

Constraints on hyperthermals

To the Editor — The abrupt warming event 56 million years ago, known as the Palaeocene–Eocene Thermal Maximum (PETM), was associated with the large-scale release of ^{13}C -depleted carbon into the ocean–atmosphere system. In sedimentary records, the event is reflected by a negative carbon isotope excursion¹. Cui *et al.*² used a carbon-cycle model to estimate the rate of carbon release during the PETM. The model assumed that the onset of the carbon isotope excursion occurred over approximately 20,000 years, an estimate based on a cyclostratigraphic model³. Here we highlight several issues that weaken the conclusions of Cui *et al.*

First, their calculation of the carbon release rate rests on the argument that the $\delta^{13}\text{C}$ values of the bulk organic matter in the Spitsbergen section that they used reflect exogenic trends. This argument assumes a constant $\delta^{13}\text{C}$ composition of organic matter, although different sources typically have different $\delta^{13}\text{C}$ values. Changing vegetation and kerogen composition affected organic $\delta^{13}\text{C}$ records of the PETM in the Arctic⁴. No data are presented to support the assumption of unchanged vegetation or kerogen composition in Spitsbergen. In fact, carbon/nitrogen ratios suggest the opposite.

Furthermore, the time between carbon fixation by marine and terrestrial primary producers and burial in sediments is typically thousands of years in modern systems, with Arctic residence times sometimes exceeding 10,000 years⁵. Although this is partly fuelled by the currently low Arctic temperatures, residence times of thousands of years should be assumed for the early Palaeogene. This would smooth the onset of the carbon isotope excursion. Indeed, Supplementary Fig. S4 of Cui *et al.*² shows that a scenario of such organic carbon residence times and a PETM carbon injection of several thousand years can reproduce the shape

and scale of the carbon excursion recorded in Spitsbergen. This scenario is consistent with much faster carbon injection rates than calculated.

We also point out that one end-member scenario for PETM carbon emission rates presented by Cui *et al.*² calls for a massive injection of 12,900 Pg C. A carbon injection of this magnitude would require an equally massive reservoir of sedimentary CaCO_3 to neutralize the CO_2 . Yet the existence of such a massive CaCO_3 reservoir would require a deep calcite compensation depth (CCD) prior to the PETM, at odds with observations^{6,7}. Cui *et al.* justify their assumption of a deep CCD by a statistical fit of smoothed model output to pre-PETM observations. However, this statistical analysis does not take into account that the Pacific Ocean alone was larger than the Atlantic, Indian and Tethys oceans combined⁸, and hence over-emphasizes the importance of smaller CaCO_3 reservoirs. The statistical fit also gives equal weight to shallow and deep sites, even though the shallow sites do not affect estimates of the CCD. The smoothed fit also fails to reproduce critical point observations; for example, Cui and colleagues' model suggests values of up to 75% CaCO_3 at 4,000 m depth in the Pacific, whereas observations⁷ indicate 0% CaCO_3 .

Finally, the precise dating of Palaeocene–Eocene boundary sequences remains a major challenge because of extreme changes in all processes (that is, climate, sea level and sediment supply) that influence the deposition of sediments in both continental and marine environments, as well as blur orbital cyclicity, particularly in siliciclastic shelf sequences. Cui *et al.* derive a duration of 19,000 years for the PETM carbon injection from a published orbital age model of the Spitsbergen section³. This model assumes that sedimentation remained constant across the onset of the

PETM, despite massive changes in climate and sea level. The constraints on the onset of the carbon isotope excursion in the Spitsbergen age model are, however, not necessarily better than estimates from other sections that constrain this interval to between 'geologically instantaneous' and 50 kyr (ref. 9). This imposes a large uncertainty in the estimate of carbon injection rates.

In light of these uncertainties, we suggest that a better-resolved age model, $\delta^{13}\text{C}$ measurements from single fossils and at higher resolution, as well as agreement with observations of carbonate preservation and the depth of the CCD, are required to quantify carbon injection rates during the PETM. □

References

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Cui *et al.* reply — We welcome this opportunity to clarify our approach and interpretations in view of the concerns expressed by Sluijs *et al.* Variation in source of organic matter is always of concern when interpreting trends in the isotopic composition of sediments. Definitive analyses of source were prevented by

thermal maturity¹. However, we note that the shift in carbon/nitrogen (and pristane/phytane) ratios — which suggests that organic matter during the Palaeocene–Eocene Thermal Maximum (PETM) was predominantly of marine origins² — occurs before the isotope excursion³ and should not significantly affect our reconstruction of it.

In addition, we did acknowledge that the input of old organic matter from soils may have affected our record. However, the active tectonic setting of the basin's hinterland would have led to a short soil residence time⁴, minimizing any potential artefact. Although the modern system is affected by the mobilization of old