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ScienceDirect
Palaeogeography, Palaeoclimatology, Palaeoecology 260 (2008) 41–49
PALAEO
www.elsevier.com/locate/palaeo

Resolving apparent conflicts between oceanographic and Antarctic climate records and evidence for a decrease in pCO_2 during the Oligocene through early Miocene (34–16 Ma)

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Received 22 March 2007; accepted 22 August 2007

Abstract

An apparent mismatch between published oxygen isotopic data and other paleoclimate proxies for the span from 26–16 Ma is resolved by calibration against global sea-level estimates obtained from backstripping 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 pCO_2 throughout the Oligocene to early Miocene (34–16 Ma). Isotopic evidence for an East Antarctic Ice Sheet (EAIS) as much as 30% larger than its present-day volume at glacial maxima during that span is consistent with seismic reflection and stratigraphic evidence for an ice sheet covering much of the Antarctic continental shelf at the same glacial maxima. Palynological data suggest long-term cooling during the Oligocene, with cold near-tundra environments developing along the coast at glacial minima no later than the late Oligocene. A possible mechanism for this long-term cooling is a decrease in atmospheric pCO_2 from the middle Eocene to Oligocene, reaching near pre-industrial levels by the latest Oligocene, and remaining at those depressed levels throughout the Miocene.
Published by Elsevier B.V.

Keywords: Oligocene; Miocene; Ice volume; Sea level; Antarctica; Oxygen isotopes

1. 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. Distal proxies for Antarctic climate and ice volume, which include deep-sea oxygen isotopic data (Miller et al., 1987; Miller et al., 1991; Zachos et al., 2001) and stratigraphic records of sea-level change at mid- to low-latitude continental margins (Haq et al., 1987; Miller et al., 1998; Kominz and Pekar, 2001; Miller et al., 2005), are relatively complete, but they include signals not directly related to changes in the ice sheet. These records provide estimates for the size of the early Oligocene ice sheet that vary greatly, from as small as ~50% of the

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0031-0182/$ - see front matter. Published by Elsevier B.V.
doi:10.1016/j.palaeo.2007.08.019

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). Estimates of ice-volume increases associated with individual large $\delta^{18}O$ increases (i.e., Oi-events of Miller et al., 1991; Pekar and Miller, 1996) similarly range from as high as twice the size of the present-day ice sheet (Haq et al., 1987), an implausibly large figure, to the claim that "changes in ice volume were of minor importance" for many of the Oi-events (Pfuhl et al., 2004). Recent studies using 2-D flexural back-stripped stratigraphic data (Kominz and Pekar, 2001; Pekar et al., 2002), paired isotopic and Mg/Ca ratio records (Lear et al., 2000, 2004), and calibration of $\delta^{18}O$ records using eustatic estimates from backstripped stratigraphic data (Pekar and DeConto, 2006; Pekar et al., 2006) have attempted to isolate the ice-volume signal. They suggest that during the Oligocene and early Miocene, the EAIS grew to slightly larger than it is today. Stratigraphic and palynological data acquired close to Antarctica (e.g., Barrett, 1986, 1989; Cooper et al., 1991; Naish et al., 2001; Raine and Askin, 2001; Thorn, 2001; Roberts et al., 2003; Ivany et al., 2006; Prebble et al., 2006) provide the most direct if inherently fragmentary and qualitative constraints on polar climate and ice-sheet dimensions. These data 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 oxygen isotopic 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. This apparent decoupling of $\delta^{18}O$ records (and implied climate change) and pCO_2 records is relevant in understanding the processes that control future as well as past climate changes because pCO_2 estimates for the Oligocene (Pagani et al., 2005) are similar to the pCO_2 levels predicted for the coming century (Watson et al., 2001). In this paper, we extend the analysis of Pekar et al. (2006) for the late Oligocene and of Pekar and DeConto (2006) for the early Miocene, to show that calibration of isotopic data against stratigraphically constrained sea-level changes allows apparent conflicts between proxies to be resolved for the entire interval between 34 and 16 Ma. Additionally, all proxies are brought into alignment with independent alkenone $\delta^{13}C$ evidence for a secular decrease in atmospheric pCO_2 during Eocene to Miocene time (Pagani et al., 2005). It is not necessary to infer, as these authors do, any decoupling between climate change and CO_2 levels, either in the late Oligocene–early Miocene or today.

