Response to "Interactive comment on the manuscript "Alluvial record of an early Eocene hyperthermal, Castissent Formation, Pyrenees, Spain" by Louis Honegger et al."

Louis Honegger et al.

In this response, the original comments are in black and responses by the authors to the reviews are written in blue. Changes in the manuscript are written in red.

We thank Referee #2 for their careful review that has allowed us to clarify several important points and improve the manuscript.

1. The title of the manuscript (Alluvial record of an early Eocene hyperthermal, Castissent Formation, Pyrenees, Spain) is misleading: When I first read it I though the authors meant that the Castissent Fm had resulted from the effects of an hyperthermal – which would be impossible. I therefore suggest something like: Alluvial record of an early Eocene hyperthermal within the Castissent Formation, Pyrenees, Spain.

We agree with the reviewer. Indeed the Castissent fm cannot be associated with an hyperthermal in its entirety because its duration of ca. 500 ka is much longer than any of the known hyperthermals of that period (between 50.5 and 49.7 Ma, i.e. S, T, U, V.). Therefore, we agree that the title could be somewhat misleading in that respect and we will follow the suggestion of the reviewer to modify the manuscript title:

"Alluvial record of an early Eocene hyperthermal ***within the*** *Castissent Formation, Pyrenees, Spain"*

2. In lines 36−40 they state that "The results show that even relatively small-scale hyperthermals compared with their prominent counterparts, such as PETM, ETM2 and 3, have left a recognizable trace in the stratigraphic record. . .". The environmental effects of the above-mentioned hyperthermals in terrestrial setting, especially those of the PETM, are very prominent (e.g., Foreman et al, 2012), a fact that made their record easily recognizable in the field. For the alleged U event (NCIE D) the information provided does not justify the above assertion. Thus, in Fig. 7 the event seems to be represented by a comparatively thin interval (<1 m), whereas the previous NCIE C, which is of smaller magnitude, is recorded by a ∼3 m thick interval. A better documentation of the sedimentological features of the alleged U event is needed, as it is the focus of the study. It would also help if such (distinctive?) features could be observed in other section(s).

This sentence in the abstract can indeed be misleading with respect to the nature of our results. In our text, "recognizable ***trace****" simply referred to the geochemical signature of the event, and not to its sedimentological "recognizable trace" on the field. In the present paper, our main point is to suggest that the U event is marked in the succession by its geochemical signature, which is not trivial given the often-assumed low preservation potential of fluvial* *deposits. Therefore, to reflect this comment of reviewer #2, we propose to change the sentence to:*

Line 39: "The results show that even relatively small-scale hyperthermals compared with their prominent counterparts, such as PETM, ETM2 and 3, have ***can leave*** *a recognizable* ***signature*** *in the* ***terrestrial*** *stratigraphic record. . ."*

About the point made by the reviewer on the correlative character of this event in other sections: we agree that it would help to distinguish the same signature in coeval successions in order to support the regional (supra-regional) nature of the driver behind the excursion. However, unfortunately, we have not yet assembled sufficient data to assess this into other sections laterally. Distinctive red intervals within the Castissent Fm do occur in the Isábena valley (Marzo et al., 1988) *but we are not yet in a position to say if those correlate with the negative CIE observed in the Chiriveta section, primarily because of a lack of temporal constraints at this resolution. We currently collaborate on developing a magnetostratigraphic frame for these deposits, but the results of this endeavour are beyond the scope of the present study.*

3. Constraint on the age of the Castissent Fm is somewhat vague. It is not based on data from the Chiriveta section itself, but on bio- and magnetostratigraphic studies of previous authors (Kapellos and Schaub, 1973; Bentham and Burbank, 1996), carried out in the Campo section, 40km westward. Based on them the authors indicate that the Castissent Fm occurs within the D. lodoensis nannoplankton zone (= NP 13), with the base and top of the nannozone being respectively situated at ca 200 m below the base of the Castissent, and at ca 100 m above its top. My doubts about the reliability of the Kapellos and Schaub zonation (1973) partly stem from the fact that shallow marine facies such as those of the Campo section are not favorable for the preservation of nannofossils, and that therefore are not entirely reliable. The NP9/NP10 boundary provides a proof of this, for K & Sch073 did situate it ABOVE the so-called Alvelina limestone, while Orue-Etxebarria et al. (2001; Marine Micropaleontology 41, 45-71) proved that it occurred BELOW such unit, a finding that permitted to correctly place the PETM interval in the Campo section (see Fig. 1 of this Comment). More to the point, as shown also in Fig 1, the location of the top NP 13 zone is somewhat ambiguous: K & Sch073 state in their text that the NP 13 zone spans from km 58.6 (base) to km 56 (top), whereas in their columnar section the top of the zone is placed at sample 32. Such uncertainty raises doubts about the magnetostratigraphic calibration of Bentham and Burbank (1996), likely based on the K & Sch073. Indeed, in Fig. 3 of the manuscript the NP13/14 boundary is placed within the C22n magnetozone, whereas in Fig. 1 (from Westerhold et al, 2017) is located within C23r.

