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Climate of the Past Discussions
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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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We very much appreciate Reviewers 1's thoughtful comments on this paper, and their encouragement to present more detail on the sedimentology of the Zumaia section. We particularly welcome their acknowledgement that cyclostratigraphy has been achieved throughout almost the entire Paleocene at the Zumaia section, and that the extension of this cyclostratigraphy across the PETM is a "beautiful idea". I appreciate comments about the title of the paper and will revise, as well as other notes on presentation of the manuscript.

Reviewer 1 identifies the fundamental question that may stand in the way of this "beau-



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tiful idea" as relating to the nature of turbidite deposition at Zumaia and whether this could substantially confound the bulk sediment chemistry we use to identify climate cycles:

"In the nearby Ermua section the SU contains lots of thick turbidites, more or less randomly distributed through the section. If one considers that distal material from these random turbidites must have settled also at Zumaia, then the Si/Fe approach appears very simplistic."

The concern appears to be that the expressed cycles and variability in Si/Fe within the siliciclastic unit could be heavily influenced by individual turbidite beds, with distinct Si/Fe bulk element chemistry. Given the spatial scale of the ∼0.45 m of the Si/Fe cycles through the PETM, which are statistically significant and robust, such event beds would need to be on the decimeter scale.

Below we review our understanding of the published evidence available on this matter, but, taking advantage of the nature of this Discussion paper, and the expertise of the Reviewers, we would very much appreciate the provision of any evidence direct evidence from the Zumaia section itself, that we might have missed for significant turbidite deposition within the body of the PETM. We will then happily integrate this into the manuscript and our interpretation of results.

1. Turbidite Deposition in the Zumaia Section

Both reviewers raise the same fundamental question, which we also accept is critical to the analysis and approach we present. That question is whether the Zumaia section is either:

1) dominated by stochastically distributed, turbidite deposition, with the variability in Si/Fe ratios dominated by variations in turbidite derived sediments. For such turbidites to explain the Si/Fe variations they need to be on the same length scale as these variations, i.e. the decimeter scale. They also, presumably, needs to be some evidence

- from field observations, sedimentary structures or grain-size distributions – of the presence of such turbidites within the SU at Zumaia.

Or,

2) the Zumaia section is dominated by fine-grained hemi-pelagic clays and fine silts, that represent hemi-pelagic deposition, or very fine scale sub-centimeter event beds that, as yet, have not been identified in any sedimentological study of the Zumaia SU.

Below we summarize the findings of the most detailed studies of grain-size, clay mineralogical and turbidite frequency from the Zumaia section. We often quote from original papers to show the original interpretations and observations of previous authors.

Schmitz et al. (1997), in their detailed study of the Zumaia section find:

"A turbidite, 8 cm thick, is found in the lower part of the grey limestone bed below the benthic extinction event. Such turbidites are common throughout the Zumaya section (in particular in the Eocene part), but rare in the 28 m thick interval studied here."

The "28 m thick interval" referred to spans the pre-PETM, the SU and the post-PETM intervals, and all of the study section that we present in the manuscript. This one ∼8cm thick turbidite is below the SU and the onset of the PETM. In the further detailed study of grain size and stratigraphic correlation between Ermua and Zumaia sections (Schmitz et al. 2001), this limestone bed is correlated across to the Ermua section, where it contains ∼12 relatively thick turbidites. This is evidence that the Zumaia section lies distal to the Ermua section and is significantly less impacted - in terms of percent contribution to total sediment thickness - by stochastic depositional events.

To summarize this early detailed work:

"The lithological succession [Zumaia PETM] across the interval displayed in Fig. 2 appears to be continuous. Although studied in detail, no unconformities have been found." Schmitz et al. (1997).

Even from this original work, there is no evidence for significant turbidite deposition, or other stratigraphic breaks, across the PETM at Zumaia. In this I would appreciate reviewers pointing me to any evidence, from the Zumaia section itself, for a stratigraphic discontinuity, or turbidite deposition within the SU.

Following up these excellent early studies on the Zumaia section, was the more recent publication of a highly detailed analysis of turbidite frequency within the Zumaia section and at the deep-water site ODP Site 1068 (Clare et al., 2015). I refer reviewers and readers to this article, but the main conclusion is that there is a significant turbidite "switch-off" precisely correlated with the PETM event at both Zumaia and ODP 1068:

"The frequency of turbidity current activity is reduced significantly at the IETM [alternate name for the PETM]. This includes a cessation of turbidity currents during the rapid warming phase, and a decrease in recurrence intensity immediately following the IETM (Fig. 5)."

"As the IETM features a major hiatus in activity, we can confidently state that no landslide-triggered turbidity currents (as well as those triggered by other processes) reached either site during that time."

