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Interactive comment on "Onset of the Paleocene–Eocene Thermal Maximum in the southern Pacific Ocean (DSDP Site 277, Campbell Plateau)" *by* C. J. Hollis et al.

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We are very pleased to receive two very positive reviews of our manuscript. Both referees agree with us that this is an important record in under-studied part of the global ocean. They also compliment us on the multiple proxy approach to analysis of the record and they highlight the challenges in interpreting these proxies, due to the unusual character of the bulk stable isotope record and the variable preservation of the foraminifera. The comments provided by the referees are very helpful in improving on this interpretation. We address the comments of each referee below and conclude with a summary of proposed improvements for the manuscript.

It is important to note, however, that from outset we recognised that this was going to be a difficult record to interpret due to the poor quality of the cores and the diagenetic overprints. Despite these impediments, we felt it was important to report the presence of a PETM at this well-known and much-cited DSDP site. The diagenetic issues are also worth publicising because of plans to re-drill this site as part of IODP Proposal 567 (Paleogene South Pacific APC Transect). Whilst new coring technology is likely to greatly improve recovery from this site, the recovered records are still expected to be compromised by diagenesis, limiting the site's usefulness for climate reconstruction.

Response to Referee 1 (Paul Pearson)

1. Relationship between the d13C record and the "onset" of the PETM

We admit that we have used the term "onset" too loosely in this article. Strictly speaking we argue that the recovery interval is missing, and so what is preserved is the onset plus at least part of the core of the PETM. We will revise use of "onset" throughout the text. However, we still contend that the bulk d13C record is consistent with a relatively complete PETM. There is certainly an interval below the PETM where carbonate content is lower than background for the Paleocene, but the d13C is very stable through the upper 50 cm of Paleocene sediment, with no evidence for "burn down" affecting the d13C record and hence no basis to infer a hiatus at the base of the PETM. The stepped decrease in d13C that occurs between the true onset at 457.27 mbsf and the core of the PETM at 457.1 mbsf is not that unusual. As well as Mead Stream, it has been widely discussed for ODP Site 690 (Bains et al., 1999; Stoll, 2005; Zachos et al. 2005; Sluijs et al. 2007), and has led to speculation that the PETM carbon release may have occurred in pulses (Sluijs et al., 2007). A point that we hope to emphasise in the revised MS is that the three steps in the CIE at DSDP 277 correspond reasonably well with the three maxima in Mag Sus and Fe. Therefore, we can be reasonably confident that we have CIE steps A-C of Zachos et al. (2005) that span cycles 1-3 of Röhl et al. (2007), and therefore our PETM interval probably spans the interval from the base of cycle 1 to the top of cycle 4 or the first ~87 Ma of the PETM (Röhl et al. 2007).

Stoll (2005) has shown that the bulk carbonate d13C is a good representation of the coccolith record at ODP 690, which also has a stepped CIE.

Differences between the bulk carbonate and single foram signals for the PETM are also well known at ODP 690. As at DSDP 277, Acarinina records a strong CIE at the onset of the PETM. Stoll (2005) has an extensive discussion on this topic but no definitive answer. All we need to say here is that Site 277 is not unusual in having a stepped bulk carbonate CIE. This is why we focus more on the much more pronounced bulk carbonate oxygen isotope excursion (OIE).

We tend to agree with the referee's comment that the fact the PETM is a warming event is often overlooked. Nevertheless, since first identified, the PETM has consistently been defined by the carbon isotope excursion (CIE) that provides a less ambiguous way of correlating the event between geographic regions and of subdividing components of the event than the variable oxygen isotope excursion or other climate proxies (e.g. Bains et al., 1999; Zachos et al., 2005; Sluijs et al., 2007; McInerney and Wing, 2011; Dunkley Jones et al, 2013). The P/E boundary is defined by the CIE (Luterbacher et al. 2000), not the associated temperature shift or other climate-related phenomena. There are many locations world-wide where the location of the PETM is fixed only by the CIE, with very little known about the accompanying changes in temperature. It is also worth making the point that in the case of modern global warming, associated climate change exhibits considerable geographic variation whereas the steady increase in atmospheric CO2 is uniform across regions. This is nicely demonstrated by the compilation undertaken by Dunkley Jones et al. (2013).

