Convergent Cenozoic CO_2 history

David J. Beerling and Dana L. Royer

Reconstructions of atmospheric carbon dioxide concentrations over the past 65 million years are heading towards consensus. It is time for systematic testing of the proxies, against measurements and against each other.

Atmospheric carbon dioxide is clearly a primary driver of global temperature change[1], but efforts to slow anthropogenic emissions from fossil fuel burning and land use change are failing. Average increases in the rates of fossil fuel CO_2 emissions more than tripled from 1% per year in the 1990s to 3.7% per year in the following decade[2]. The Earth's atmosphere is steadily heading towards a burden of greenhouse gases not seen for some 20 million years. This burden will lead to a warmer future both in our lifetime and for generations to come as the energy balance of the Earth system slowly comes into equilibrium with rising greenhouse gas concentrations. Our planet's climatic future can be estimated from an understanding of ancient climate change without recourse to computer models of Earth's climate system — but only if we have reliable information on past concentrations of CO_2 in the atmosphere[3].

The past 65 million years (Myr) of Earth history is known as the Cenozoic era and encompasses large climate variations, including the transition from an ice-free planet to the onset of the Pleistocene glacial–interglacial cycles. This interval also saw the origin and worldwide diversification of grasses with the C_4 photosynthetic pathway that today dominate savannas[4]. Over the past 50 Myr, the Cenozoic climate trend is characterized by a deep-sea cooling of approximately 12 °C thought to have been forced by changes in atmospheric greenhouse gas composition[3].

A decade ago, efforts to reconstruct atmospheric CO_2 levels during this era showed fundamental disagreements between different proxy indicators of atmospheric CO_2 concentrations[5]. This was especially true for the first half of the Cenozoic, with discrepancies between proxies[5] spanning a range from less than 300 ppm to more than 3,000 ppm. Our extensive compilation of 370 revised estimates of Cenozoic CO_2 levels (see Supplementary Information) reveals better agreement and documents a coherent pattern of CO_2 change, with a clear connection to global temperature