"However, Schmitz et al. (2001) developed a high-resolution biostratigraphic and isotopic correlation across the IETM for these locations. Interpretation of stratigraphic logs (Schmitz et al., 2001) indicates a significant (greater than ten-fold) reduction in turbidity current activity at Ermua, coincident with the peak CIE at the IETM (Fig. 7). Turbidites emplaced during the IETM interval at Ermua are also considerably (<30%) thinner. . .. a decrease in turbidite recurrence at the start-IETM at Ermua provides support for a prolonged break in turbidity current activity."

So, not only is there no published evidence, that I can find, of turbidites during the SU at Zumaia, and no evidence of turbidites within the SU during our own sedimentological logging of the section, but there is also independent evidence for a major slow-down, if not total pause, in turbidite activity reaching the Zumaia section during the SU.

I hope the above discussion helps to clarify that proposing stochastic turbidite deposition to explain the variability in Si/Fe ratios at Zumaia goes against the published evidence for turbidite recurrence rates through the Zumaia PETM section, as well as our own observations, and those of independent, detailed sedimentological logs of the section (Schmitz, Clare, myself).

2. Grain size patterns within the Zumaia Section

We appreciate being redirected back to the key pioneering work of Schmitz et al. (1997, 2001) on the Zumaia section, and agree that integrating a more detailed presentation of this work would help our argument. In particular, Schmitz et al. (2001) clearly establish two key points about the Siliciclastic Unit (SU) of Zumaia:

1) that, during the SU, the coarse component of detrital (non-carbonate) material falls dramatically. To quote directly:

"In samples from just about the transition from greenish marls to the non-calcareous SU at Zumaia, the siliciclastic fraction >28$\mu$m represents <0.5% of the bulk sediment (on a carbonate free basis), compared with values typically in the range of >1.6 to >3.3% in the marls and limestones below and above the SU."

In other words, >99.5% of the detrital clastic material within the SU has a grain size <28 $\mu$m. At the time this was noted as a remarkable finding, as, combined with initial estimates of sedimentation rates based on the total duration of the CIE, it required a marked increase in sedimentation rates but with a fall in mean grain size, and almost total loss of the coarse siliciclastic component. This finding fits well with the absence of turbidite acitivity during the Zumaia SU and with sedimentation throughout the SU of Zumaia being dominated by fine-grained hemi-pelagic clays. Indeed, to quote directly:

"At both Ermua and Zumaia, there is an exceptional minimum in grain size at the interval at or close to the base of the SU, representing a further strong evidence for the correlation [of the SU and PETM between the two sites] proposed here." (Schmitz et al. 2001).

So, not only is there strong evidence for a reduction in grain size at Zumaia during the onset of the SU, this is also an event that can be correlated between Ermua and Zumaia, and is consistent with the marked reduction in turbidite-dominated sedimentation during the SU at Ermua, and absence of turbidites at Zumaia.

3. Basin-wide patterns of reduced PETM turbidite frequency – Ermua and ODP 1068.

We are grateful to Reviewer 1 to refer us back to the more proximal, up-slope Ermua section, within which the presence of turbidites during the SU should give us cause to stop and check for evidence of similar processes occurring at Zumaia. However, we request some clarification of their statement:

“In the nearby Ermua section the SU contains lots of thick turbidites, more or less randomly distributed through the section.”

They are absolutely correct that turbidites contribute a significant proportion of the rock section at Ermua above and below the SU – estimated to be 50-60% by the detailed analysis of Schmitz et al. (2001). They are also correct that there are a great many turbidites within the SU – estimates to be ∼160 by Schmitz et al. (2001). However, there is a major reduction in turbidite thickness during the SU at Ermua, from an average thickness of ∼7.8 cm below the SU to ∼1cm within the SU (Schmitz et al. 2001). This change results in a ∼five fold decrease in the contribution of turbidtes to rock section, to around 10% within the SU (Schmitz et al., 2001).

So, yes, we accept there are turbidites in the SU of the Ermua section, but the story from this section is that turbidite thickness and contribution to overall sediment thickness dramatically reduces during the PETM. This is fully consistent with the observed “turbidite switch off” observed at Zumaia, and indicates a basin-wide change in depositional processes that dramatically reduced the frequency of turbidites at Ermua (Schmitz et al. 2001) Zumaia and ODP 1068 (Clare et al. 2015).