2. Foram preservation and diagenesis

We are forced to admit that upon review of our SEMs, all the forams in this record are affected by diagenesis, with clear evidence of overgrowths and recrystallisation. We cannot confidently use visual examination as a basis for stating that the forams in the PETM are any better preserved than below or above the PETM. The "stringent" criteria referred to in the text relates to geochemical criteria. Specifically in relation to diagenesis, this means we have not used specimens or parts of LA-ablation profiles with Sr/Ca values lower than 0.8 or higher than 1.6 in the determination of paleotemperatures from Mg/Ca ratios. Following the recommendation of Referee 2, we have constructed cross-plots to show how these criteria are applied (Fig. R1).

These cross-plots explore the relationship between Mg/Ca ratios, silicate contamination and diagenesis. The full dataset consists of average elemental ratios across selected integrated laser ablation profiles (visually screened for the effects of silicate contamination and diagenesis). This dataset has been first plotted as cross-plots of Al/Ca and Mg/Ca for Cibicides and Acarinina (the only two genera that have records spanning the entire studied interval). The data have been colour coded to differentiate samples from within the PETM and the pre-PETM interval extending down to 462.2 m. A significant linear correlation is observed for both genera, confirming that silicate contamination results in anomalously high Mg/Ca values where Al/Ca >4 (3.4 and 3.7 being the calculated screening limits with method explained in the MS). For Cibicides, silicate contamination is seen to be more common within the PETM than in the pre-PETM interval or elsewhere in the record. This is consistent with other evidence for an increase in clay within the PETM. This pattern is also evident for Acarinina but Al/Ca values are generally higher and more pre-PETM samples show evidence of silicate contamination. This may reflect differences in morphology, with the smoother surface of Cibicides providing fewer opportunities for clay particles to become fixed to the test wall. The second set of cross plots consists of data that has first been screened for silicate contamination using the screening limit of Al/Ca > 3.4 or 3.7. The Sr/Ca ratio is used as a proxy for diagenesis, with the typical ratio in Eocene foraminifera being 1 to 1.4 (Creech et al., 2010) and the values < 0.8 or > 1.6 are considered to reflect dissolution or recrystallization (Eggins et al., 2003; see also Kozdon et al., 2013). Linear regression lines are shown for the three groups and the correlation co-efficient is added where it is significant. For Cibicides, most values lie within the screening limits but there are some significant differences in the clusters of PETM and pre-PETM samples. First, we note that the overall trend for all the samples is roughly horizontal, suggesting that the Sr/Ca ratio is generally stable around ∼1 for varying Mg/Ca. However, we observe that there is a weak negative trend and stronger and steeper negative trend for PETM and pre-PETM samples, respectively. This suggests that diagenesis has a significant effect on pre-PETM Mg/Ca values for Cibicides, and may also have a small effect on PETM values. The net effect would be to introduce a warm bias to pre-PETM temperatures, and possibly also to some PETM temperatures.

For Acarinina, a clearer relationship is observed between Sr/Ca and Mg/Ca. The effects of diagenesis appear more evident, overall, probably reflecting the thinner test and greater surface area relative to the smooth walled Cibicides. The overall trend is consistent with predictions and observation form other studies: a negative correlation indicates that as diagenesis progresses Sr/Ca decreases and Mg/Ca increases (Eggins et al. 2003; Kozdon et al. 2013). The slope of the trend lines indicate that the pre-PETM interval is most affected by diagenesis, and the PETM is the least affected. As for Cibicides, this implies that temperatures based on the Mg/Ca are significantly overestimated in the pre-PETM interval and also, but to a lesser extent, overestimated in the PETM.