2. Calibration of isotopic records to glacioeustasy

Ice-volume changes and their associated changes in sea level were determined by calibrating detrended amplitudes of apparent sea level (ASL, defined as eustasy plus water loading effects) to $\delta^{18}O$ amplitudes for Oi-events identified by Miller et al. (1991) and Pekar and Miller (1996) in deep-sea records (Pekar et al., 2002, 2006; Pekar and DeConto, 2006). ASL estimates are based on 2-D flexural backstripping of stratigraphy in boreholes drilled primarily under the auspices of the New Jersey Coastal Plain Drilling Program (Miller et al., 1996; Pekar et al., 1997; Miller et al., 1998; Kominz and Pekar, 2001; Pekar and Kominz, 2001). Oi-events are inferred to represent ice growth, and are defined by global increases in benthic $\delta^{18}O$ values >0.5‰ and coeval shifts in western equatorial planktonic $\delta^{18}O$ records (Miller et al., 1991). Each calibration in this study is based on linear regression of records from individual sites (Pekar et al., 2002, 2006). They range from 0.12–13‰/10 m ASL for Weddell Sea ODP Sites 689 and 690 (Fig. 1) to 0.20‰/10 m for southern Atlantic Ocean Site 522, 0.23‰/10 m for equatorial Pacific Ocean Site 1218, 0.32‰/10 m for southern Atlantic Ocean Site 1090, and 0.35‰/10 m for Equatorial Atlantic Ocean Site 929. 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. Correlation between deep-sea $\delta^{18}O$ and ASL amplitudes is good to excellent for each site, with a correlation coefficient (r^2) for regressions ranging from 0.73 to 0.99 (Pekar et al., 2002, 2006). This suggests that although deep-sea $\delta^{18}O$ values are assumed to contain a significant bottom-water temperature signal, any temperature lowering scales more or less linearly with respect to increased ice volume (Pekar et al., 2002). The calibrations for Sites 929 and 1090 use a single $\delta^{18}O$ event (Mi1, 23.0 Ma, 56±25 m ASL), which results in an isotopic range of ~0.2 to 0.5‰ (0.35±0.15‰ mean value) and 0.18 to 0.46‰ (0.32± 0.14‰ mean value) per 10 m ASL, respectively. 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 ≤2.0 °C. This is based on the average modern *Cibicidoides* spp. value of 2.7‰

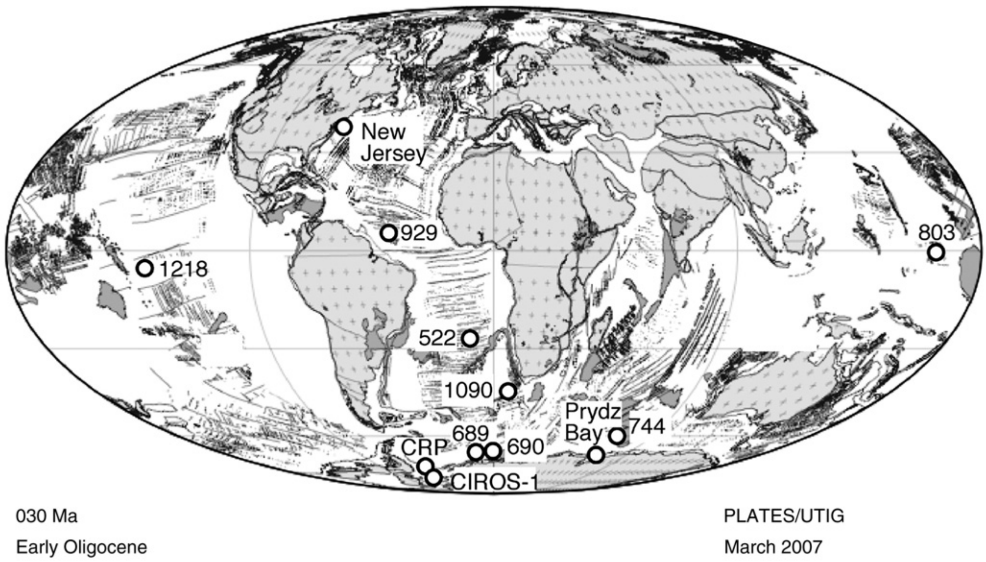

Fig. 1. Map showing plate tectonic reconstructions at ~30 Ma (Lawver et al., 2007), with the paleo-locations of DSDP and ODP Sites 522, 689, 690, 744, 803, 929, 1090, and 1218; Antarctic sites (CRP = Cape Roberts project, CIROS-1, and Prydz Bay), as well as the New Jersey borehole site used in this study.

in ~2.0 °C waters (Shackleton and Kennett, 1975) or 3.34‰ adjusted for equilibrium with calcite. The Greenland Ice Sheet probably was not present during the Oligocene, based upon vegetation evidence for insufficiently cold conditions in the northern hemisphere (e.g., Wolfe, 1978), and this would have reduced the average deep-sea $\delta^{18}O$ value by 0.07‰. While the existence in the Oligocene of a substantial West Antarctic Ice Sheet is still controversial (Ivany et al., 2006; Rocchi et al., 2006; Sorlien et al., 2007) the average deep-sea $\delta^{18}O$ value would be approximately the same in either case (3.02‰ with an ice sheet, and 2.96‰ without; Pekar et al., 2006). Ice in a polythermal EAIS during the Oligocene most likely had significantly higher $\delta^{18}O$ values (e.g., ~−35‰) than is the case today (i.e., −45‰ to −55‰; DeConto and Pollard, 2003). The existence of higher values is supported by floral evidence for appreciably warmer conditions in the Ross Sea region during the Oligocene than is the case today (>9 °C warmer; Prebble et al., 2006). This would have reduced the mean isotopic value of the oceans by an additional 0.25‰. Taken together, these considerations suggest that an isotopic value of ~3‰ in calcite is consistent with a fully glaciated East Antarctic continent during the Oligocene. Uncertainties in estimating ice volume from calibrated isotopic records relate to temperature variability that exceeds the calibration for a given site based on long-term changes in deep-sea circulation patterns as well as salinity variations among the sites. During the late Oligocene, for example, a warmer deep-sea water mass is thought to have expanded and replaced a colder water mass at a number of sites in both the Atlantic and Pacific basins (Pekar et al., 2006). While the potential exists for salinity to affect ice-volume estimates from calibrated records, the range in salinity between water masses in the deep sea today (e.g., North Atlantic Deep Water [34.95‰] and Antarctic Bottom Water, AABW [34.65‰]) is about 0.3‰, resulting in an isotopic uncertainty of only ± 0.1‰. The lower $\delta^{18}O$ value associated with lower salinity cold deep water such as proto-AABW is equivalent to an underestimate of ice volume. In our analysis, offsets between calibrations among the different sites are ascribed to temperature variability between ocean basins. For example, $\delta^{18}O$ values for Mi1 that are ~0.4‰ lighter at Sites 929 and 1218 than at Site 1090 are attributed to colder bottom water at the latter, and are adjusted accordingly. Calibrated isotopic records provide a new means for estimating Paleogene ice volume, with a high degree of confidence based on the good to excellent correlation in calibrations. This approach circumvents a shortcoming of alternative methods, such as the use of covariance between $\delta^{18}O$ records from tropical planktonic and deep-sea benthic foraminifers assuming little to no temperature signal in planktonic $\delta^{18}O$ values. Indeed, Pleistocene data for tropical surface-dwelling planktonic foraminifers indicate substantial temperature changes (2 °C), equivalent to ~50 m ASL change between glacial and interglacial periods (Guilderson et al., 1994). Therefore, ice-volume estimates using this approach can only provide a maximum value.