Onset of the CIE

I note Reviewer 1's comment about the onset of the CIE. In fact, our new carbon isotopic data fit well with those of Schmitz across the PETM onset, and in particularly through the 'marker' limestone interval (-0.7 to 0 m), the precursor marl interval (0 to 0.3 m) and into the SU. To quote from the original Schmitz et al. (1997) paper:

"From the topmost few centimetres of the limestone and across the 30-40 cm of marls immediately below the benthic extinction event, $\delta$13C shows a negative shift on the order of 1.4-1.8 ‰ (Figs. 2 and 3). From values around 1.2 ‰ in the uppermost few centimetres of the limestone, $\delta$13C falls to values in the range -0.2 ‰ to -0.6 ‰ in the marl interval between +0.30 and 0.35 m. In the poorly calcareous parts of the overlying clay interval $\delta$13C values continue to fall (except for the +0.35-0.40m sample), reaching extremely negative values of -3.9 ‰ to -4.5 ‰ at some levels in the interval 2-3.3 m above the zero level (Fig. 3)."

This closely describes the pattern of isotopic change within our new analyses. I also note that Schmitz et al. (1997) place the main phase of the Benthic Foraminifera Extinction event (BEE) at ~0.3 m (attached Figure 1). Independent assessment of the BEE by our co-author Laia Alegret (pers. comm.) is that:

"The gradual but rapid disappearance of benthic foraminifera reveals significant environmental stress during the last ~12 kyr of the Paleocene [through the precursor marls], and the main phase of extinction of benthic foraminifera (Benthic foraminiferal Extinction Event, BEE) coincides with the onset of the negative CIE at ~0.3 m".

So there is an issue of defining where the CIE excursion "starts". In the attached Figure (Figure 2), we show the co-variation between $\delta$13C and carbonate content (wt % CaCO3), which clearly shows a bimodal distribution between points within the lowermost portion of the SU (0.38 to 0.95 m; marked in red), with low carbonate contents and very negative $\delta$13C values, and all data points from below the onset of the SU (below 0.34 m). It is clear that the data point at 0.34 m is at the negative $\delta$13C and low





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carbonate end of all the “pre-CIE” values, and may be the initiation of the CIE, but the major rapid shift in $\delta$13C is coincident with the drop in carbonate content at the start of the SU. We use this to argue that the distinctive onset of the CIE is close to the onset of the SU, and not at ~0 m. Note that both $\delta$13C and wt% CaCO3 values for the marl layer (0 to 0.3 m) are not unusual relative to the marl / limestone couplets of the latest Paleocene, but are made to look anomalous by the unusually high wt% CaCO3 and more positive $\delta$13C values of the marker limestone bed.

This is not to say that there are not significant environmental perturbations prior to the onset of the CIE. There is evidence for an early shift in both benthic (Alegret pers. comm.) and planktonic foraminiferal assemablages within this marl unit (Schmitz et al. 1997). Further the distinct precursor limestone bed is itself an unusual feature within the typically thinner, and lower CaCO3 “limestone-marl” couplets of the latest Paleocene. We don’t speculate on the nature of these precursor environmental changes might be, or be caused by, BUT, they do underline the potentially great importance and utility of the Zumaia section, because, unlike many deep-ocean sites, it appears to be more continuous and expanded across the onset of the event. This is part of the driving motivation of this study, to use this feature to trace the cyclostratigraphy of Zumaia, that exists before and after the PETM, through the event itself, for the benefit of future work on this succession.

Figure 1. Excerpt from Figure 2 of Schmitz et al. (1997); note the position of the Benthic Foraminiferal Extinction Event (BEE).

Figure 2. $\delta$13C against wt% CaCO3 for samples taken below and through the onset of the SU (-4.02 to 0.95 m). Key samples labelled with depth in the section.

Clare, M. A., Talling, P. J., and Hunt, J. E., 2015, Implications of reduced turbidity current and landslide activity for the Initial Eocene Thermal Maximum - evidence from two distal, deep-water sites: Earth and Planetary Science Letters, v. 420, p. 102-115.

Schmitz, B., Asaro, F., Molina, E., Monechi, S., Salis, K. v., and Speijer, R. P., 1997, High-resolution iridium, d13C, d18O, foraminifera and nannofossil profiles across the latest Paleocene benthic extinction event at Zumaya: Palaeogeography Palaeoclimatology Palaeoecology, v. 133, p. 49-68.

Schmitz, B., Pujalte, V., and Nunez-Betelu, K., 2001, Climate and sea-level perturbations during the Initial Eocene Thermal Maximum: evidence from siliciclastic units in the Basque Basin (Ermua, Zumaia and Trabakua Pass), northern Spain: Palaeogeography Palaeoclimatology Palaeoecology, v. 165, no. 3-4, p. 299-320.

