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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 δ^{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 δ^{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 δ^{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 δ^{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 δ^{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 δ^{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 δ^{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 δ^{18}O values >0.5‰ and coeval shifts in western equatorial planktonic δ^{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 δ^{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 δ^{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 δ^{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 δ^{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‰