3. Synthesis of Antarctic cryospheric history between 34 and 16 Ma

A growing body of evidence from a diverse array of records from various regions around the world (Figs. 1 and 2), including the Antarctic itself, indicates that an ice sheet larger than the present-day EAIS existed during parts of the Oligocene and early Miocene. The integrated record is consistent with a general decrease in pCO_2 levels through the same interval.

3.1. 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. 2). Oligocene ice volume was greatest during glacial maxima between ~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, except between 32.3 and 30.1 Ma and between 24.0 and 23.2 Ma, with ice volume as low as 30–40% of the modern EAIS. 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), with the possibility of brief episodes (<100 ky duration) of lower ice volume. These estimates, which are consistent with paired Mg/Ca ratio and isotopic evidence for ice volumes 30 to 50% larger than the present-day EAIS (equivalent to 70–90 m of ASL change; Lear et al., 2000, 2004), suggest that at glacial maxima the ice sheet would have extended seaward of the present-day coastline and across at least part of the continental shelf. At glacial minima, the ice sheet would have retreated as much as several hundred kilometers inland of the modern coastline.

3.2. Stratigraphic and seismic evidence

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 part of the Ross Sea (Bartek et al., 1997) and late Oligocene to possibly early Miocene in the eastern part of the Ross Sea (Sorlien et al., 2007; Fig. 2). At Prdyz Bay, core data from ODP Leg 117 corroborate early Oligocene grounding at the shelf break about 550 km beyond the present grounding line. This implies that for the ice sheet to have maintained a steady-state profile during the Oligocene, it would have been substantially thicker than the present-day ice sheet (Hambrey et al., 1991). 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. Lithofacies, microstructures identified on sedimentary grains, and clay analysis from the Cape Roberts and CIROS-1 cores also indicate gradual cooling and an increasing glacial influence during the Oligocene (Fig. 2; Ehrmann, 2000; van der Meer, 2000; Fielding et al., 2001; Powell et al., 2001).

3.3. Palynological evidence

Palynological and leaf data from boreholes located in the western Ross Sea indicate 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; Thorn, 2001; Roberts et al., 2003; Prebble et al., 2006). 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.

3.4. Ice-rafted debris

Ice-rafted debris (IRD) and glaciomarine sediments recovered in cores from the Ross Sea (Hayes et al., 1975; Barrett, 1986, 1989; Harwood et al., 1989), Weddell Sea (Barker et al., 1988), Prydz Bay (Barron et al., 1991) and Kerguelen Plateau (Breza and Wise, 1992; Wise et al., 1992) indicate that ice sheets reached the Antarctic coastline at least intermittently through the Oligocene and early Miocene (Fig. 2). A more quantitative reading of the record is not possible because the distribution of IRD is influenced not only by the size of the ice sheet, but by its thermal regime, the erodability of the substrate, ice flux to the grounding line, ocean

