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 excursion[1]. 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 model[3]. 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 $\delta^{13}C$ values of the bulk organic matter in the Spitsbergen section that they used reflect exogenic trends. This argument assumes a constant $\delta^{13}C$ composition of organic matter, although different sources typically have different $\delta^{13}C$ values. Changing vegetation and kerogen composition affected organic $\delta^{13}C$ records of the PETM in the Arctic[4]. 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 years[5]. 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 combined[8], 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 observations[7] 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 section[3]. 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, $\delta^{13}C$ 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. ❐

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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 maturity[1]. 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 origins[2] — occurs before the isotope excursion[3] 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 time[4], minimizing any potential artefact. Although the modern system is affected by the mobilization of old

permafrost carbon — yielding the residence times of 10,000 years or more discussed by Sluijs *et al.* — this is an unlikely source of sedimentary carbon for the Central Basin of Spitsbergen before or during the PETM. As Supplementary Fig. S4 in our paper[3] shows, a more appropriate soil residence time of 1,000 to 2,000 years, combined with a short-lived carbon injection of 1,000 years, does not resemble our record. Moreover, a 1,000-year pulse should have led to a significant shallow-water acidification event[5] (see also Supplementary Fig. S11 of ref. 3), which is not evident in existing data[6,7].

The claim that our deep initial calcite compensation depth (CCD) is inconsistent with observations ignores our statistical treatment, which shows that a deep initial CCD is marginally more consistent with observations than is the shallower CCD of our other end-member scenario. There is also no statistical basis for the claim by Sluijs *et al.* that the Pacific data are more important than those from other basins just because the Pacific is larger; it is simply even more under-sampled than the other basins. Indeed, shallow sites are not irrelevant, because they define the shape of the lysocline. In any event, we used no data shallower than 1,000 m in our analysis. The approach we take to compare model data using smoothed model profiles and regional grouping is justified because point-by-point comparisons would be overwhelmed by mismatches in water depth between the data and the modelled bathymetry. Moreover, our approach is consistent with how modern data are considered in the literature[8], given the considerable variability in the amount of $CaCO_3$ (weight %) at any depth in every ocean basin. This natural variability underlies our final conclusion that we cannot rule out either of the two scenarios we proffer.

There is no evidence for substantial variations in sedimentation rate or unconformities in the PETM interval of the Spitsbergen sections. Wavelet spectra in the depth domain from both the Longyearbyen section and core BH9-05 indicate relatively constant sedimentation, and cycle frequencies remain mostly constant over the PETM interval[3,9]. Only an unaccounted-for increase in sedimentation rate would lead us to overestimate the duration of the onset of the carbon-isotope excursion, and multiple transitional isotopic values and the absence of steps in the Spitsbergen $\delta^{13}C$ curve clearly testify to the absence of major unconformities during the onset.

In summary, Sluijs *et al.* seem to argue for a shorter duration but smaller total quantity of carbon release than we presented as our preferred scenario[3]; therefore, our rate estimates (for example, quantity divided by duration) are less dissimilar than their comments imply. Thus, although we acknowledge that uncertainties remain concerning the detailed chronology of the PETM carbon isotope excursion and the source and magnitude of carbon addition, these uncertainties do not pose a significant challenge to our central conclusion that the PETM may be a best-case analogue for a future with 'business as usual' utilization of fossil fuels. ❐

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