In summary, we have shown how screening has been applied to exclude samples with significant levels of silicate contamination and diagenesis. We have shown that diagenesis tends to be higher in the pre-PETM interval than in the PETM. We have shown that Acarinina is more affected by both silicate contamination and diagenesis than Cibicides. And we have shown how diagenetic effects may affect temperature estimates (even for samples within the screening limits), probably overestimating pre-PETM temperatures relative to the PETM.

Therefore, although we lack visual evidence to support our hypothesis that the extreme OIE at the "onset" of the PETM in this record is an artefact of preservation changes across the P/E boundary, we do have geochemical evidence in the form of Sr/Ca ratios. In addition we observe and increase in the d18O gradient between bulk carbonate and

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benthic foraminifera: from <0.6 in all but one sample below the PETM to >1.1 in 2 of 3 samples within the PETM. A low gradient is also observed above the PETM (0.23 – 0.42).

We have added a figure (Fig. R2) to show the general distinctions between moderate and poor preservation, based on SEM images and LA-ICPMS profiles, but acknowledge that others may term these preservation states, poor and very poor.

In relation to the specific comments on the text:

P. 246: Correct: insert "is inferred to have".

P. 250. Correct. Move the text from Mg/Ca methods to this location, and revise to say. "Individual specimens from five foraminiferal genera were used for stable isotope analysis and elemental geochemistry. Specimens were selected for analysis based on visual assessment of their preservation under a stereo microscope. Wherever possible, analyses were performed on Morozovella aequa, Acarinina coalingensis, Subbotina patagonica, S. roesnasensis, and Cibicides proprius/praemundus. The following species were substituted when these species were not available: Morozovella subbotinae, M. acuta, M. apanthesma, Acarinina soldadoensis, A subsphaerica, A. esnaensis, A. nitida and Cibicidides tholus. The stable isotope signature of Acarinina soldadoensis, A subsphaerica, A. nitida and all species of Morozovella indicates they were mixed layer dwellers (Olsson et al., 1999; Quillévéré and Norris, 2003), and therefore are appropriate indicators of near surface conditions. Subbotina patagonica is inferred to have had a deep planktonic habitat (Pearson et al., 2006), within the thermocline. There is no data on the habitat of S. roesnasensis."

Delete lines 8-11 on p. 251.

P. 256. The zones are missing, so they are not shown on Fig. 2. An unconformity is shown to lie between NP6 and NP9, which is consistent with the text.

P. 256. Include something on forams. Yes, this important text to be added after line 8,

p. 256. “The genus Morozovella has its lowest occurrence at the base of the PETM and greatest diversity within the PETM. Two species of Morozovella are restricted to the PETM: M. aequa and M. velascoensis. The latter species has rarely been found outside the PETM in the SW Pacific but M. aequa ranges into the middle late Eocene on mainland New Zealand (Hornibrook et al. 1989).”

P. 257. There are two few cycles present for spectral analysis or to conclude that there are four obliquity cycles. However, we have commented earlier on the likelihood that that they correspond to the precession cycles described by Röhl et al. (2007).

P. 258. Reword statement of duration of onset to: the lower rate is consistent with the duration of the interval from the base of the PETM to the base of Cycle 5 (87 kyrs).

P. 260. Unnecessary sentence to be deleted.

P. 262. Incoming of Morozovella and diversity of the genus to be noted here.

Referee 2 (Reinhard Kozdon)

The referee asks that we give greater consideration to the potential impacts of diagenesis on Mg/Ca, d18O and d13C. We have addressed this in our response to Referee 1, who made a similar general comment.