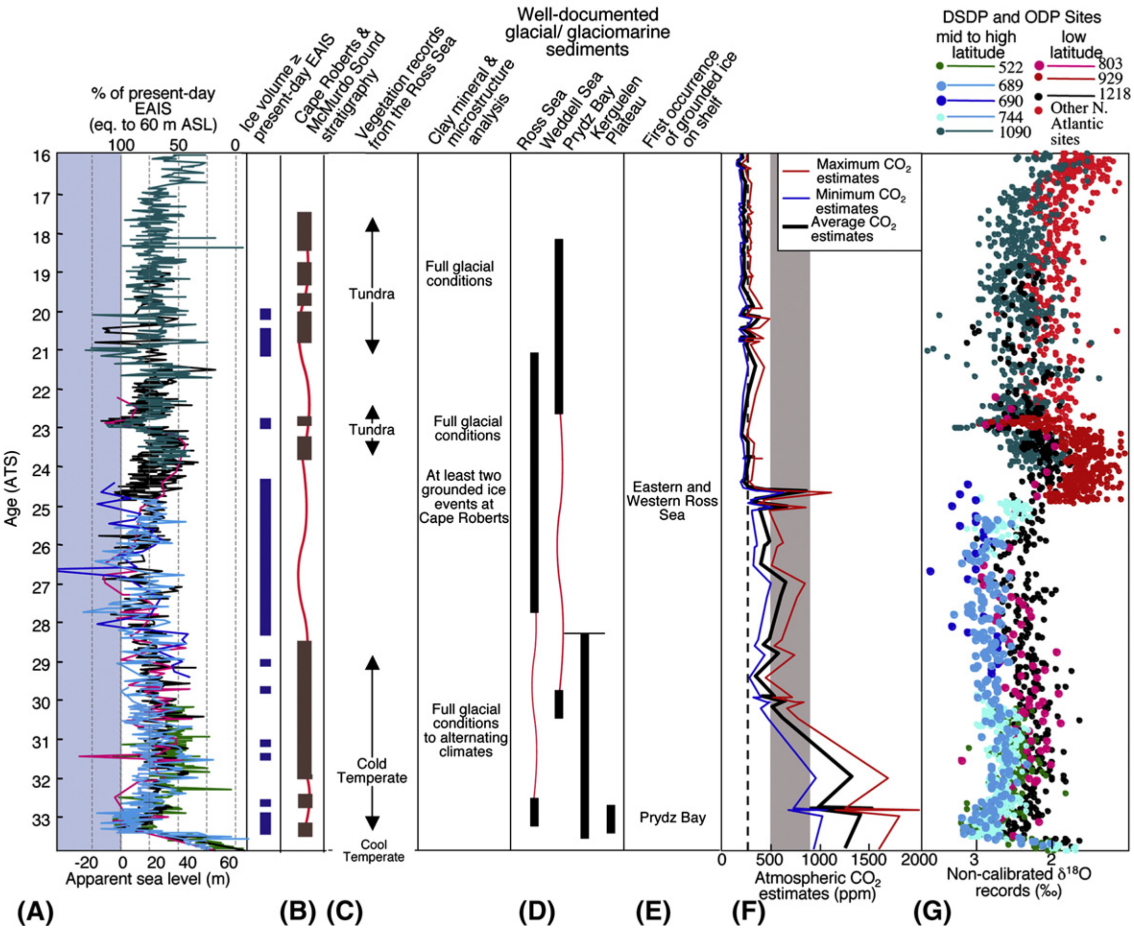

Fig. 2. (A) Apparent sea-level (ASL) estimates are derived by applying $\delta^{18}O$ to ASL calibrations to $\delta^{18}O$ records (Pekar et al., 2002, 2006) from Sites 522, 689, 690, 744, 803, 929, 1090, and 1218. The upper x-axis is the percent of the present-day EAIS (equivalent to ~60 m ASL). The lower x-axis is ASL change, with zero representing sea level resulting from ice volume equivalent to the present-day EAIS, and with increasing values representing sea-level rise and negative numbers representing ice volume greater than the present-day EAIS volume. Good agreement exists between the ice-volume estimates from each of the calibrated records, in spite of different calibrations being used for each record. Thick blue lines represent times when ice volume was ≥ than present-day EAIS based on calibrated isotopic records. (B) Thick brown lines represent times for which sediment was preserved and the red wavy lines represent times for which hiatuses have been identified in cores from the Cape Roberts Project (based on Florindo et al., 2005). Note the excellent agreement between ice volume ≥ than present-day EAIS and the timings of the hiatuses. (C) Biological (Askin, 2001) and sedimentological (Ehrmann, 2000; van der Meer, 2000) data from Cape Roberts Project that show evidence for long-term climate cooling and full glacial conditions in Antarctica. (D) Well-documented glacial/glaciomarine sediments shown in brown lines, with red wavy lines indicating hiatuses and horizontal line indicating top of recovered sediments. (E) 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; Chow and Bart, 2003; Sorlien et al., 2007). Note that evidence for grounded ice 550 km beyond the present-day location in Prydz Bay during the Oligocene suggests a much larger ice sheet existed than is present today (Hambrey et al., 1991). (F) 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 in pCO_2 is due to the uncertainty involved in using carbon isotopic composition of sedimentary alkenones ($\delta^{13}C$ 37:2). The dashed line represents pre-industrial values (280 ppm), while the shaded box represent values that are predicted for the present century (Watson et al., 2001). (G) Deep-sea $\delta^{18}O$ 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 $\delta^{18}O$ 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, 2006). Recently published isotopic records from Sites 1090 and 1218 (dark blue and black circles, respectively) are characterized by generally heavier values than those used in the 2001 composite for the latest Oligocene and early Miocene, consistent with our interpretation of a more heavily glaciated Antarctic continent.

circulation and surface water temperatures (Ehrmann and Mackensen, 1992).