Defining with confidence the age of the fluvial Castissent formation is indeed a challenge. The question of the age model of the Castissent is also raised by reviewer #3.
The only time-constraint available for the study location itself is that of remains found in the Chiriveta area and belonging to European Mammals zone MP10 (Badiola et al., 2009). In order to better constrain independently the Chiriveta section itself, we studied the option of U/Pb

dating on pedogenetic carbonate nodules; however the analysis error of recent work (Methner et al., 2016) lays between 0.8-1.4 Ma, which is critical on our 0.8 Ma interval.

We therefore rely, as mention by Reviewer #2, on bio- and magnetostratigraphic studies of previous authors carried out in the Campo section, 40km westward such as Kapellos and Schaub, (1973) and Bentham and Burbank (1996) as well as Marzo et al. (1988), Tosquella (1995) and Payros et al. (2009).

Reviewer #2 points out the difference of the position of the NP13/NP14 regarding magnetozone C22n in our figures 1 and 3. In figure 3 of our manuscript, the limit between NP13 and NP14 is placed within Chron C22n based on the available data in this section (i.e., biostratigrafic data from Kapellos and Schaub 1973 (K&Sch73) and the magnetozones of Bentham and Burbank 1996 (B&B96)). As mentioned by reviewer #2, this is not in line with Fig. 1 which show the location of NP13/NP14 at the base of C21r as reported in GTS 2012. This difference had already been observed by Payros et al., (2009) (their figure 9). Although the position of the above-mentioned limit is disputable and based on available data, it doesn't affect the upper part of our age model because, to constrain the Castissent Formation, we use the limit between C22r and C22n which is below NP13/NP14 in both models and is at 49.695±0.043 Ma according to the recent astrochronologic age models of Westerhold et al. (2017).
Reviewer #2 further raises a concern about the validity of B&B96 magnetostratigraphy in the Campo section because "the calibration of Bentham and Burbank (1996), [is] likely based on the K & Sch073". We note however that the work of K&Sch73 is not cited in the paper of B&B96, so it is not clear to us to what extent the magnetostratigraphic age model of B&B96 should be taken with caution. For instance, B&B96 place the base of the Campo section, and the so-called Alveolina limestone, in C24r. According to the updated biostratigraphy of this section cited by reviewer #2 (Orue-Etxebarria et al., 2001), the Alveolina limestone is deposited during NP10, which is still in C24r. We therefore consider that the magnetozone interpretation of B&B96 in this section may still be valid, although we are open to more data and constraints if available.

However, for the lower time-constraint of the Castissent formation used in this study (i.e., the limit between NP12 and NP13 at ca. 50.5), we rely on the biostratigraphy work of K&Sch73, Tosquella (1995) and Payros et al. (2009).

In figure S2, we however investigate several correlation options encompassing different climatic scenarios in the time-interval inferred by the bio- and magnetostratigraphic studies of previous authors in order to suggest the most plausible correlation between global and local isotopic record.

Considering these observations, we will modify the paragraph as follow and added a supplementary Table (S1) regarding slope estimation:

*Line 115: "**In the Chiriveta location, stratigraphic constraints are limited to the identification of European Mammals zone MP10 (Badiola et al., 2009), which gives an age range of between 50.73 to 47.4 Ma (GTS2012). This age span is refined by bio- and magnetostratiphic data from the Castissent Fm. outcrops of the Campo location, about 40 km further west***

(Bentham and Burbank, 1996; Kapellos and Schaub, 1973; Payros et al., 2009; Tosquella, 1995; Tosquella et al., 1998) (fig. 3). *Because of its outcropping extent, the Castissent Fm. has been mapped from west to east across these sections (Chanvry et al., 2018; Nijman, 1998; Nijman and Nio, 1975; Poyatos-Moré, 2014)****. The low slope of the Castissent Fm. (ca. 2.3 × 10^{-4} m/m, see supplementary Table S1) indicate an elevation drop of ca. 1 m between the Chiriveta section and the Campo section. Given an average flow depths of 3.75 m in the Castissent channels based on measurement in the Chiriveta and La Roca sections, we thus assume no significant time-lag of deposition between both sections.***

