Descent into the Icehouse

Ellen Thomas

Department of Geology and Geophysics, Yale University, New Haven, Connecticut 06520 and Department of Earth & Environmental Sciences, Wesleyan University, Middletown, Connecticut 06459, USA

Geologists have long recognized (e.g., Lyell, 1830–1833) that during the Cenozoic, a world without significant polar ice sheets (Greenhouse World) was transformed into one with large ice sheets at both poles (Icehouse World: Miller et al., 1991), with concomitant major changes in land and ocean biota (e.g., Prothero et al., 2003). When and where cooling occurred, when the ice sheets started to form on each hemisphere, whether they persisted once formed, and the cause(s) of the cooling have long been debated (e.g., Thomas et al., 2006). This issue of Geology contains two contributions to this debate, one on northern hemispheric cooling (Schouten et al., 2008, p. 147 of this issue), the other on tropical climate and biotic changes (Pearson et al., 2008, p. 179 of this issue). Where do these contributions fit in the overall debate?

Over the last few decades, estimates of the timing of initiation of glaciation have been increasing. In the early 1970s, Antarcitca was thought not to have been cold enough for continental ice sheets until the late Miocene (Denton et al., 1971). Since the mid-1970s (Kennett and Shackleton, 1976), oxygen isotopic records of benthic foraminifera, documenting a combination of global ice volume and deep-sea (thus high-latitude surface) water temperatures, have become available (Zachos et al., 2001; Fig. 1), documenting stepwise combined cooling and glaciation, with the most important steps 1) close to the Eocene/Oligocene boundary; 2) in the middle Miocene, and 3) at the beginning of the Plio-Pleistocene ice ages (Fig. 1). These records were interpreted as indicative of a cooling of ~5 °C in the earliest Oligocene and Antarctic glaciation in the middle Miocene (Kennett and Shackleton, 1976), but after recovery of lowermost Oligocene ice-rafted material, a consensus developed in the 1990s that Antarctic ice sheets reached sea level in the earliest Oligocene, with Northern hemispheric ice sheets developing millions of years later, in the late Miocene (e.g., Zachos et al., 2001). The existence of a world with only a south polar ice sheet was seen as in agreement with the hypothesis that the opening of the Southern Ocean gateways led to the development of the Antarctic Circumpolar Current (ACC), reducing meridional heat transport to Antarctica by isolating the continent within a ring of cold water, causing formation of a continental-scale ice sheet (with feedbacks) (e.g., Kennett, 1977).

During the past few years, these views have been questioned. First, it has been difficult to accurately date the opening of Southern Ocean gateways and the initiation of the ACC, recent estimates ranging from middle Eocene (Livermore et al., 2007) to late Oligocene (Lyle et al., 2007). Second, climate modeling results indicate that the change in meridional heat transport associated with ACC onset was insignificant (e.g., Huber and Nof, 2006), and that changes in ocean circulation alone do not lead to Antarctic glaciation (De Conto and Pollard, 2003). The latter concluded that an Antarctic ice sheet could begin to form only when the concentration of greenhouse gases dropped (Fig. 1; Pagani et al., 2005). There is a striking similarity between the modeled results of De Conto and Pollard (2003) and high-resolution data from a Pacific Ocean site (Coxall et al., 2005), both showing an orbitally modulated, two-step Oi-1 event. Additional data from Pacific Ocean sites led to re-examination of the premise that northern-latitude ice sheets post-dated the Antarctic ice sheet (Tripati et al., 2005), and ocean drilling in the Arctic Ocean provided evidence of ice-rafting in the middle Eocene (Moran et al., 2006), and development of dinoflagellate biostratigraphy dated ice-rafting in the Norwegian-Greenland Sea as middle Eocene (Eldrett et al., 2007; Tripati et al., 2008).
that Cenozoic cooling was caused mainly by changing in the late Eocene and early Oligocene was approximate that boundary. Between the two steps of oxygen isotope event is defined by the last occurrence of the planktic foraminiferal genus 192 GEOLOGY, February 2008. Establish that the Eocene/Oligocene boundary, before the isotope event. In addition, they finally extinctions in shallow-water organisms, as well as planktic and isotopederived temperatures for coeval sections in the southern hemisphere (14–15 °C for the middle Eocene, declining to ~10 °C by the end of the Eocene; Dutton et al., 2002; Poole et al., 2005). As Schouten et al. point out, such temperatures might appear high for an environment where we observe ice rafting, but could represent summer rather than annual temperatures. The article by Pearson et al. (p. 179 in this issue) presents data from Tanzanian sections, a veritable treasure trove of beautifully preserved fossil material. Pearson et al. (2007) documented the tropics remained warm until the end of the Eocene, and that long-term middle Eocene cooling as seen in the deep-sea record is limited to high latitudes. Their article in this issue confirms the two-step nature of Oi-1, and suggests that only part of this event reflects ice-volume increase. Interpretation of this event as wholly due to ice-volume increase thus probably is incorrect, and benthic Mg/Ca data are not reliable temperature proxies during changes in carbonate ion concentration (Lear et al., 2004).

Pearson et al. (this issue) also establish that extinctions in shallow-water organisms, as well as in planktic organisms, started ~0.5 m.y. before the isotope event. In addition, they finally establishes that the Eocene/Oligocene boundary, defined by the last occurrence of the planktonic foraminiferal genus 197, Cenozoic evolution of Antarctic glaciation, the circum-Antarctic Current, and their impact on global paleoceanography: Journal of Geophysical Research, v. 82, p. 3843–3860. Kennett, J.P., 1977, Cenozoic evolution of Antarctic glaciation, the circum-Antarctic Current, and their impact on global paleoceanography: Journal of Geophysical Research, v. 82, p. 3843–3860.

Where does that leave us in the debate on Eocene/Oligocene global cooling? The cooling in the late Eocene and early Oligocene was truly a global event, affecting organisms from high to low latitudes, thus supporting the view that Cenozoic cooling was caused mainly by decreasing CO₂ levels in the atmosphere, with subsequent processes such as ice albedo and weathering feedbacks. Proxy records for atmospheric CO₂ values, however, show strong variability in the middle-late Eocene (Pearson and Palmer, 2000; Pagani et al., 2005), and no precise correlation with glaciation events (Fig. 1). We need more detailed and accurate proxy records of past CO₂ levels, as well as more geographically diverse records of temperature changes across the late Eocene and Oligocene before we can truly understand when, how, and why the Earth descended into the Icehouse state.

REFERENCES CITED
Lyell, C., 1830–1833, Principles of Geology, being an inquiry how far the former changes of the earth’s surface are referable to causes now in operation: London, John Murray, Vols. 1–3.