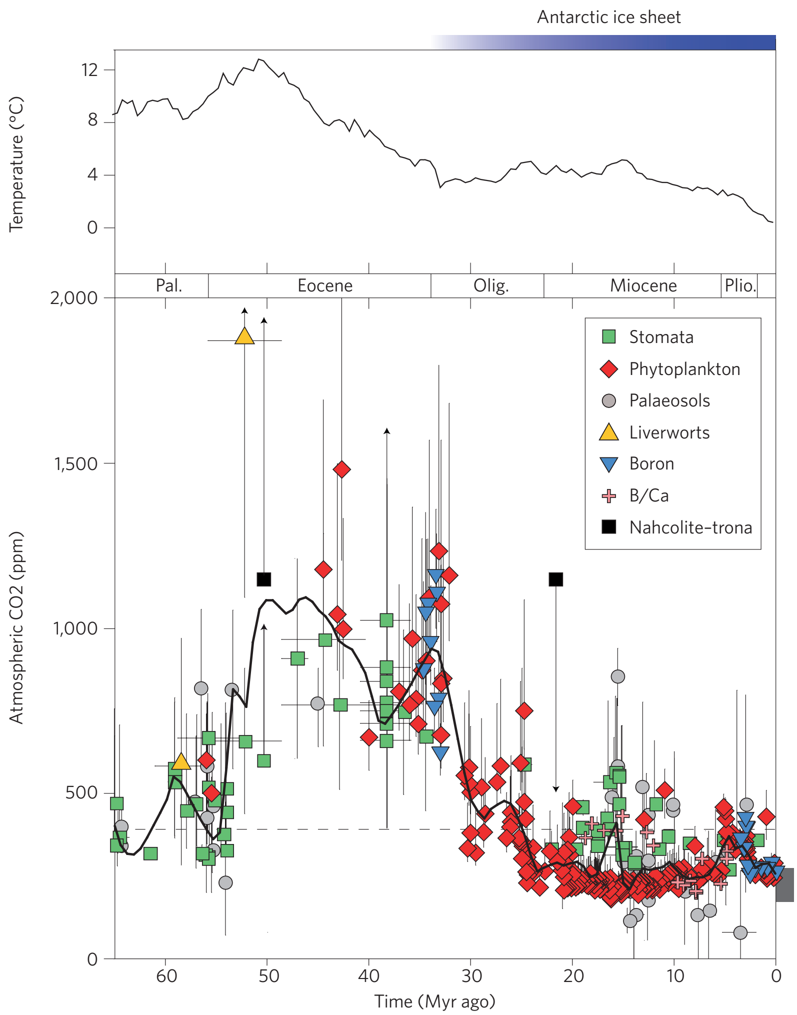

Figure 1 | Earth's Cenozoic atmospheric CO_2 history by proxy. Deep-sea temperatures[3] (upper panel) generally track the estimates of atmospheric CO_2 (lower panel) reconstructed from terrestrial and marine proxies following recent revisions (see Supplementary Information). Errors represent reported uncertainties. Symbols with arrows indicate either upper or lower limits. The vertical grey bar on the right axis indicates glacial–interglacial CO_2 range from ice cores. The top blue bar indicates approximate timing of ice-sheet development on Antarctica. Horizontal dashed line indicates the present-day atmospheric CO_2 concentration (390 ppm).

(Fig. 1). Notably, peak Cenozoic warmth 52 Myr ago corresponds with maximum reconstructed CO_2, and the rapid inception of Antarctic glaciation to the Eocene–Oligocene boundary (33–34 Myr ago) follows a sharp fall in CO_2.

Evolving CO_2 proxy science

Development of proxies of atmospheric CO_2 levels to constrain the evolution of greenhouse gas concentrations in the Earth's atmosphere represents a formidable interdisciplinary scientific challenge. The process begins with identifying a clear response in a biological or geochemical system to changes in atmospheric or oceanic CO_2 concentrations. This response must be sufficiently large to be detected in the fossil or sedimentary record and it must persist in the fossil record without alteration at a later stage. If these conditions are met, the proxy can be calibrated against modern systems. Finally, the proxy must be shown to detect known changes in atmospheric CO_2 concentrations over a time span also covered by independent reconstructions or records.

Although each stage requires assumptions and introduces errors, the challenges are not insurmountable. Several CO_2 proxies for both terrestrial and marine realms are widely employed[5], with others continuing to become available[6,7] (Fig. 2). Many of these proxies have been applied to reconstructing Cenozoic CO_2 levels (Fig. 1), but of these, four have been specifically identified by the 2007 report of the Intergovernmental Panel on Climate Change[8] as showing the most promise. The two terrestrial-based proxies are based on the abundance of stomatal pores on fossil leaves and on the carbon isotope composition of carbonates in fossil soils. The two marine-based examples use the carbon isotope composition of phytoplankton and the boron isotope composition of fossil foraminifera.

Recent advances in the science underpinning key stages of development in all four of these proxies are refining estimates of ancient CO_2 levels. Most noticeably, the rigorous assessment of biological respiration and carbonate formation in soils has reduced CO_2 estimates from fossil soils by ~50%, thereby largely resolving their long-standing discrepancy with other methods[9]. The boron CO_2 proxy has also significantly improved, and newer CO_2 reconstructions address earlier limitations associated with an incorrect isotopic fractionation factor[10], diagenetic alteration, and gaps in our understanding in the evolution of