[…]

Line 139: ***Considering the data available and their resolution, we suggest a depositional age span*** *between* ***50.5*** *and* ***49.7*** *Ma for the Castissent Fm (reported in green on Fig. 1)."*

4. The completeness of the studied section is debatable In the first paragraphs of chapter 5.4 ("Preservation potential of hyperthermals in continental sections"), the authors acknowledge that alluvial-fluvial stratigraphic records are considered incomplete by many authors (e.g., Shanley and McCabe, 1994; Wright and Marriott, 1993; Turner et al., 2015; Barrell, 1917; Sadler, 1981). In the present case, Marzo et al. (1988) concluded that "The sedimentation of the Castissent Formation was structurally controlled by an interplay of vertical basement movement due to thrust stacking in the hinterland and surficial thrust displacement to the foreland resulting in alternating southward and northward shift of the fluvial system". The Chiriveta section is close to the foreland thrust (Montsec thrust) and, in such dynamic scenario, it is doubtful that it would have accumulated a (near) continuous succession. But, even if that were the case, it seems rather improbable that the section would be complete enough to have recorded ALL the minor NCIES detected in the ODP 1263 site, as shown in Fig. 7.

Referee #2 refers, rightly, to a long-standing debate in Earth sciences: the completeness of the stratigraphic record. This debate is beyond the reach of our study, but we want to contribute because we believe that our findings, if correct, may suggest that alluvial records may be less punctuated than sometimes considered. There are two aspects here in the reviewer comment that we wish to respond to: 1) the inherent incompleteness of fluvial stratigraphy, and 2) incompleteness due to structural deformation in an active basin.

1. *To assess whether it was plausible or not that the Castissent Fm. recorded hyperthermal events, in the second part of chapter 5.4, we calculated the compensation time scale (Tc) of the formation, which represents an estimate of the autogenic time-scale of the fluvial system linked to avulsion processes (Wang et al., 2011) . The Tc obtained for this study is of 22,000 yrs, i.e. twice as short as the inferred duration of the hyperthermal U and smaller CIEs preceding it, which have typical durations of ca. 40,000 yrs. According to this perspective, it is therefore not unrealistic that such "events" are recorded in the Castissent fm. We also develop this point in our response to referee #1.*
2. *Based on paleogeographical reconstructions, the Castissent Formation, at the Chiriveta section, is deposited near or at the axis of the Tremp-Graus basin, transported on the back of the Montsec thrust and approximately 4km away from the thrust emergence (Nijman, 1998). In this area, subsidence is the highest, with rates of between 0.1 and 0.29 mm/yr (this study and Marzo et al., 1988). This represents between 50 and 150m of accumulation during the Castissent time interval (0.8 Ma).*

> *Based on an inferred total horizontal displacement of the Montsec of 7 km (Whitchurch et al., 2011, Farrell et al., 1987), a period of activity lasting 26 Ma (Whitchurch et al., 2011) and a thrust dip between 6° and 20° (Clevis et al., 2004), we estimate a vertical movement of between 25 and 90 m during the Castissent time-interval. This vertical displacement is thus no more than equal to sedimentation rate in the basin axis. This is consistent with the general absence of growth strata in the basin axis, although growth strata can indeed be observed closer to the Montsec.*

In conclusion, the rates of accumulation, distance to the main structures, and characteristic compensation time scale together suggest that hyperthermal events of ca 40ky duration can be plausibly recorded in the Castissent Fm, despite its situation in a tectonically active fluvial basin.

We agree with referee #2 comment, which is complementary to some of referee #1's comments and we will therefore develop and reorganize chapter 5.4 consequently.

