Warming without high CO_2?

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Over the next century, increasing levels of greenhouse gases are expected to raise Earth's mean surface temperatures by some 2–5 °C. To help understand future climate change, Earth scientists are examining ancient periods of extreme warmth such as the Miocene Climatic Optimum of about 14.5–17 million years ago (Myr). Fossil floral and faunal evidence indicate that this was the warmest time of the past 35 million years; mid-latitude temperatures were as much as 6 °C higher than at present. Many workers believe that high CO_2 levels, in combination with oceanographic changes, caused Miocene global warming by the greenhouse effect. But in the June issue of *Paleoceanography*, Pagani, Arthur and Freeman[1] present evidence for surprisingly low CO_2 levels of about 180–290 parts per million by volume (p.p.m.v.) throughout the early to late Miocene (9–25 Myr). These authors conclude that greenhouse warming by high CO_2 cannot explain Miocene warmth, and that other mechanisms must have had a greater influence.

In their study, Pagani *et al.* used a relatively new molecular-isotopic approach that has been effective in tracing CO_2 in glacial–interglacial cycles of the past several hundred thousand years[2,3]. A record of surface water $[CO_{2(aq)}]$ can be obtained from $C_{37:2}$ alkenones in marine sediments, because isotopic fractionation during phytoplankton photosynthesis is largely controlled by $[CO_{2(aq)}]$, cell growth rate and cell geometry. Assuming the effects of cell growth rate and cell geometry are minimal in low-nutrient waters, $[CO_{2(aq)}]$ may be estimated by comparing $C_{37:2}$ alkenone $\delta^{13}C$ with the $\delta^{13}C$ of total CO_2 as recorded by planktonic foraminifera. Atmospheric CO_2 can then be calculated from $[CO_{2(aq)}]$ values based on Henry's law.

Pagani and colleagues' CO_2 record bears little relation to an expected association between CO_2 and long-term climate change during the Miocene (Fig. 1, overleaf). In particular, low CO_2 values span the warm Climatic Optimum which ended around 14.5 Myr, whereas rising CO_2 levels accompany global cooling and expansion of the East Antarctic Ice Sheet about 12.5–14 Myr (as inferred from the oxygen-isotope composition of benthic foraminifera from deep-sea sediment cores). Rising CO_2 during the middle Miocene may eliminate a reverse greenhouse effect as the main cause of East Antarctic Ice Sheet expansion.

Several sources of uncertainty in calculating $[CO_{2(aq)}]$ may increase CO_2 estimates, but only minimally. Miocene $[CO_{2(aq)}]$ values may be artificially low if the $\delta^{13}C$ of surface-water total CO_2 is overestimated. Foraminiferal $\delta^{13}C$ may overestimate $[CO_{2(aq)}]$ either because of species-dependent effects or because of the carbonate-ion effect on seawater $\delta^{13}C$ (ref. 4). However, $[CO_{2(aq)}]$ values are primarily controlled by variations in the $\delta^{13}C$ of $C_{37:2}$ alkenones, and even a 0.5–1‰ overestimation of surface-water $\delta^{13}C$ would yield only slightly higher CO_2 values[1]. Similarly, underestimation of sea-surface temperature from foraminiferal $\delta^{18}O$ (due to a possibly lesser ice-volume effect) would increase calculated CO_2 only slightly.

Pagani and colleagues' low CO_2 values of 180–290 p.p.m.v. (present-day value is 360 p.p.m.v.) will fuel debate on long-term CO_2 history during the Cenozoic era. Some geochemical models[5–8] suggest that increased global chemical weathering and erosion during the past 40 Myr progressively consumed atmospheric CO_2. Others argue that there was little change in either global weathering rates or CO_2 (ref. 9). Low Miocene CO_2 levels are consistent with palaeo-pH data[10], which indicate little difference from the present-day ocean. Similarly, CO_2 trends on the timescale of 10^5–10^6 years are in line with foraminiferal $\delta^{13}C$ records of organic-carbon burial relative to calcium carbonate (Fig. 1). High $\delta^{13}C$ values between 13 and 17.5 Myr, termed the Monterey Excursion, indicate greater burial of organic carbon which may have been sufficient to draw down CO_2 from the atmosphere during this time[11]. Thus, low Miocene CO_2 is supported by some independent geochemical data.