3.5. Reconciling larger ice volume during the Oligocene and Miocene

The development of an ice sheet appreciably larger than the present-day EAIS would have been possible under conditions of lowered sea level via a positive feedback to ice-sheet growth. Ice volume at the last glacial maximum, for example, was 20–25% larger than it is now, mainly as a result of lower sea level (Denton and Hughes, 2002; Huybrechts, 2002), and in spite of considerable over-deepening of the Antarctic shelf. Over-deepening limits the ability of the ice sheet to encroach on the shelf through a combination of ice-sheet loading, tectonically driven subsidence outpacing sediment accumulation, and the effects of glacial erosion (Cooper et al., 1991). In order to evaluate how large the ice sheet might have been at any time, it is useful to consider the relative roles of these processes as a function of time. Glacial erosion became a factor only after the ice sheet grew to continental scale during the Oligocene, and perhaps as late as the Miocene. Seismic and stratigraphic data from the Ross Sea (Bartek et al., 1997; Rocchi et al., 2006) and Prdryz Bay (Cooper et al., 1991; Hambrey et al., 1991) suggest the removal of hundreds of meters of sediment from the shelf during the Oligocene and early Miocene. Sedimentation rates were high during much of the Oligocene and early Miocene, but decreased markedly during the Miocene, most likely to levels less than the rate of tectonically driven subsidence (Powell, 2005). This would have contributed to Miocene and later over-deepening of the shelf, but only modestly. Modeling of shelf bathymetry suggests that although ice loading is an important phenomenon, only a fraction of the inward slope of the modern shelf is attributable to a delayed isostatic response of the ice-sheet load (Ten Brink and Cooper, 1992). We suspect, therefore, that the Antarctic shelf became progressively over-deepened since the Oligocene, primarily by erosion beneath grounded ice, and that it was markedly less over-deepened during the Oligocene and early Miocene than it is today. This would have permitted the ice sheet to advance more readily across the shelf.

3.6. Relation between climate and pCO_2 during the Oligocene and early Miocene

A comparison of these records to atmospheric pCO_2 estimates (Pagani et al., 2005) suggests a strong if nonlinear link between climate and pCO_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 the “mid”-Oligocene and early Miocene (28 to 17 Ma), with volumes generally not decreasing below 50% of modern levels at glacial minima. During this same interval, pCO_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). In spite of the overall fit of long-term records, several higher frequency mismatches stand out. First, an abrupt increase in ice volume is inferred across the Eocene/Oligocene boundary during an interval in which pCO_2 decreases more smoothly. Numerical modeling by DeConto and Pollard (2003) showed that rapid expansion of the ice sheet may reflect a combination of gradual pCO_2 lowering coupled with ice-climate feedbacks and orbital forcing. A second mismatch relates to two anomalously high pCO_2 estimates in the lower Oligocene above the level of the inferred abrupt increase in ice volume. These data are from DSDP Sites 511 and 513, located in the South Atlantic Ocean (Pagani et al., 2005). Today these sites are near surface waters that have mixed with deeper waters. If similar conditions occurred during the Oligocene, the surface waters would contain a higher CO_2 content and therefore result in an overestimation of atmospheric pCO_2.

3.7. Resolving the apparent decoupling of isotopic records with other climate records and pCO_2 estimates

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 pCO_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 $\sim$25 Ma, with $\delta^{18}O$ records from mainly southern sites below and Atlantic sites above (Fig. 2), and interpreted at face value (Pekar et al., 2002, 2006). Our results indicate that there was no abrupt warming, nor any significant deglaciation in Antarctica. Therefore, the paleoclimate record is not decoupled from pCO_2 estimates. An explanation for the apparent decoupling between non-calibrated isotopic composite records and other climate proxies, as well as with pCO_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 and DeConto, 2006; Pekar et al., 2006). This is supported by high δ^{18}O values from Weddell Sea 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.

4. Conclusions

The apparent decoupling between deep-sea δ^{8}O records and pCO$_2$ 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. Ice volume in Antarctica increased from near zero during the late Eocene to perhaps 30% greater than the present-day EAIS by the mid-Oligocene during glacial maxima, and generally not less than 40% of the EAIS during interglacials for the remainder of the Oligocene and early Miocene. These estimates agree well with paired isotopic and Mg/Ca ratio records, and they are consistent with biological and stratigraphic data from sites proximal to Antarctica that indicate a cooling trend during the Oligocene and a significant ice sheet present at glacial maxima during the Oligocene and early Miocene. The long-term decrease in pCO$_2$ estimates for the Eocene and Oligocene, reaching near present-day levels by the latest Oligocene and into the early Miocene, are consistent with our interpretation of a cold climate in Antarctica during this interval. The strong link shown here between cryospheric changes and pCO$_2$ estimates is relevant to understanding not only past climate change, but also for understanding future climate changes because Oligocene pCO$_2$ levels are comparable to those predicted for the coming century.

Acknowledgments

This research was supported in part by National Science Foundation grant OCE 99-11121 to N. Christie-Blick and S.F. Pekar. We thank C. Sorlein and an anonymous reviewer for helpful comments on the manuscript. The Lamont-Doherty Earth Observatory Contribution Number is 7039.

References

Askin, C.B., 2001. Glacial influence from clast features in Oligocene and Miocene strata cored in CRP-2A and CRP-3, Victoria Land Basin, Antarctica. Terra Antarctica 7, 493–501.

Barker, J., Larsen, B., Baldaug, J.G., 1988. Evidence for late Eocene to early Oligocene Antarctic glaciation and observations on late Neogene glacial history of Antarctica: results from Leg 119 (write out all editors) In: Barron, J., Larsen, Baldauf, J. (Eds.), Proceedings of the Ocean Drilling Program. Scientific Results, vol. 119. Ocean Drilling Program, College Station Texas, pp. 869–891.