We propose to revise the wording of the text referred to (p. 250, ln 6) as noted above. It is important to note that the aim of the foraminiferal isotope analysis was to provide constraints on the bulk isotope and Mg/Ca data. Based on the relatively poor preservation of the material, we fully expected to find the data somewhat compromised by diagenesis. We recognise that there may well be scope for further detailed work on the isotopic character of the foraminifera in this record of the type that the referee has pioneered, but this is outside the aims of the current study.

For LA-ICPMS analysis, we recognise that the methodology outlined on pp. 251-253 can be improved to clarify that we followed exactly the approach the referee recommends. After visual examination and cleaning, specimens were ablated. The LA depth

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profiles were then carefully screened to identify and exclude zones of contamination, diagenesis, or elemental anomalies of uncertain origin (see Fig. R2). After this process, average values were determined for the selected segments on the profiles, not the entire profiles (Data plotted in Fig. R1). Further screening was then performed on these average values to derive the Mg/Ca values used for temperature reconstructions (Fig. 3 of MS). We agree that further study should be undertaken on the profiles to directly quantify diagenetic variation through this interval. However, this is outside the scope of the current study.

Response to other comments: We have added Mn/Ca and Ba/Ca plots to Fig. 3 but they don't add much to the record as they show very similar trends to Al/Ca. Perhaps include in the supplementary material?

We found the suggestion of adding cross-plots most helpful. Although they were part of our working files, we have not interrogated them sufficiently and are very pleased to see how well they appear to resolve questions relating to diagenesis (Fig. R1)

P. 259 (23-29). We agree that our results are in good agreement with Kozdon et al. (2013) , with very similar relationships between Sr/Ca and Mg/Ca, and an order of magnitude lower than the changes observed in laboratory experiments (compare our Fig. R1 with Kozdon et al. 2013, Fig. 6).

Page 259, ln 22. Noted.

Fig. 4d. We thought it unnecessary because Mg/Ca is shown in Fig. 4c and d18O in Fig. 2 but yes, it's possible (at least for d18O).

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Caption to Figure R2 Scanning electron microscope (SEM) images of moderately and poorly preserved foraminifera specimens from DSDP Site 277 and corresponding trace element/Ca profiles through the test wall. A) moderately preserved Morozovella aequa. The profile selected during the screening process is highlighted by the grey bar. Note the elevated trace element/ca ratios on the exterior of the test and the increase in Al/Ca ratio on the interior of the test. Ti/Ca displays a patchy distribution as it is approaching the resolvable limit. B) Moderately preserved Acarinina and the corresponding trace element/Ca profile. C) Moderately preserved Subbotina and trace element/Ca profile. D) Moderately preserved Cibicides eocaneus and trace element/Ca profile. E) Poorly preserved Morozovella aequa, showing evidence of sediment infilling, and calcite overgrowths, with calcite rhombs on the test exterior apparent near the base of the image. Trace element/Ca ratios are substantially elevated above those of biogenic calcite, and note the unusual Ba/Ca profile. F) Poorly preserved Acarinina displaying coarsely crystalline diagenetic outgrowths. G) Poorly preserved Subbotina specimen with a ‘chalky’ outer appearance. Note the Ba/Ca peak. H) Poorly preserved Cibicides truncatus, displaying a coarse, granular texture uncharacteristic of this species, and attributed to micron-scale recrystallization.

Interactive comment on Clim. Past Discuss., 11, 243, 2015.

