Dear Editors,

We submit a revised version of our manuscript entitled "Alluvial record of an early Eocene hyperthermal within the Castissent Formation, Pyrenees, Spain”.

We followed the referees’ comments, responded to them point-by-point and modified the main text accordingly. Please find attached here the following documents.

1) Point-by-point reply to the comments

2) Marked-up manuscript version

Best regards,

Louis Honegger and co-authors

Response to “Review CP-2019-88 Honegger et al.”

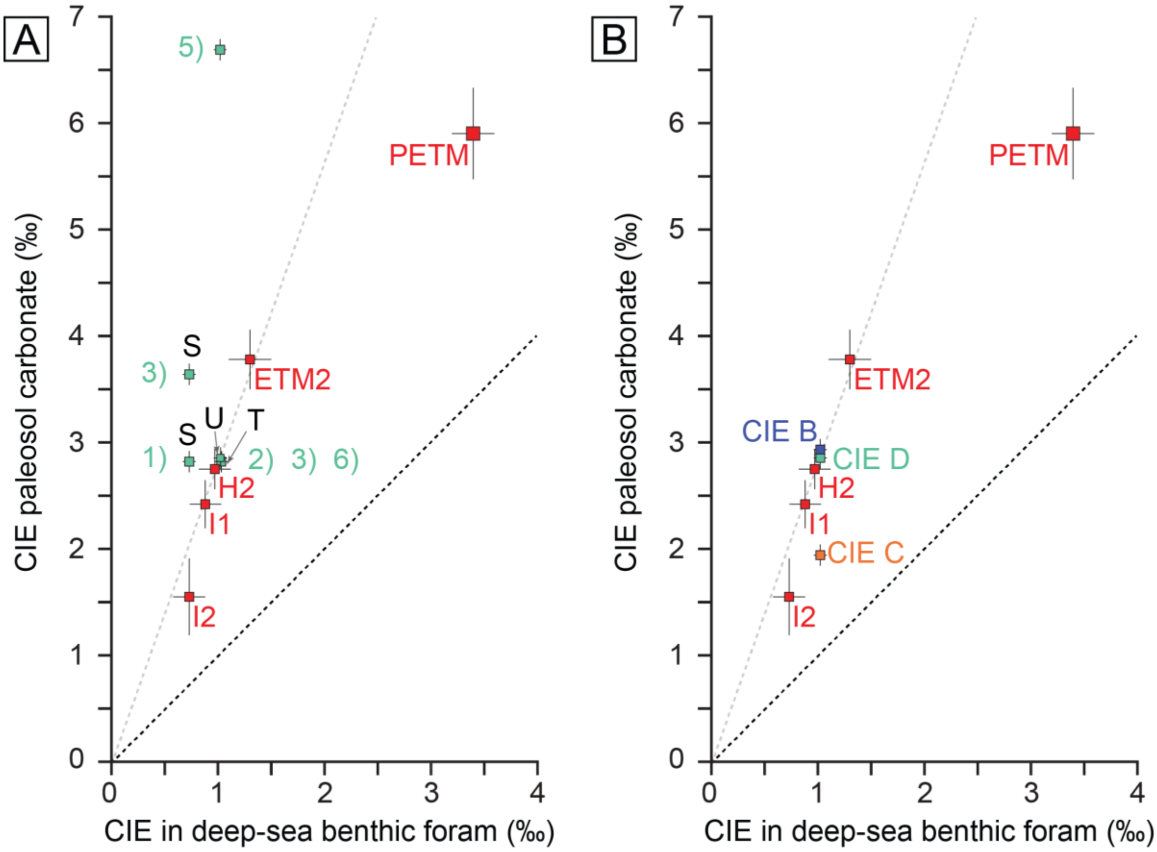
Louis Honegger et al.

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 the reviewer #1 for his work on and appreciation of our study. We greatly value his expertise and views on our study because his work provided some of the motivation for the research questions we are currently pursuing. We answer below point by point to each item raised.

> The only concern is the scaling of the U labeled hyperthermal in the deep sea and the CIE D in the carbonate nodules of the Chiriveta record. How do the events labeled B and C plot in Figure S2? However, the overall pattern in the carbon isotope records of marine and the Chiriveta record match well reinforcing the age model preferred.

Below, please find the modified figure incorporating in inset B, CIE B, C and D plotted regarding the CIE amplitude in soil nodules and in deep-sea into what is now Figure S3 (previously Fig. S2). CIE C is off trend, but both CIE D and B plot in the trend of I1, I2, H2 and ETM2. We favor CIE D as correlative to hyperthermal U because it is the only CIE in our record with a magnitude larger than 2 standard deviation.



