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Interactive comment on "Orbital forcing of terrestrial hydrology, weathering and carbon sequestration during the Palaeocene-Eocene Thermal Maximum" *by* Tom Dunkley Jones et al.

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Author Comment to Victoriano Pujalte (Referee 2) Second Comment

Again, we very much appreciate the second set of discussion provided by Victoriano Pujalte. This is a significant contribution of thinking and time that he's taken to consider the issues presented. His latest comments are very helpful in clarifying our thinking, and, I think, move closer to a consensus on the available evidence and its interpretation.

I do have a few minor points of note, clarification or uncertainty, that would all benefit

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Discussion paper

from Victoriano's short response if there is still time!

Point 1: Sedimentation during PETM differed fundamentally from that prevailing during the Paleocene

Paragraph 1 – agree entirely.

Paragraph 2 – "During Paleocene times the sedimentation was dominated by calcareous deposits.." and "stacks of hemipelagic deposits, with and without intercalated thin-bedded calciclastic turbidites, were deposited on the basin floor."

Zumaia is one of these basin floor locations dominated by hemipelagic deposits. We fully agree with this, BUT it is very important to note that these Paleocene hemipelagic "marls", that exhibit strong precession-forced cyclicity, are only 40 – 60% weight percent calcium carbonate (%CaCO3). This means that 40-60 % of the sediment content is siliciclastic, presumably clays and fine-grained silts, even during "quiet" hemipelagic background deposition, away from any recognized thin turbidites.

This, I think, is important. It poses the question – what drives the precession cyclicity in carbonate content through the Paleocene? Assuming that the site is above the lysocline, and not subject to extensive carbonate dissolution, there are two first-order options:

1. Cycles in pelagic carbonate productivity;

2. Cycles in the mass flux of fine-grained (non-turbidite) hemipelagic clays and fine silts to the basin floor. As Victoriano notes, probably derived form climate-induced variations in the weathering of regional terrestrial catchments.

Or some combination of 1 and 2.

It is important to note that the hemipelagic deposits of the Paleocene are roughly 50:50 carbonate / non-carbonate, so either of these could be the forcing mechanism of precession cycles through the Paleocene. I raise this point, as there is no a priori evidence for why the delivery rates of fine-grained clay material to the Zumaia section cannot be the continuous factor explaining both the observed late Paleocene and intra-PETM cyclicity.

Paragraph 3 – This is extremely helpful, and the real regional context that we are very grateful for Victoriano providing. In particular:

1. The massive and basin-wide increase in siliciclastic delivery to, and accumulation within, the Basque Basin.

2. The decoupling of coarse- and fine-grained deposition across the basin.

This is fully consistent with the observations at Zumaia – the greatly increased accumulation of fine-grained material on the basin floor during the PETM.

Paragraph 4 – this refers to my key point above. This statement implies that the hemipelagic deposits are "autochthonous". I can't see how this can be the case when they are only 50% carbonate? I.e. there is a $\sim$50% allochthonous, siliciclastic component. Precession cyclicity in these units could be forced by either carbonate production (autochthonous) or sediment supply (allochthonous) processes. I am not aware of a clear line of evidence or published study that can distinguish which driver is dominant within these deposits?

Given this, I think the argument that, in deep-marine hemipelagic sequences, Paleocene sedimentation is controlled by autochthonous processes (pelagic carbonate production), whilst intra-PETM deposits are controlled by allochthonous processes inserts a false disjunction between these successions. Yes, we fully agree there is a very large change in the system during the PETM, but, within the Zumaia deep-basin floor succession, there is continuity in the contribution of a fine-grained, allochthonous clay component that is present both before and during the PETM. It's within this hemipelagic clay component during the PETM that we continue to trace Fe cycles that are present as precession-cycles in the Paleocene.

So this, I think, is where we are slightly talking across each other. Victoriano (rightly) sees a great deal of structural and sedimentological complexity within the allochthonous component of other sections in the Basque Basin, and that varies between sections both before and during the PETM, such that extracting a coherent signal of external climate forcing would be difficult if not impossible. At Zumaia, however, this allochthonous component (non-carbonate component, ∼50%) clearly does not impact the identification of precession-forced variations in bulk sediment character during the late Paleocene. Rather, we contend that it is at least as likely that the precession signal is actually forced by this allochthonous component, as much as by carbonate production. Further, that this is also the most likely driver of the continued cyclcity that we observe with the PETM at Zumaia.

Point 2. Completeness of the PETM at Zumaia

Again, we agree with Victoriano that the PETM Zuamaia section is complete, given all evidence to date. This also fits with our isotopic correlations between Zumaia and the other most complete PETM deep-ocean and terrestrial sections (Big Horn Basin).

I too can't answer the question of how complete the Zumaia record is at the fine scale, I can just say that, as yet, there is no sedimentological, isotopic or biostratigraphic evidence for any significant hiatus within the Zumaia SU.

Precession / Half-Precession. This is a very interesting point, and we accept that there are two potential distinct interpretations of the observed cyclcity through the PETM, and that this touches into current discussion of the duration of the event. We identify 10 cycles, similar to the 10 cycles identified within the highest-resolution record available to date of the PETM – that of the terrestrial paleosols in the Big Horn Basin. Within the existing cyclostratigraphic and other constraints on the duration of the PETM from deep-ocean sites, these observed cycles during the PETM at Zumaia are interpreted as representing half-precession variations, which can be generated in hydrological records of regions with annual "double rains". The argument for this is not circular –

the cycles are statistically significant and they are consistent with the highest-resolution cyclostratigraphic record available to date Big Horn Basin). The secondary question is whether they are precession or half-precession cycles, and we follow the current best estimates of PETM total duration to identify these as half-precession cycles.

Averaged sedimentation rates. This is another point where I think we can actually agree with Victoriano. The very good agreement in the shape of the CIE of Zumaia and the primary PETM deep-ocean sites and the Big Horn Basin (Figure 5 original paper) demonstrates that our age model, at the scale of the onset, body and recovery of the CIE, does not diverge from these other sites. In other words, using an "average" sedimentation rate approach - based on constraints from the CIE onset and recover - for the modelling component of our study would not diverge in any significant way from the age model currently used. This is a positive of the study, as it means our Earth System model results are robust to uncertainty in the finer points of our preferred age model. In other words they would not change under the assumption of an "average" intra-PETM sedimentation rate age model preferred by Victoriano.

Point 3. Turbidity Activity at Zumaia

I'll leave arguments about recurrence rates of turbidites and other high-energy deposition across the Basque Basin to others. But fully agree with Victoriano's clear statement that:

"Calciclastic turbidites are indeed absent in the SU itself [at Zumaia], the reason for which is explained below. But it is logical to conclude, from the observations in the Barinatxe section (Fig. B), that the accumulation of the SU at Zumaia resulted from a high number of small-scale depositional events, probably driven by underflow plumes or very diluted turbidites."

I'm very happy that the clay-grade deposition during the SU at Zumaia occurred within a very high number of small-scale deposition events. Perhaps these processes were not so dissimilar to the depositional processes of the (50%) non-carbonate clay-grade component in the late Paleocene. Regardless, these many multiple events have consistent enough bulk sediment chemistry to develop the observed elemental cycles on the ∼0.5 m scale. Which is consistent with our interpretation that these are driven by the nature of erosion and sediment supply from the terrestrial catchments, the ultimate source of this fine-grained siliciclastic material.

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