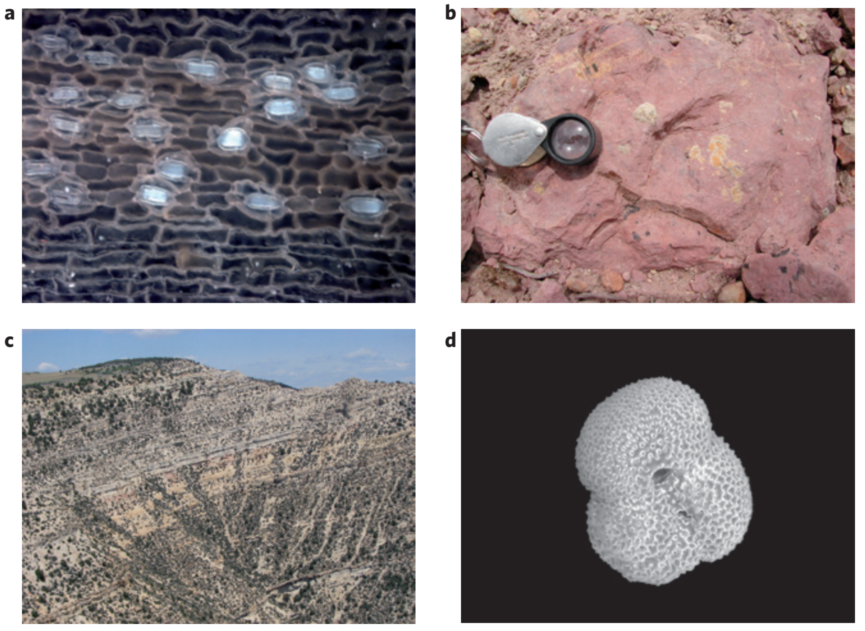

Figure 2 | Fossil materials recording Earth's past CO_2 history. **a**, Fossil conifer cuticles from *Metasequoia* with stomata and epidermal cells; **b**, carbonate nodules; **c**, fossils soils known as palaeosols; and **d**, fossil foraminifera shells are all used to reconstruct past atmospheric CO_2 levels. *Metasequoia* image courtesy of G. Doria, Yale University; palaeosol image courtesy of G. Bowen, Purdue University.

seawater boron isotopes and alkalinity[5]. Meanwhile, Bayesian approaches for calibrating stomatal reconstructions have mostly revised the resultant CO_2 estimates upwards[11], and quantification of cell-size effects on phytoplankton carbon isotope fractionation has increased the consistency of this method[12].

The consensus emerging for Earth's Cenozoic CO_2 history by proxy is promising, but a twofold variation in estimates derived from the different techniques remains. It raises legitimate concerns over the credibility of the estimates of ancient atmospheric CO_2 concentrations. Given what is at stake — understanding the climatic future of our planet as we fail to halt anthropogenic CO_2 emissions — we argue that it is important to identify pathways to greater credibility.

Scientific communities engaged in modelling past, present and future changes in the oceanic and land surface carbon sinks[13] organized to provide extensive intermodel comparisons and benchmarking against observational datasets and other evidence. Similar activities could also build greater confidence and credibility in the science of CO_2 proxy reconstruction. We therefore propose a two-step process for achieving this.

First, we suggest that proxy reconstructions of past atmospheric CO_2 concentrations should be targeted to the past 800,000 yr, to compare the estimates with instrumental and CO_2 records obtained from bubbles trapped in ice cores[14]. Verification activities should also be linked to the development of standardized Bayesian probabilistic techniques[6,11,15] for handling the propagation of uncertainties generated by analytical and calibration procedures. Second, we propose focusing on obtaining CO_2 records from numerous proxies for two relatively recent globally warm climate intervals: the middle of the Pliocene epoch (3.6–2.6 Myr ago) and the Mid-Miocene climatic optimum (18–15 Myr ago). Both intervals are characterized by a rich record of palaeoclimate evidence documenting the thermal state of the planet, and the availability of detailed terrestrial and marine fossil depositories for breathalysing Earth's ancient atmospheric CO_2 concentration.

Early results provide increasing confidence in atmospheric CO_2 reconstructions. Four proxies — boron isotopes[16] and B/Ca ratios[17] in carbonate shells, fossil leaf stomata[18] and the isotopic signature of compounds produced by phytoplankton[19] — seem sensitive to glacial–interglacial CO_2 changes, although the B/Ca method is not yet calibrated with laboratory culture experiments. Furthermore, concurrent estimates of Pliocene CO_2 levels by numerous methods agree well, with a difference of only about 50 ppm[20].

We recognize that it will not be easy to constrain Earth's CO_2 history by proxy, but it is crucial to continue to reduce uncertainties. Apart from climate model simulations, a clear understanding of Earth's CO_2-rich past is our only chance to grasp the consequences of our unabated exponential consumption of fossil fuels. ❐

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Additional information

Supplementary information accompanies this paper on www.nature.com/naturegeoscience.