Barrera, E., Baldauf, J., Lohmann, K.C., 1993. Strontium isotope and benthic foraminifer stable isotopic results from Oligocene sediments at Site 803. In: Berger, W.H., Kroenke, L.W., Mayer, L.A. (Eds.), Proceedings of the Ocean Drilling Program. Scientific Results, vol. 130. Ocean Drilling Program, College Station, pp. 269–279.

Barrett, P.J. (Ed.), 1986. Antarctic Cenozoic history from the MSSTS-1 Drillhole, McMurdo Sound. Bulletin, vol. 237. Department of Scientific and Industrial Research, Scientific Information Publishing Centre, Wellington, New Zealand, pp. 1–174.

Barrett, P.J. (Ed.), 1989. Antarctic Cenozoic history from CIROS-1 Drillhole, McMurdo Sound. Bulletin, vol. 245. Department of Scientific and Industrial Research, Scientific Information Publishing Centre, Wellington, New Zealand, pp. 1–254.

Barron, J., Larsen, B., Baldauf, J., 1991. Evidence for late Eocene–early Oligocene Antarctic glaciation and observations on late Neogene glacial history of Antarctica, results from Leg 119 (write out all editors) In: Barron, J., Larsen, B., Baldauf, J. (Eds.), Proceeding of the Ocean Drilling Program. Scientific Results, vol. 119. Ocean Drilling Program, College Station, Texas, pp. 869–891.

Bartek, L.R., Andersen, J.L.R., Oneacre, T.A., 1997. Substrate control on distribution of subglacial and glaciomarine seismic facies based on stochastic models of glacial seismic facies deposition on the Ross Sea continental margin, Antarctica. Marine Geology 143, 223–262.

Billups, K., Channell, J.E.T., Zachos, J., 2002. Late Oligocene to early Miocene geochronology and paleoceanography from the subantarctic South Atlantic. Paleoceanography 17. doi:10.1029/2000PA000568.

Breza, J.R., Wise, S.W., 1992. Lower Oligocene ice-rafted debris on the Kerguelen Plateau: evidence for East Antarctic continental glaciation (write out all editors) In: Wise, S.W., Schlich, R., Palmer, A.A. (Eds.), Proceedings of the Ocean Drilling Program. Scientific Results, vol. 120. Ocean Drilling Program, College Station, Texas, pp. 161–178.

Chow, J.M., Bart, P.J., 2003. West Antarctic Ice Sheet grounding events on the Ross sea outer continental shelf during the middle Miocene. Palaeogeography, Palaeoclimatology, Palaeoecology 198, 169–186.

Cooper, A.K., Barrett, P.J., Hinz, K., Traube, V., Leitchenkov, G., Stagg, H.M.J., 1991. Cenozoic prograding sequences of the Antarctic continental margin: a record of glacio-eustatic and tectonic events. Marine Geology 102, 175–213.

Coxall, H.K., Wilson, P.A., Palike, H., Lear, C.H., Backman, J., 2005. Rapid stepwise onset of Antarctic glaciation and deeper calcite compensation in the Pacific Ocean. Nature 433, 53–57.

DeConto, R.M., Pollard, D., 2003. Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO$_2$. Nature 421, 245–249.

Denton, G.H., Hughes, T.J., 2002. Reconstructing the Antarctic ice sheet at the Last Glacial Maximum. Quaternary Science Reviews 21, 193–202.

Ehrmann, W.U., 2000. Smectite content and crystallinity in sediments from CRP-2/2A, Victoria Land Basin. Antarctica 7, 575–580.

Ehrmann, W.U., Mackensen, A., 1992. Sedimentological evidence for the formation of an east Antarctic ice sheet in Eocene/Oligocene time. Palaeogeography, Palaeoclimatology, Palaeoecology 93, 85–112.

Fielding, C.R., Naish, T.R., Woolfe, K.J., 2001. Facies architecture of the CRP-3 drillhole, Victoria Land Basin, Antarctica. Terra Antartica 8, 217–224.

Florindo, F., Wilson, G.S., Roberts, A.P., Sagnotti, L., Verosub, K.L., 2005. Magnetostratigraphic chronology of a late Eocene to early Miocene glacimarine succession from the Victoria basin, Ross Sea, Antarctica. Global and Planetary Change 45, 207–236.

Guilderson, T.P., Fairbanks, R.G., Rubenstone, J.L., 1994. Tropical temperature variations since 20,000 years ago: modulating interhemispheric climate change. Science 263, 663–665.

Hambrey, M.J., Ehrmann, W.U., Larsen, B., 1991. Cenozoic glacial record of the Prydz Bay continental shelf, East Antarctica (write out all editors) In: Barron, J., Baldauf, J. (Eds.), Proceedings of the Ocean Drilling Program. Scientific Results, vol. 119. Ocean Drilling Program, College Station, Texas, pp. 77–132.

Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. Science 235, 1156–1167.

Harwood, D.M., Barrett, P.J., Edwards, A.R., Rieck, J.J., Webb, P.-N., 1989. Biostratigraphy and chronology. In: Barrett, P.J. (Ed.), Antarctic Cenozoic History from CIROS-1 Drill Hole, McMurdo Sound. Bulletin, vol. 245. Department of Scientific Industrial Research, Wellington, New Zealand, pp. 231–239.

Hayes, D.E., Frakes, L.A., 1975. (write out all co-authors) Initial Reports Deep Sea Drilling Program 28. (US Government Printing Office), Washington, pp. 1–1017.