Line 398:
"5.4 ***Possible implication for the*** *preservation potential of hyperthermals in continental deposits"*

Lines 399 to 406 were removed

Lines 406:
"Major events such as the PETM event have proven to be detectable in both marine and continental environments (e.g.; Abels et al., 2016; Koch et al., 1992), but the signal and preservation potential of smaller scale climatic events (e.g. hyperthermal events L to W in Lauretano et al., 2016), ***may be more difficult to detect*** *(Foreman and Straub, 2017****) because of the inherent highly dynamic nature of sedimentation in fluvial deposits****.* ***To address this issue in the present case study****, we calculated the compensation time scale (Tc)* ***of the Castissent Fm****."*

Lines 419 to 424 were removed

Line 424:
"Using an average sedimentation rate of 0.17 ***mm/yr and an average channel depth of 3.75m,*** *we obtained a mean Tc of 22,000 yrs****, which means that*** *hyperthermal events of 40 kyrs* ***duration (time-scale of hyperthermal U and preceding CIE) have the potential to*** *be recorded* ***despite fluvial system dynamics****."*

Line 427:
"Our estimate of preservation potential assumes steady sedimentation rates throughout the section. But, sedimentation in terrestrial records is not uniform (steady) but rather highly variable, resulting in spatial and temporal changes in facies and deposition rates ranging from < 0.1 to 1-2 mm/yr (Bowen et al., 2015; Kraus et al., 2015; Marriott and Wright, 1993). However, mean accumulation rates give a reasonable estimate approximating more realistic (i.e., variable) sedimentation rates as observed in the Bighorn Basin (Bowen et al., 2015).

Additionally, we analyse the vertical movement of the nearby structures to evaluate their potential influence on disrupting deposition at Chiriveta during Castissent times. The Chiriveta section was deposited near or at the axis of the Tremp-Graus basin (Nijman, 1998), which is bounded by the Bóixols thrust in the north and the Montsec thrust in the south (Marzo et al., 1988). The Tremp-Graus basin is transported as a piggy-back basin on the Montsec thrust emerging at the time approximatively 4 km south of the studied section (Nijman, 1998). In the basin axis, subsidence is the highest with rates of 0.1 to 0.29 mm/yr (this study and Marzo et al., (1988)). Taking into account a vertical movement rate of the Montsec thrust of 0.03 to 0.1 mm/yr during the Castissent time-interval (based on a horizontal displacement of 7 km, a period of activity lasting 26 Ma and a thrust dip between 6° and 20° (Clevis et al., 2004; Farrell et al., 1987; Nijman, 1998; Whitchurch et al., 2011), we estimate that the vertical displacement is no more than equal to sedimentation rates in the basin axis. This is consistent with the general absence of growth strata in the basin axis, although growth strata can indeed be observed closer to the Montsec (Nijman, 1998).
The rates of accumulation, distance to the main structures, and characteristic compensation time scale, together suggest that hyperthermal events of ca. 40 kys duration can be recorded in the Castissent Fm. These results confirm that, despite its highly dynamic nature, fluvial sedimentation may contain valuable record of high-frequency events, even in active tectonic contexts."

Lines 448 to 458 were removed

5. Section 4.1 of the manuscript ("Overview 0f the Castissent Fm at the Chiriveta section) seems to be misplaced. I suggest to remove it from the Results section and place it after the Chapter 2, Geological setting.

We understand Reviewer #2's point of view as section 4.1 didn't specified enough that the section logged in this study is not based on a previous work. We would however prefer to keep this section at its current place because we think our description is an integral part our study. We will modify the title and introduction of section 4.1 to stress this point.

Line 203:
"4.1 ***Sedimentology of the Castissent Formation at Chiriveta***
We here describe the section logged and sampled in this work (Fig. 4). At Chiriveta*, the Castissent Fm. is a paleosol-rich succession, which shows greyish-yellow…"*

6. I have not had the time to check out all the references, but in a quick glance I can point out that some of them are incomplete:

   Hunger, T.: Climatic signals in the Paleocene fluvial formation of the Tremp-Graus Basin, Pyrenees, Spain. University of Geneva., 2018. Is that a Thesis? How many pages? It is published or unpublished?

Completed.
It's a master thesis, published on the open archives of the University of Geneva. It is however not an open access document.

The correct reference reads:

Hunger, T.: Climatic signals in the Paleocene fluvial formation of the Tremp-Graus Basin, Pyrenees, Spain, MSc Thesis, University of Geneva, pp. 123. https://archive-ouverte.unige.ch/unige:124264, 2018

Poyatos-Moré, M.: Physical Stratigraphy and Facies Analysis of the Castissent Tecto-Sedimentary Unit., 2014. Is that a Thesis? If so, from which University? How many pages? It is published or unpublished?

Modified. It's a PhD thesis.