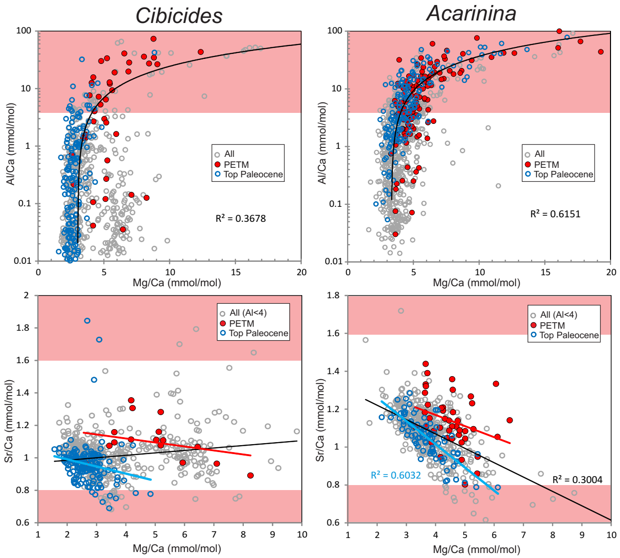

Figure R1

Fig. 1. Figure R1. Cross-plots of Mg/Ca, Al/Ca and Sr/Ca

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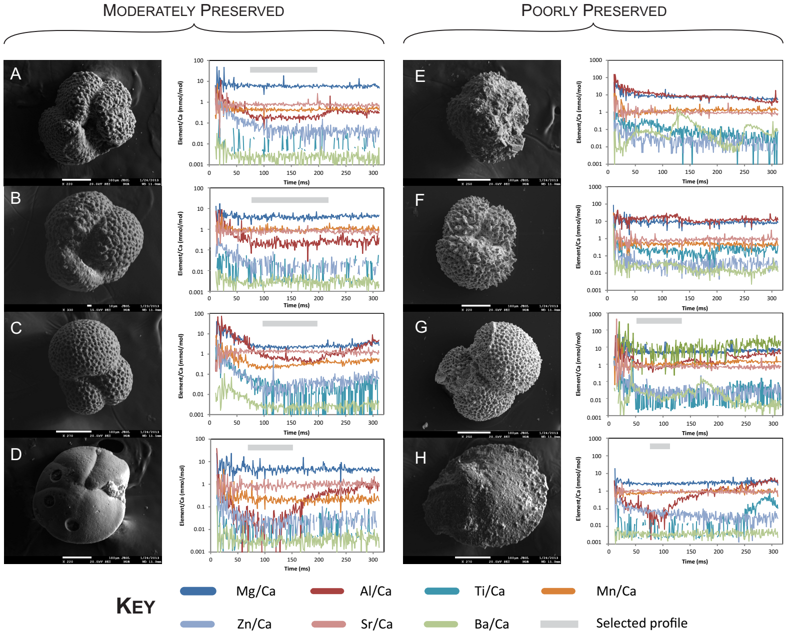

Fig. 2. Figure R2. Scanning electron microscope (SEM) images of moderately and poorly preserved foraminifera specimens from DSDP Site 277 and corresponding trace element/Ca profiles through the test wall

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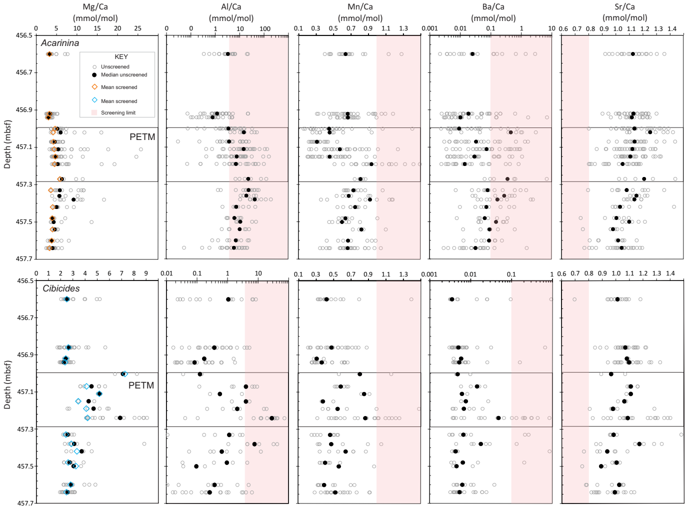

Figure 3 (revised)

Fig. 3. Figure 3 (revised), Ba/Ca and Mn/Ca profiles added

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