. These calibrations range from as low as 0.12‰/10 m ASL for the Weddell Sea Site 690 to 0.35‰/10 m for Equatorial Atlantic Ocean Site 929, with good to excellent correlation (see Pekar et al., 2002; Pekar et al., 2006 for discussion). Differences among the calibrations are attributable to variability in deep-sea temperatures among the sites between glacial maxima and minima at the million-year time scale. Oligocene $\delta^{18}O$ values of 3‰ or greater in deep-sea records are consistent with an EAIS of modern size and with bottom water temperatures $\leq$ 2.0° C (see Pekar et al., 2006 for discussion).

Discussion: Synthesis of Antarctic cryospheric history between 34-16 Ma

Calibrated isotopic records

Calibrated isotopic records indicate that ice volume increased from near zero during the late Eocene to 25% larger than the present-day EAIS (equivalent to an ASL lowering of 75 m) by the earliest Oligocene (33.5 Ma; Fig. 1). Oligocene ice volume was greatest at ~29 and 25 Ma, being some 30% larger than the present-day EAIS (equivalent to 80 m of ASL lowering). The EAIS was generally smaller between 33 and 29 Ma (with the exception of isotope event Oi1b [31.7-31.4 Ma]) and between 26 and 23.2 Ma, with ice volume during glacial maxima close to 80% of the present-day EAIS. Our calibrated records also show that ice volume rarely decreased below 50% of the present-day EAIS during Oligocene glacial minima. Ice volume during most of the early Miocene (23-16 Ma) was comparable to that of the Oligocene, ranging from 50 to 130% of the present-day EAIS (Pekar and DeConto, 2006).

Evidence from Antarctica

Stratigraphic evidence from boreholes and marine seismic reflection data indicate that the EAIS extended across the shelf at glacial maxima since the earliest Oligocene. Seismic data indicate ice grounding on the shelf, in some cases approaching the shelf edge, as early as the early Oligocene near Prydz Bay (Cooper et al., 1991; Hambrey et al., 1991), and no later than the late Oligocene in the western and eastern parts of the Ross Sea (Bartek et al., 1997; Sorlien et al., in press; Fig. 1). Hiatuses recognized at ~34 Ma, ~29-25 Ma, and ~23 Ma in the Cape Roberts boreholes coincide with times of maximum ice volume based on calibrated isotopic records (Fig. 1).

Palynological and leaf data from boreholes located in the western Ross Sea indicate a gradual cooling during the Oligocene, ranging from cool temperate during the latest Eocene to cold temperate during the early Oligocene to near-tundra-like conditions associated with glacial minima in the late Oligocene (e.g., Raine and Askin, 2001). Near-tundra-like conditions continued into the early Miocene. These records are thought to be from sediments preferentially representing interglacial intervals. The match between the timing of hiatuses in Antarctic cores and times of maximum ice volume suggests that during glacial times, these locations would have been either subaerially exposed or covered by ice.

Resolving the apparent decoupling of isotopic records with other climate records and $p\mathrm{CO}_2$ estimates

A comparison of these records to atmospheric $p\mathrm{CO}_2$ estimates (Pagani et al., 2005) suggests a strong if nonlinear link between climate and $p\mathrm{CO}_2$ levels during the Oligocene and early Miocene. A sharp increase in ice volume at 33.5 Ma (early Oligocene) was followed by a decrease to about 80% of the present-day EAIS at glacial maxima. Ice volume at glacial maxima then gradually increased to between 100 and 130% of present-day levels between “mid” Oligocene and early Miocene (28 and 17 Ma), with volumes generally not decreasing below 50% of modern levels at glacial minima. During this same interval, $p\mathrm{CO}_2$ generally decreased, reaching near-modern levels by the late Oligocene, and then continued at these levels throughout the early Miocene (Pagani et al., 2005).

Calibration of deep-sea $\delta^{18}O$ records against independently measured apparent sea-level changes resolves the hypothesized conflict between oceanographic and Antarctic climate records and evidence for a decrease in $p\mathrm{CO}_2$ during late Oligocene to early Miocene time (see Zachos et al., 2001; Pagani et al., 2005). The apparently abrupt decrease in $\delta^{18}O$ values in the late Oligocene is an artifact of the way in which the record was spliced together at ~25 Ma, with $\delta^{18}O$ records from mainly southern sites below and Atlantic sites above (Fig. 1) and interpreted at face value (Pekar et al., 2002; Pekar et al., 2006). Our results indicate that there was no abrupt warming, nor any significant deglaciation in Antarctica. Therefore, the paleoclimate record is not decoupled from $p\mathrm{CO}_2$ estimates.

An explanation for the apparent decoupling between non-calibrated isotopic composite records and other climate proxies, as well as with $p\mathrm{CO}_2$ estimates, is that a warmer (presumably more saline) bottom water mass increased spatially in the deep sea in a number of ocean basins during the late Oligocene and early Miocene (Pekar et al., 2006; Pekar and DeConto, 2006). This is supported by high $\delta^{18}O$ values from Weddell Sea ODP Sites 689 and 690 between the “mid” Oligocene and the top of the available record at 24.5 Ma compared with coeval lower latitude isotopic records from the Atlantic and Indian Ocean basins.

