PALAEOCLIMATE

How it went down last time

The Palaeocene–Eocene Thermal Maximum 55 million years ago was triggered by the sudden release of carbon to the ocean–atmosphere system. The carbon may have been removed almost as abruptly 100,000 years later, in the form of organic carbon.

David Archer

The recent global warming is not the first climate change event this old Earth has undergone. The most tantalizing analogue to our present situation occurred 55 million years ago, and is known as the Palaeocene–Eocene Thermal Maximum event. Atmospheric CO_2 rose dramatically, the deep ocean warmed, and sea surface temperatures at high latitudes increased by about 5 °C. Just like in comedy, the key to resolving the climate and carbon cycle changes is timing. Writing in *Nature Geoscience*, Bowen and Zachos[1] propose a new chronology for the event and recovery that raises questions about the fate of the carbon.

In the geological record, the Palaeocene–Eocene Thermal Maximum (PETM) is marked by a rapid change in the $\delta^{13}C$ signature of organic carbon and carbonates preserved in marine and terrestrial sediments. The shift towards more negative values indicates the rapid release of isotopically light carbon, that is, carbon species with a relatively high concentration of ^{12}C relative to ^{13}C. An abundance of ^{12}C generally indicates that a carbon species has been formed by biological activity. In the case of the PETM, the carbon released to the atmosphere was probably derived from organic compounds in soils, peats or sediments.

The classic chronology[2] suggests that the shift to more negative values, and hence the release of the carbon, occurred relatively quickly, and that a slow recovery to background values began immediately. The timescale for the period of recovery was about 100,000 years, comparable to the timescale for a feedback from the chemical weathering of rocks. This consumes atmospheric CO_2 and scrubs the carbon cycle of excess carbon and its isotopic signature. The weathering feedback is based on the idea that chemical weathering is limited by the availability of fresh water, and so rates — and CO_2 consumption — would increase in a warmer, wetter world[3]. Understanding the timing of feedbacks is key: the severity and longevity of this climate perturbation was dependent on feedbacks that removed the carbon from the atmosphere, such as rock weathering and the growth of carbon pools in the biosphere.

The PETM is thought to share similarities with global warming from anthropogenic CO_2 emissions. Primarily, the estimated amount of carbon released during the event is similar to estimates of the amount available to be released from fossil fuels today. And, just as during the PETM, the $\delta^{13}C$ signature of modern carbonates and organic carbon is becoming progressively more negative as CO_2 levels rise. We have therefore begun looking at the recovery from the PETM to understand how the modern carbon cycle may respond to ever-increasing emissions. A slow and steady recovery is fairly easy to explain.

However, the new chronology derived by Bowen and Zachos[1] suggests that after the initial rapid carbon isotope excursion, there was a plateau of more negative isotopic values lasting for 100,000 years. This was followed by a fast return to background levels, far faster than in the previous chronology. The residence time for carbon, and hence the recovery time, could have been shorter than expected if the carbon inventory at the surface of the Earth was lower than today, or if the weathering flux was higher. A smaller carbon stock is not inconceivable: the carbon inventory might have been depleted by changes in the carbonate chemistry of the oceans[4] or lower CO_2 solubility in a warmer ocean. However, the CO_2 content of the atmosphere in that hothouse time was probably higher than today, which would have increased the ocean carbon content.

Alternatively, if the rate of weathering increased more than linearly with atmospheric CO_2 levels, excess weathering

Figure 1 | Carbon in the biosphere. The PETM was caused by the release of several thousand gigatonnes of carbon to the atmosphere. Bowen and Zachos[1] propose that the recovery to background levels happened much more quickly than previously thought, and suggest that much of the carbon could have been taken up by the biosphere.

might have driven a faster recovery. Estimates of weathering rates from more recent interglacial–glacial cycles suggest that weathering rates can, counter-intuitively, be higher in cold climates, under special conditions[5]. Perhaps the PETM was also a special case for the weathering feedback.

Alternatively, Bowen and Zachos propose that the uptake of carbon by the biosphere speeded the recovery. On geologic timescales, geochemists have been conditioned to look away from organic carbon as a stabilizer of atmospheric CO_2 concentrations, because the organic carbon cycle is also charged with maintaining the atmospheric oxygen concentration. An imbalance of the oxidative weathering of organic carbon relative to its burial in sediments could double atmospheric oxygen, or deplete it, in a few million years. However, the amount of carbon we're talking about — a few thousand gigatonnes — could easily be mopped up by organic carbon with minimal effects on oxygen levels, just as atmospheric oxygen is only very slightly affected by fossil fuel combustion today.