The correct reference reads:

Poyatos-Moré, M.: Physical Stratigraphy and Facies Analysis of the Castissent Tecto-Sedimentary Unit, PhD Thesis, Universidad Autónoma de Barcelona, pp. 284. https://ddd.uab.cat/record/127119, 2014

The list of authors of the reference "Payros, A. and Tosquella, J.: Filling the North European Early/Middle Eocene (Ypresian/Lutetian) boundary gap: insights from the Pyrenean continental to deep-marine record, Palaeogeogr. Palaeoclimatol. Palaeoecol., 280, 313–332, doi:10.1016/j.palaeo.2009.06.018, 2009" is incomplete. Either include all the authors (Payros, A., Tosquella, J., Bernaola, G., Dinarès-Turell, J., Orue-Etxebarria, X., and Pujalte, V.,), or quote it as Payros, A., Tosquella, J, et al.

Thanks. Modified

7. Some previous papers should be referenced. In lines 60-63 the manuscript states that "In coastal marine sections, Early Eocene hyperthermal events are generally associated with an enhanced flux of terrigenous material, interpreted as linked to accelerated hydrological cycle and higher seasonality (Bowen et al., 2004; Dunkley Jones et al., 2018; Nicolo et al., 2007; Payros et al., 2015; Slotnick et al., 2012): : :" To my knowledge, one of the first paper pointing out this fact was: Schmitz, B., Pujalte, V., Núñez-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. Palaeogeogr. Palaeoclimatol. Palaeoecol. 165, 299–320

This is correct. Thanks for noticing. We have added this reference to the manuscript.

In lines 63-65 the manuscript states that "Several studies document a spatially heterogeneous hydrological climatic response during the PETM (Bolle and Adatte, 2001; Carmichael et al. 2017; Kraus and Riggins, 2007)". The paper by Giusberti, L., Boscolo Galazzo, F., Thomas, E., 2016. Variability in climate and productivity during the Paleocene–Eocene Thermal Maximum in the western Tethys (Forada section). Clim. Past 12, 213–240, should be acknowledged, as their compilation made evident such climatic variability.

Thank you for pointing out this study. We added this reference to the manuscript.

It was as well added line 386:

"Such a climatic behaviour, was already described for the PETM, during the pre-onset excursion (Bowen et al., 2014) ***and in the core CIE of the PETM (Giusberti et al., 2016)****…"*

Several typographical corrections, sentence reformulations and minor precisions have as well been implemented in this second version of the manuscript. Below are listed the majors ones.

Line 250:
A sub-chapter ***5.1.1 Identifying the CIE*** *was added.*
Line 251:
"In continental successions, the carbon isotope composition of pedogenic carbonate nodules—which consists of calcareous concretions between 1 mm and 4 cm diameter formed in situ in the floodplain— ***have been shown to be sensitive to environmental conditions during their formation (e.g., Millière et al., 2011a, 2011b), and are therefore a promising tool to track how environments respond to carbon cycle perturbation*** ~~*have been proven to reflect global δ13C variations (Abels et al., 2016; Koch et al., 1992; Schmitz and Pujalte, 2003), and may therefore be considered, sometimes together with the oxygen isotope composition (δ18O), as reliable proxy for environmental condition occurring during their formation (e.g., Millière et al., 2011a, 2011b).*~~ *The carbon isotope composition of the soil carbonate nodules depend on the δ13C value of the* ***atmospheric CO2 and*** *soil CO2, which in turn is a function of the δ13C of the atmospheric CO2 ,****and*** *the overlying plants, as well as* ***the*** *soil respiration* ***flux and the partial pressure of atmospheric CO2*** *(Abels et al., 2012; Bowen et al., 2004; Caves et al., 2016; Cerling, 1984). "*

Line 267:
"…nodules, ***which*** *is consistent with* ***a large compilation of data from eastern Eurasia (Caves Rugenstein and Chamberlain, 2018)****"*

Line 302:
"…varies between 0.1-0.29 mm/y, ***consistent with sedimentation rates reported for other Eocene floodplain successions (Kraus and Aslan, 1993)****."*

Line 307:
A sub-chapter ***5.1.2 Mechanisms causing the CIE*** *was added.*

Line 319:
*"****A release of 500 to 1500 Gt of carbon in the form of methane would imply a marine CIE of 0.8 to 2.3‰ or 0.3 to 0.9‰ if the carbon origin is dissolved organic carbon (DOC) (Sexton et al., 2011). The latter seems more plausible regarding the observed amplitude of ~1‰ measured in the marine record for hyperthermal U (Westerhold et al., 2017) and the supposed origin linked to the oxygenation of deep-marine DOC of post-PETM hyperthermals (Sexton et al., 2011). A global shift of -1‰ in δ13C can however not fully explain the 3‰ shift in δ13C observed in this study.*** *"*