Summary

The apparent decoupling between deep-sea $\delta^{18}O$ records and $p\mathrm{CO}_2$ estimates and stratigraphic and vegetation data from Antarctica during the late Oligocene and early Miocene is resolved by calibrating the isotopic records, resulting in a consistent view of cryospheric and climate change in Antarctica between 34 and 16 Ma. It is not necessary to infer that any decoupling between climate change and CO_2 levels occurred, either in the late Oligocene or early Miocene.

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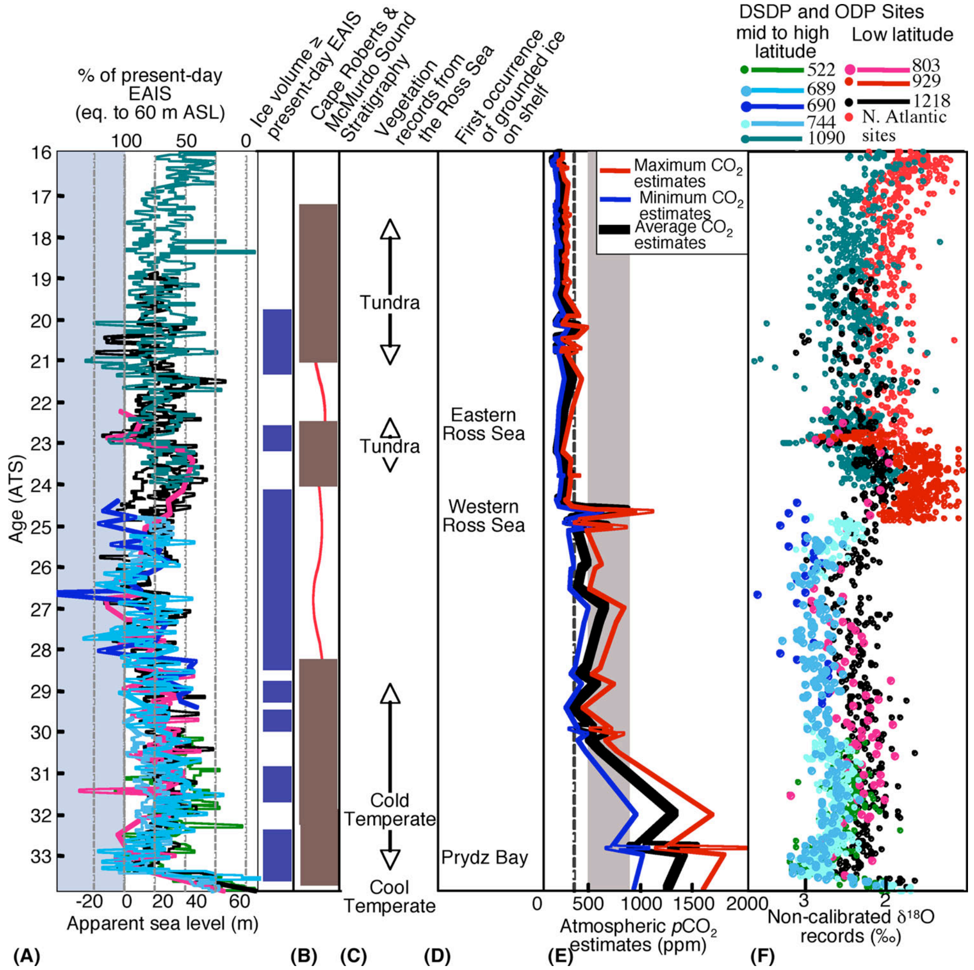

Figure 1. Modified from Pekar and Christie-Blick, 2007. (A) Apparent sea-level (ASL) estimates are derived by applying δ^{18}O to ASL calibrations to δ^{18}O records (Pekar et al., 2002; Pekar et al., 2006). The upper x-axis is the percent of the present-day EAIS (equivalent to ~60 m ASL). The lower x-axis is ASL change, with zero representing present-day sea level. Good agreement exists between ice-volume estimates from each of the calibrated records, in spite of different calibrations being used for each record. Blue bars represent times when ice volume was ≥ than present-day EAIS based on calibrated isotopic records. (B) Brown bars represent preserved sediment and red wavy lines, hiatuses identified in cores from the Cape Roberts Project (based on Florindo et al., 2005). Note the excellent agreement between ice volume ≥ present-day EAIS and the timings of the hiatuses. (C) Biological data (Askin, 2001) from Cape Roberts Project that show evidence for long-term climate cooling and full glacial conditions in Antarctica. (D) First occurrence of grounded ice based on core and seismic data around Antarctica (Cooper et al., 1991; Hambrey et al., 1991; Bartek et al., 1997; Sorlien et al., 2007). (E) pCO$_2$ estimates from Pagani et al. (2005) show decreasing values during the Oligocene, reaching pre-industrial levels by the latest Oligocene and continuing into the early Miocene. The range shown is due to the uncertainty involved in using carbon isotopic composition of sedimentary alkenones. The dashed line represents pre-industrial values (280 ppm), while the shaded box represent values that are predicted for this century (Watson et al., 2001). (F) Deep-sea δ^{18}O composite modified from Zachos et al. (2001), and including Sites 803 (Barrera et al., 1993), 1090 (Billups et al., 2002), and 1218 (Lear et al., 2004). The abrupt δ^{18}O decrease at circa 24.5 Ma is due to a change in the source of data from high latitude to low latitude sites, with Southern Ocean sites below and mainly western equatorial Atlantic Site 929 above (Pekar et al. 2002; Pekar et al., 2006).

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