The harder aspect to explain may be the plateau itself. During the plateau, the carbon cycle seems to be resisting a return to its previous equilibrium. We know that carbon flushes through the surface carbon cycle continuously: it is released from the solid Earth in volcanic gases and deep-sea hot-spring fluids, and eventually returns as carbonates. Therefore, the presence of a plateau seems to suggest an ongoing release of light carbon after the initial pulse. But it would need to be just enough to counteract the flushing of the carbon from the atmosphere.

The simplest way to reach such a plateau is a continuous release of carbon at a uniform rate, although this would tend to pull the ^{13}C down slowly, on a timescale of about 100,000 years[6]. Adding ^{12}C from the system more quickly than that — in accordance with the new chronology — and then staying at that steady value for 100,000 years would take a delicate balancing act. Perhaps some organic reservoir was released abruptly, continued degassing slowly for 100,000 years — by coincidence, just enough to replenish the loss of light carbon — and then just as abruptly reformed again.

Unfortunately, it is really hard to determine the timings of events so far in the past[7]. Bowen and Zachos[1] have not written the last word on the timing and duration of the PETM, but they have shown that it will be very revealing, and perhaps relevant to our own distant future, to get this nailed down solidly. ❐

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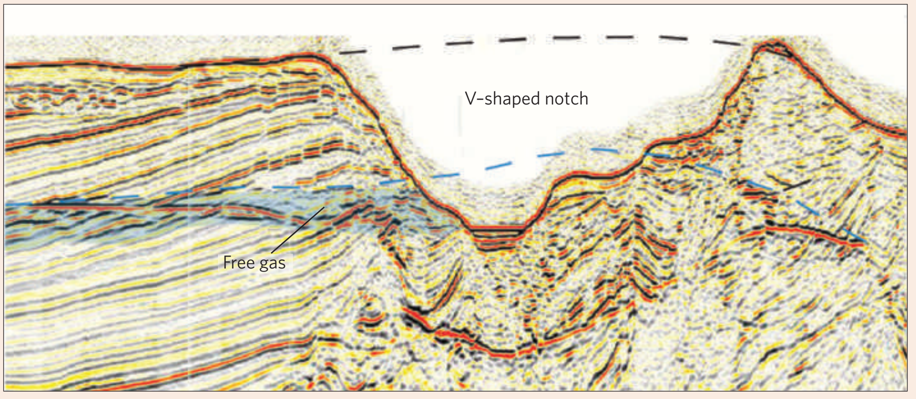
MARINE GEOLOGY

Release through erosion

Methane is continually produced by microbes that decompose organic matter in sediments at the bottom of the sea. And thermal decomposition of organic matter buried deep beneath the ocean causes methane to seep up from depth. Both methane sources can become trapped in subsurface reservoirs, either as gas or locked into gas hydrate — if the pressure and temperature are just right. Today, huge reservoirs of methane are found, mainly along continental margins. However, slight changes in temperature or pressure have the potential to destabilize the reservoirs, either slowly through venting or catastrophically through seafloor failure. In the latter case, large amounts of methane could enter the oceans and — unless the gas is oxidized quickly — the atmosphere.



GSA GEOLOGY

Catastrophic destabilization may have occurred about 50,000 years ago offshore from Japan, near the Nankai trough. Nathan Bangs and colleagues at the University of Texas imaged the sea bed and subsurface using three-dimensional seismic data and cores of sediment drilled from the ocean bottom (*Geology* **28,** 1019–1022; 2010). The images reveal a large, sharp-edged, V-shaped notch that cuts 400 m through the ocean floor, down into hydrate-laden sediments.

In the same region, there are signs that strong currents at the bottom of the ocean could have eroded away tens of metres of sea floor. Taking this observation together with the evidence for hydrate destabilization, the researchers hypothesize that erosion of the sediments above a methane reservoir may have unroofed over-pressured gas and hydrate-laden sediments, and sparked a positive feedback loop.

Based on the volume of eroded material and the concentration of hydrates in the sediments, the eroded notch alone could have released 1.51×10^{11} m^3 of methane, approximately 3% of the quantity found in the atmosphere at present.

Bottom currents strong enough to erode seafloor sediments are not uncommon. More surprises from the bottom of the ocean may therefore be in store.

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