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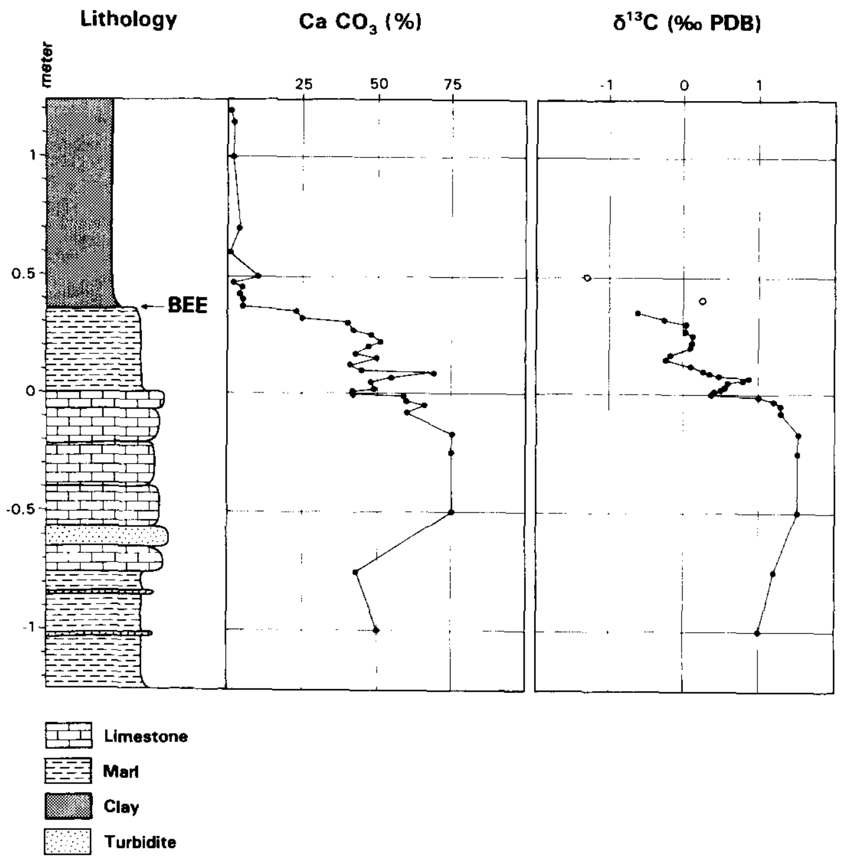


**Fig. 1.**

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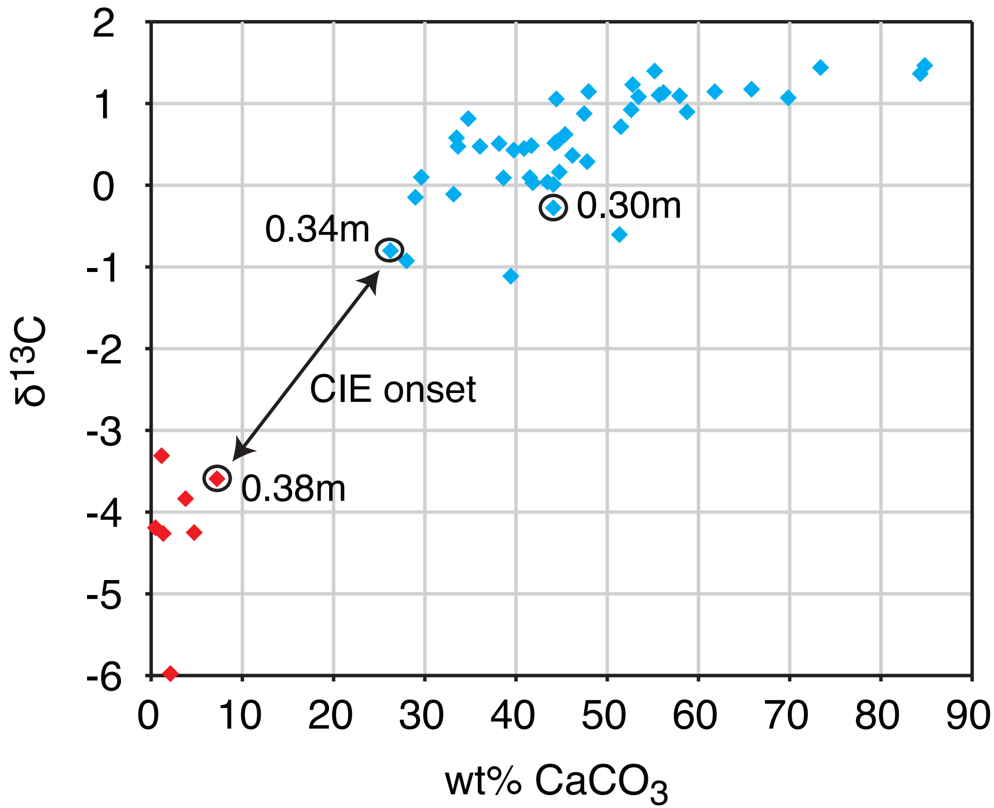
2
1
0
-1
-2
-3
-4
-5
-6
δ13C
0
10
20
30
40
50
60
70
80
90
wt% CaCO3
0.34m
0.30m
CIE onset
0.38m

**Fig. 2.**