The section 5.4 Preservation potential of hyperthermals in continental sections is informing but a bit out of context. It is clear to the community that higher sedimentation rates allow a more detail insight. This section, if kept in the manuscript, also needs to discuss that sedimentation is not uniform (steady) in terrestrial records but highly dynamic (50m away from the section things will look very different, see Bighorn Basin Project results where outcrops studies and drill cores allow a 3D view).

We agree with referee #1's comment that partially echoes similar comments from referee #2.

We will reorganize chapter 5.4 as follow:

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

Abstract Line 23 – Hyperthermal cannot be "potential analogues, in the geological record, to the ongoing anthropogenic modification of global climate". Background conditions 50+ million years ago were much different. But the events can help to test the assumptions made by climate models and revise them for a better understanding of the climate system dynamics.

Thanks. Comparing the geological past with the current situation is often done, but we agree that the analogy has limitations and that the genuine value of investigating hyperthermals must be more clearly exposed. Inspire by the referee's wording of it, we thus propose to change this sentence in the abstract to:
*Line 24: "**Documenting** how the Earth system responded to rapid **climatic shifts during hyperthermals provides** fundamental **information to constrain climatic models.**"*

Line 44-45: remove "towards icehouse conditions eventually reached later in the Cenozoic"

Removed.

Line 48: "Turner et al., 2014" change to Kirtland-Turner et al. 2014 in the entire text

Done

Line 51: "e.g., Westerhold et al., 2018"; add Lourens et al. 2005, Sexton et al. 2011, Kirtland-Turner et al. 2014, Lauretano et al. 2015, 2016. They published the records used.

Modified

Line 52: “Early Thermal Maximum (ETM) 2, H2, I1, I2, and ETM3/X events”– correct to Eocene Thermal Maximum. Change the wording of the sentence to clarify the nomenclature (ETM is only for 1, 2, 3; H1 H2 etc. are from Cramer et al. 2003 revised by Lauretano: : :, Sexton et al. 2011 suggested the relative to magnetochron scheme, see Westerhold et al.). In Figure 1 the text refers to this, please streamline the manuscript text accordingly.

*The sentence was modified accordingly: “**Eocene** Thermal Maximum (ETM) 2 **and 3**, H2, I1 and I2 events.*
Figure 1 was modified with the naming schemes of Cramer et al., (2003), Lauretano et al., (2016) and Westerhold et al., (2017).
The last sentence of chapter 2 was modified to:

*Line 140: “…this period was marked by 4 hyperthermals labelled S**/C22rH3**, T**/C22rH4**, U**/C22rH5** and V**/C22nH1** (**Cramer et al., 2003**; Lauretano et al., 2016; Westerhold et al., 2017).”*

Line 54: “In the stratigraphic record, these events are primarily characterized by important negative carbon isotope excursions (NCIEs)” – rephrase!, they are characterized by a paired negative excursion in carbon and oxygen isotope data; do not use NCIE throughout as it confuses with the commonly used CIE (Carbon Isotope Excursion) abbreviation for the e.g. PETM.

The sentence will be rephrased as suggested and all NCIE in the text will be modified to “CIE”.

Line 150: please specify the target material of the X-ray tubes (Mo, Rh?).

The target material of the X-ray tubes is Cu. This information was added in chapter 3.3 Majors and trace element composition.
*Line 179: “…using a PANalytical PW2400 XRF spectrometer **with copper tube (Cu)** at the University of Lausanne…”*

Line 180: provide tie-points to ODP 1263 as a table in the supplement and add the age to your data tables of isotope as well as XRF results.

Tie-points have been added in the new Table S3. Age have been added in the Table S2

One important thing would be to show images of the soil nodules from the Chiriveta record in the supplement.

Images of the soil nodules have been added as well as an image of the iron oxides nodules mentioned at line 374 (Figure S1).

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.*** *"*

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.*** *"*

Response to "Review of "Alluvial record of an early Eocene hyperthermal, Castissent Formation, Pyrenees, Spain""

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 #3 for their work and appreciation of our study and the valuable propositions of improvements suggested. We answer below point by point to each item of concern.

1) I think this paper would benefit from a more detailed description of the model used to constrain the age of these deposits. Was the placement of the Castissent Formation within European Mammal Zone MP10 based on the same outcrops sampled here, and if not, what is the proximity of that site? Although the authors state that many of the well-dated sections within the Castissent Formation can be physically correlated to the current study area, how can the authors be confident that these are not time-transgressive deposits? Finally, I am skeptical that the age designation bracket of 50.534-0.025 and 49.695-0.043 Ma can be realistically applied to this unit. That extremely precise age range is based on orbital tuning of a marine record, correlated to a continental record, correlated to the current study area. I am not disputing the correlation, just that the precision of the marine record might not be retained through two iterations of lithostratigraphic correlation.