Huybrechts, P., 2002. Sea-level changes at the LGM from ice-dynamic reconstructions of the Greenland and Antarctic ice sheets during the glacial cycles. Quaternary Science Reviews 21, 203–231.

Ivany, L.C., Van Simaeys, S., Domack, E.W., Samson, S.D., 2006. Evidence for an earliest Oligocene ice sheet on the Antarctic Peninsula. Geology 34, 377–380.

Kominz, M.A., Pekar, S.F., 2001. Oligocene eustasy from two-dimensional sequence stratigraphic backstripping. Geological Society of America Bulletin 113, 291–304.

Lawver, L.A., Dalziel, I.W.D., Gahagan, L.M., 2007. The plates 2006 atlas of plate reconstructions (750 Ma to present day). Plates Progress Report No. 305-0307, University of Texas Technical Report No. 193. 153 pp.

Lear, C.H., Elderfield, H., Wilson, P.A., 2000. Cenozoic deep-sea temperature and global ice volumes from Mg/Ca in benthic foraminiferal calcite. Science 287, 269–272.

Lear, C.H., Rosenthal, Y., Coxall, H.K., Wilson, P.A., 2004. Late Eocene to early Miocene ice sheet dynamics and the global carbon cycle. Paleoceanography 19, PA4015. doi:10.1029/2004PA001039.

Miller, K.G., Fairbanks, R.G., Mountain, G.S., 1987. Tertiary oxygen isotope synthesis, sea-level history, and continental margin erosion. Paleoceanography 2, 1–19.

Miller, K.G., Wright, J.D., Fairbanks, R.G., 1991. Unlocking the ice house: Oligocene–Miocene oxygen isotopes, eustasy, and margin erosion. Journal of Geophysical Research 96, 6829–6848.

Miller, K.G., Mountain, G.S., Blum, P., Gartner, S., Alm, P.G., Aubry, M.P., Burckle, L.H., Guerin, G., Katz, M.E., Christensen, B.A., Compton, J., Damuth, J.E., Deconinck, J.F., de Verteuil, L., Fulthorpe, C.S., Hesselbo, S.P., Hoppie, B.W., Kotake, N., Lorenzo, J.M., McCracken, S., McHugh, C.M., Quayle, W.C., Saito, Yoshiki, S., S.W., ten Kate, W.G., Urbat, M., Van Fossen, M.C., Vecsei, A., Sugarman, P.J., Mullikin, L., Pekar, S., Browning, J.V., Liu, C., Feigenson, M.D., Goss, M., Gwynn, D., Queen, D.G., Powars, D.S., Heibel, T.D., Bukry, D., 1996. Drilling and dating New Jersey Oligocene–Miocene sequences; ice volume, global sea level, and Exxon records. Science 271, 1092–1095.

Miller, K.G., Mountain, G.S., Browning, J.V., Kominz, M., Sugarman, P.J., Christie-Blick, N., Katz, M.E., Wright, J.D., 1998. Cenozoic global sea level, sequences, and the New Jersey Transect: results from coastal plains and continental slope drilling. Reviews of Geophysics 36, 569–601.

Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., Pekar, S.F., 2005. The Phanerozoic record of global sea-level change. Science 312, 1293–1297.

Naish, T.R., Woolfe, K.J., Barrett, P.J., Wilson, G.S., Cliff, A., Bohaty, S.M., Bucker, C.J., Claps, M., Davey, F.J., Dunbar, G.B., Dunn, A.G., Fielding, C.R., Florindo, F., Hannah, M.J., Harwood, D.M., Henrys, S.A., Krissek, L.A., Lavelle, M., van der Meer, J.J.M., McIntosh, W.C., Niessen, F., Passchier, S., Powell, R.D., Roberts, A.P., Sagnotti, L., Scherer, R.P., Strong, P.C., Talarico, F., Verosub, K.L., Villa, G., Watkins, D.K., Webb, P.-N., Wonik, T., 2001. Orbitally induced oscillations in the East Antarctic ice sheet at the Oligocene/Miocene boundary. Nature 413, 719–723.

Pagani, M., Zachos, J.C., Freeman, K.H., Tipple, B., Bohaty, S., 2005. Marked decline in atmospheric carbon dioxide concentrations during the Paleogene. Science 309, 600–603.

Pekar, S., Miller, K.G., 1996. New Jersey Oligocene “Icehouse” sequences (ODP Leg 150X) correlated with global δ^{18}O and Exxon eustatic records. Geology 24, 567–570.

Pekar, S.F., Kominz, M.A., 2001. Two-dimensional paleoslope modeling: a new method for estimating water depths for benthic foraminiferal biofacies and paleo shelf margins. Journal of Sedimentary Research 71, 608–620.

Pekar, S.F., DeConto, R.M., 2006. High-resolution ice-volume estimates for the early Miocene: evidence for a dynamic ice sheet in Antarctica. Palaeogeography, Palaeoclimatology, Palaeoecology 231, 101–109.

Pekar, S.F., Miller, K.G., Browning, J.V., 1997. New Jersey Coastal Plain Oligocene Sequences. In: Miller, K.G., Snyder, S.W. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, 150X. (Ocean Drilling Program), College, Texas, pp. 187–206.

Pekar, S.F., Christie-Blick, N., Kominz, M.A., Miller, K.G., 2002. Calibrating eustasy to oxygen isotopes for the early icehouse world of the Oligocene. Geology 30, 903–906.