Furthermore, Pagani *et al.* find that short-term CO_2 minima coincide with glacial cooling on the 10^4–10^5-year scale. Coeval maxima in foraminiferal $\delta^{13}C$ support the idea that organic-carbon burial was linked to CO_2 drawdown on such timescales[12,13]. This finding squares with known mechanisms of climatic change during the past several hundred thousand years, in which high CO_2 clearly increased global warming. In short, CO_2 variability seems to contribute to

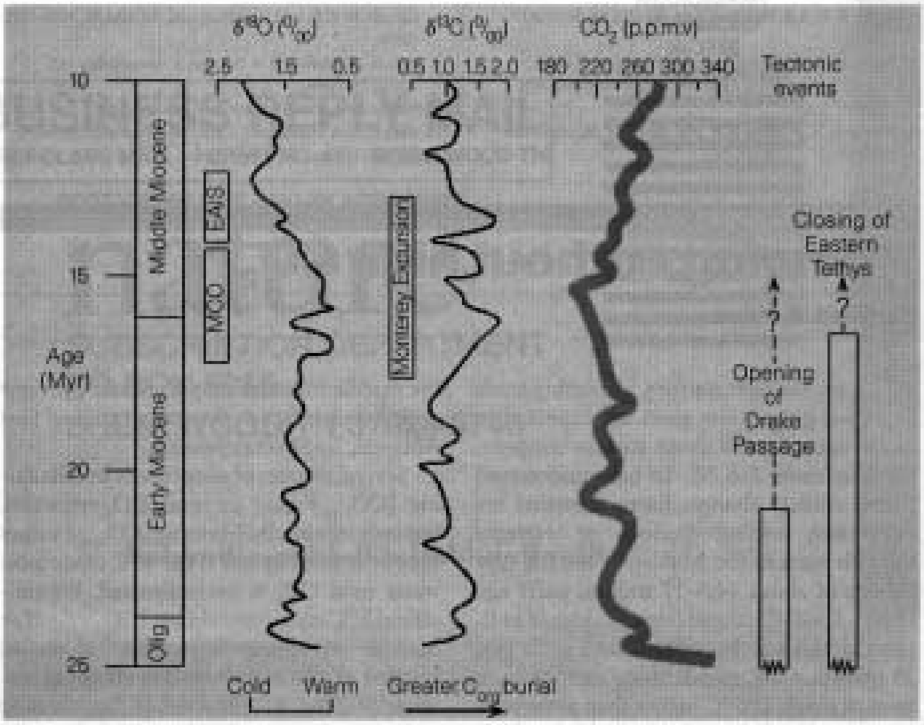

Figure 1 **Tracing climate change in the Miocene. Shown here are records of ice volume and temperature (based on foraminiferal $\delta^{18}O$) and relative organic-carbon burial (based on foraminiferal $\delta^{13}C$), compared with the CO_2 estimates of Pagani *et al.*[1], and tectonic events that may have affected ocean heat transport. Trends in CO_2 are consistent with organic-carbon burial and CO_2 drawdown during the Monterey Excursion, but cannot explain the Miocene Climatic Optimum (MCO) or expansion of the East Antarctic Ice Sheet (EAIS).**

climatic changes on the glacial–interglacial timescale, but may be partly decoupled from long-term climate change.

If Pagani *et al.* are right, then how can one explain the high temperatures of the Miocene Climatic Optimum, or middle Miocene global cooling and expansion of the East Antarctic Ice Sheet? Other possible controls include different greenhouse gases (water vapour and methane, for example), and ocean circulation. On million-year timescales, the openings and closings of ocean 'gateways' caused by changes in continental geography may affect ocean heat transport. There are large uncertainties in dating these events, but the opening of the Drake Passage (between 22 and 32 Myr; ref. 14) and closure of the eastern Tethys Ocean probably reduced meridional ocean heat transport to the Southern Hemisphere[15–17], and may account for a large part of Miocene climate change. As Pagani *et al.* point out, low CO_2 levels may also have increased the sensitivity of the climate system to heat and vapour transport. Alternatively, changes in atmospheric water vapour and moisture supply to the Antarctic continent may have promoted both global cooling and growth of the East Antarctic Ice Sheet.

The exciting possibility that CO_2 levels were low during the Miocene has implications for our understanding of many elements of Earth system history, including climate, ocean chemistry, global chemical weathering and the evolution of CO_2-sensitive biota. It also raises the prospect that projected CO_2 levels in the next century (perhaps 560–720 p.p.m.v.) may be the highest of at least the past 25 Myr. Associated greenhouse warming may therefore reach the levels of the early Cenozoic. Nevertheless, low Miocene CO_2 underscores the potential importance of different greenhouse gases, ocean circulation and other mechanisms in past as well as present global change. □

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