European Mammal Zone MP10 was found next to the Chiriveta section which is the only direct dating available. A first-hand estimation of the slope of the Castissent Fm. based on grain-size give a slope of $1*10^{-4}$. This would imply a difference of elevation of 1 m between the Campo section (40 km away from the study area, where most of the dating is done) and the Chiriveta section. Considering a mean sedimentation rate of 0.17 m/kyr at the Chiriveta section (this study), it represents a potential lag of ca. 6 kyr between both sections. Therefore, we can make the assumption that the time between upstream or downstream deposition is short enough to not alter significantly the correlation between both sections. Moreover, the correlation of the under- and overlying formations (Castigaleu and Perrarua respectively) adds an additional constraint. A short diachronicity cannot be ruled-out but synchronism on the scale of these two outcrops is a reasonable hypothesis.

We however agree with Referee #3 comments that the extreme age precision from orbital tuning cannot be applied as such for our section. We acknowledge the dating precision of the author in the previous sentence, but ages are rounded up for the Castissent extension. We will change the manuscript accordingly:

*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 138: ***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)."*

2) The authors note that unlike most marine hyperthermal records, the oxygen and carbon isotopic records are not coupled in the Castissent Formation (the oxygen does not reflect hyperthermal events, whereas the carbon does). Why might this be? Is there evidence of isotopic resetting of the O system (petrographic or other)? How deeply have these rocks been buried? This seems to suggest that even in well-preserved systems, oxygen isotopic records should be used and viewed with caution.

Frequently, oxygen and carbon isotopes are not coupled during hyperthermal events in continental record as already observed by Schmitz and Pujalte, (2003), Bowen et al., (2001) for the PETM. Similarly, small changes in δD are also frequently observed in mid-latitude CIE section (Smith et al. 2007; Tipple et al. 2011). Though the precise mechanisms that produce stable $\delta^{18}O$/δD are still debated, mid-latitude precipitation $\delta^{18}O$ appears to be relatively insensitive to changes in atmospheric pCO_2 and warming, particularly in greenhouse climates (Winnick et al. 2015). Further, the stable $\delta^{18}O$ value (around -5.5‰) throughout the Chiriveta section is likely additionally stabilized by its position close to the coast, which will buffer coastel precipitation $\delta^{18}O$ values relative continental interiors (Kukla et al 2019). This coastal influence is clearly seen in Figure 6 where oxygen isotopes values of the Bighorn Basin have a more continental (i.e., more negative) $\delta^{18}O$ signature then that in the Pyrenees, which is in line with the paleogeography of both basins at the time. This consistency between our results and the ones from the Bighorn Basin suggests a relative good preservation of the oxygen isotopic signal.

However, because sediments from this section might have been buried between 2-3 km and that oxygen isotopes are more prone to diagenesis than carbon oxygen and might therefore not preserve a primary signal, we use them with caution.

The manuscript was modified accordingly:

Line 267:

"Pre-PETM $\delta^{18}O$ values from carbonate nodules from the same area (–4.5 ± 0.4 ‰) (Hunger, 2018) show similar values than the Chiriveta section's measurements (–6.0 ± 0.4 ‰). ***Oxygen and carbon isotopes are not coupled during hyperthermal events in continental record as already observed by Schmitz and Pujalte, (2003), Bowen et al., (2001)*** *for the PETM isotopic excursion.* ***Though the precise mechanisms that produce stable $\delta^{18}O$ during CIE are still***

debated, mid-latitude precipitation δ¹⁸O appears to be relatively insensitive to changes in atmospheric pCO₂ and warming, particularly in greenhouse climates (Winnick et al. 2015). In contrast, *the* ***stable*** *$\delta^{18}O$ value of soil carbonates from the Pyrenean foreland basin (excluding the PETM) (–5.3 ± 0.9 ‰)* ***is likely additionally stabilized by its position close to the coast (****Cerling, 1984,* ***Kukla et al 2019)*** *compared for example to those of the Bighorn Basin (–9.0 ± 0.6 ‰).* ***This is in line with a more continental paleogeographical position of the Bighorn Basin compared to the Tremp-Graus Basin at the time (Seeland, 1998)****."*

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). "*

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

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

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*"**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.** "*