Pekar, S.F., DeConto, R.M., Harwood, D.M., 2006. Resolving a late Oligocene conundrum: deep-sea warming versus Antarctic glaciation. Palaeogeography, Palaeoclimatology, Palaeoecology 231, 29–40.

Pfuhl, H.A., McCave, N.I., Schellenberg, S.A., Ferretti, P., 2004. Changes in South Ocean circulation in late Oligocene to early Miocene time. In: Exon, N.F., Kennet, J.P., Malone, M.J. (Eds.), The Cenozoic Southern Ocean: Tectonics, sedimentation, and climate change between Australia and Antarctica. Geophysical Monograph Series, vol. 151. American Geophysical Union, Washington D.C., pp. 173–190.

Powell, R.D., 2005. Sediment yields of Quaternary advancing and retreating temperate tidewater glaciers with an example of how these may constrain continental landscape evolution. Fall Meeting Supplement, Abstract H53I–03. EOS Transaction American Geophysists Union, vol. 86(52).

Powell, R.D., Laird, M.G., Naish, T.R., Fielding, C.R., Krisseck, L.A., van der Meer, J.J.M., 2001. Depositional environments for strata cored in CRP-3 (Cape Roberts Project), Victoria Land Basin, Antarctica: paleoglaciological and paleoclimatological inferences. Terra Antartica 8, 207–216.

Prebble, J.G., Raine, J.I., Barrett, P.J., Hannah, M.J., 2006. Vegetation and climate from two Oligocene glacioeustatic sedimentary cycles (31 and 24 Ma) cored by the Cape Roberts project, Victoria Land Basin, Antarctica. Palaeogeography, Palaeoclimatology, Palaeoecology 231, 41–57.

Raine, J.I., Askin, R.A., 2001. Oligocene and Early Miocene terrestrial palynology of the Cape Roberts drillhole CRP-2/2A, Victoria Land Basin, Antarctica. Terra Antartica 7, 389–400.

Roberts, A.P., Wilson, G.S., Harwood, D.M., Verosub, K.L., 2003. Glaciation across the Oligocene–Miocene boundary in Southern McMurdo Sound, Antarctica: new chronology from the CIROS-1 drill hole. Palaeogeography, Paleoclimatology, Palaeoecology 198, 113–130.

Rocchi, S., LeMasurier, W.E., Di Vincenzo, G., 2006. Oligocene to Holocene erosion and glacial history in Marie Byrd Land, West Antarctic, inferred from exhumation of the Dorrel Rock intrusive complex and from volcano morphologies. Geological Society of America Bulletin, 118, 991–1005.

Shackleton, N.J., Kennett, J.P., 1975. Late Cenozoic oxygen and carbon isotopic changes at DSDP Site 284: implications for glacial history of the Northern Hemisphere and Antarctic (write out all editors) In: Kennett, J.P., Houtz, R.E. (Eds.), Initial Reports of the Deep Sea Drilling Project 29, Washington (US Government Printing Office), pp. 801–808.

Sorlien, C.C., Luyendyk, B.P., Wilson, D., Decesari, R., Bartek, L., Diebold, J., 2007. Oligocene developments of the West Antarctic Ice Sheet recorded in eastern Ross sea strata. Geology 35, 467–470.

Ten Brink, U.S., Cooper, A.K., 1992. Modeling the bathymetry of the Antarctic continental shelf. In: Yoshida, Y., Kaminuma, K., Sharaishi, K. (Eds.), Recent Progress in Antarctic Earth Sciences. TERRAPUB, Tokyo, pp. 763–771.

Thorn, V.C., 2001. Oligocene and Early Miocene phytoliths from CRP-2/2A and CRP-3, Victoria Land Basin, Antarctica. Terra Antartica 8, 407–422.

van der Meer, J.J.M., 2000. Microscopic observations on the upper 300 metres of CRP-2/2A, Victoria Land Basin, Antarctica. Terra Antartica 7, 339–348.

Watson, R.T., Albritton, D.L., Barker, T., Bashmakov, I.A., Canziani, O., Christ, R., Cubasch, U., Davidson, O., Gitay, H., Griggs, D., Halsnaes, K., Houghton, J., House, J., Kundzewicz, Z., Lal, M., Leary, N., Magadza, C., McCarthy, J.J., Mitchell, J.F.B., Moreira, J.R., Munasinghe, M., Noble, I., Pachauri, R., Pittock, B., Prather, M., Richels, R.G., Robinson, J.B., sathaye, J., Schneider, S., Scholes, R., stocker, T., Sundararaman, N., Swart, R., Taniguchi, T., Zhou, D., 2001. Climate change 2001: synthesis report, 2001. Intergovernmental Panel on Climate Change, Geneva, Switzerland. 184 pp.

Wise, S.W., Breza, J.R., Harwood, D.M., Wei, W., Zachos, J.C., 1992. Paleogene glacial history of Antarctica in light of Leg 120 drilling results (write out all editors) In: Wise Jr., S.W., Schlish, R., Palmer, A.A. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results. Ocean Drilling Program, vol. 120. College Station, Texas, pp. 1001–1030.

Wolfe, J.A., 1978. A paleobotanical interpretation of Tertiary climates in the Northern Hemisphere. American Scientist 66, 694–704.

Zachos, J.C., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms and aberrations in global climate 65 Ma to present. Science 292, 686–693.