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

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Abstract. T~~During t~~he late Palaeocene to the middle Eocene (57.5 to 46.5 Ma) recorded a total of 39 hyperthermals—periods of rapid global warming ~~recorded~~ documented by prominent negative carbon isotope excursions (~~NCIE~~CIEs) as well as peaks in iron content—have been recognized in marine cores. ~~Understanding~~ Documenting how the Earth system responded to rapid climatic shifts ~~warming~~ during ~~these~~ hyperthermals ~~is~~ provides fundamental information to constrain climatic models. ~~because they represent potential analogues, in the geological record, to the ongoing anthropogenic modification of global climate.~~ However, while hyperthermals have been well documented in the marine sedimentary record, only a few have been recognized and described in continental deposits, thereby limiting our ability to understand the effect and record of global warming on terrestrial ~~surficial~~ systems. Hyperthermals in the continental record could be a powerful correlation tool to help connect marine and continental ~~records~~deposits, addressing issues of environmental signal propagation from land to sea. In this study, we generate new stable carbon isotope data ($\delta^{13}C$ values) across the well-exposed and time-constrained fluvial sedimentary succession of the early Eocene Castissent Formation in the South-Central Pyrenees (Spain). The $\delta^{13}C$ values of pedogenic carbonate reveal—similarly to the global records— stepped ~~NCIE~~CIEs, culminating in a minimum $\delta^{13}C$ value that we correlate with the hyperthermal event "U" at *ca.* 50 Ma. This general trend towards more negative values is most probably linked to higher primary productivity leading to an overall higher respiration of soil organic matter during these climatic events. The relative enrichment in immobile elements (Zr, Ti, Al) and higher estimates of mean annual precipitation together with the occurrence of small iron-oxide~~s~~/hydroxide~~-s~~ nodules during the ~~NCIE~~CIEs suggest intensification of chemical weathering and/or longer exposure of soils in a highly seasonal climate. The results show that even relatively small-scale hyperthermals compared with their prominent counterparts, such as PETM, ETM2 and 3, ~~have~~ can leave~~ft~~ a recognizable ~~trace~~ signature in the terrestrial stratigraphic record, providing insights into the dynamics of the carbon cycle in continental environments during these events.

1 Introduction

~~Starting~~ From~~at~~ the end of the Palaeocene, a period of global warming reached its climax during the Early Eocene Climatic Optimum (EECO) (Westerhold and Röhl, 2009; Hyland and Sheldon, 2013). The EECO started *ca.* 53 Ma ago and lasted until *ca.* 49 Ma ago (Westerhold et al., 2018), after which the climate began to cool ~~towards icehouse conditions eventually reached later in the Cenozoic~~ (~Eocene-Oligocene transition, Zachos et al., 2001, 2008). Superimposed on, and coeval to, this globally warm epoch, brief ~~-~~periods of pronounced global warming known as “hyperthermals” standout as anomalies outside of background climate variability (Kirtland-Turner et al., 2014; Dunkley Jones et al., 2018). The Palaeocene-Eocene Thermal Maximum (PETM; ~56 Ma) was the first of these events to be identified globally because of its exceptional magnitude and preservation in both marine and continental deposits (Koch et al., 1992). To date, for the late ~~Paleocene~~Palaeocene – early Eocene period, a total of 39 hyperthermal events of lesser magnitude have been identified from marine cores (Lourens et al., 2005; Sexton et al., 2011; Kirtland-Turner et al., 2014; Lauretano et al., 2015, 2016; Westerhold et al., 2018)~~ (e.g., Westerhold et al., 2018)~~, among which the most prominent and studied are the ~~Early~~ Eocene Thermal Maximum (ETM) 2 and 3,~~,~~ H2, and I1 and~~,~~ I2~~, and ETM3/X~~ events (Cramer et al., 2003; Lourens et al., 2005; Nicolo et al., 2007; Lunt et al., 2011; Deconto et al., 2012; Kirtland-Turner et al., 2014; Lauretano et al., 2016; Westerhold et al., 2017) (Fig. 1). In the marine stratigraphic record, these events are primarily characterized by ~~important~~ paired negative excursion in carbon and oxygen isotope ~~excursions~~ data~~(NCIEs)~~ exceeding background variability (Cramer et al., 2003; Nicolo et al., 2007; Zachos et al., 2008; Sluijs and Dickens, 2012; Lauretano et al., 2016), i.e. typically with amplitude greater than the standard deviation (SD) of pre-hyperthermal background values.

In deep marine settings, the ~~NCIEs~~ carbon isotope excursions (CIE) are typically paired with an increase in iron concentration and decrease in carbonate content, indicating ocean acidification potentially linked with high atmospheric CO_2 concentrations (Nicolo et al., 2007; Slotnick et al., 2012; Westerhold et al., 2018). 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 (Schmitz et al., 2001; Bowen et al., 2004; Nicolo et al., 2007; Slotnick et al., 2012; Payros et al., 2015; Dunkley Jones et al., 2018), although several studies document a spatially heterogeneous hydrological climatic response during the PETM (Bolle and Adatte, 2001; Kraus and Riggins, 2007; Giusberti et al., 2016; Carmichael et al., 2017). In fluvial systems, the abrupt warming of the PETM was found to be associated with expansion and coarsening of alluvial facies combined with an increase of the magnitude of flood discharge (Foreman et al., 2012; Pujalte et al., 2015; Chen et al., 2018), as well as enhanced pedogenesis (Abels et al., 2012). Yet, how continental systems reacted to the other, smaller-magnitude hyperthermals of the early Eocene remains to be documented. In particular, because of the subaerial nature and ~~important~~ lateral preservation dynamics of alluvial systems (e.g., Foreman and Straub, 2017; Straub and Foreman, 2018), the extent to which fluvial successions can provide complete and faithful archives of past climatic events, especially those with the smallest magnitudes, is still largely unknown~~a matter of debate~~ (Foreman and Straub, 2017; Trampush et al., 2017; Straub and Foreman, 2018). Addressing this question is particularly critical for studies ~~attempting to~~focussing on ~~understand~~ environmental signal propagation in source-to-sink systems (e.g., Castelltort and Van Den Driessche, 2003; Duller et al., 2019; Romans et al., 2016; Schlunegger and Castelltort, 2016), which require high-resolution continental-marine correlations such as those provided by the PETM (e.g., Duller et al., 2019) ~~but also~~or by other hyperthermals of the early Eocene.

To address these issues, we explored ~~some aspects of~~ the geochemical signature (carbon and oxygen stable isotopes, major and trace elements) and ~~of~~ the sedimentology of the fluvial deposits of the Ypresian age Castissent Fm. (South-Central Pyrenees, Spain, Fig. 2)~~, whose deposition took place during the late EECO~~. First, we generated a new carbon isotope profile from a paleosol succession rich in carbonate nodules across the Castissent Fm. in order to compare these results with a global $\delta^{13}C$ record. The data suggest that this fluvial succession preserves a record of hyperthermal "U" event at *ca.* 50 Ma, ~~adding~~ providing important constraints to its depositional the age ~~of this Formation~~. Second, we used the major and trace element composition of bulk floodplain material in order to explore the climatic impact of such ~~minor~~ hyperthermal, including empirical reconstructions of mean annual precipitation, allowing us to discuss soil dynamics during global warming. This study identifies for the first time in a continental succession an event so far only recorded in marine sediments, thereby demonstrating the global breadth of these climatic events and the complementarity of oceanographic and terrestrial archives.

2 Geological setting

The Castissent Formation comprises ~~is a Ypresian age~~ fluvial deposit of Ypresian age ~~Formation that~~ crop~~s~~ping out in the Tremp-Graus Basin (South-Pyrenean foreland basin, Marzo et al., 1988, Fig. 2).~~, which developed during the Paleocene to Eocene and is bounded by the Bóixols thrust in the North, and the Montsec thrust in the South (Marzo et al., 1988).~~ The Castissent Fm. is defined by its prominent overall sand-rich character, and is composed ~~in detail~~by ~~of~~ three coarse-grained ~~multistorey~~ channels complexes (labelled as Members A, B and C) separated by four marine incursions (M0 to M3) inferred from the observation of marginal coastal bioclast-rich horizons developed up into the upper deltaic plain and correlative with finer dark-grey mudstones and calcretes in the fluvial segment of the Castissent (Marzo et al., 1988). This major fluvial progradation is correlated westwards with deep-water turbidite sequences of the Arro and Fosado Formations in the Ainsa Basin (Fig. 3, Mutti et al., 1988; Nijman and Nio, 1975; Nijman and Puigdefabregas, 1978; Pickering and Bayliss, 2009). In the upstream, eastern counterparts of the Castissent Fm., the channel complexes are intercalated with yellow to red coloured paleosols. Sub-spherical to slightly elongated carbonate nodules with a diameter ranging from 1 mm to 4 cm are omnipresent in the paleosols (Fig. S1). Studies of the Castissent Fm. tentatively attributed its occurrence to an important pulse of exhumation and thrust activity in the hinterland at *ca.* 50 Ma, in possible combination with a late-Ypresian sea-level fall (Puigdefabregas et al., 1986; Marzo et al., 1988; Whitchurch et al., 2011; Castelltort et al., 2017), both resulting in reduced available accommodation space enhancing progradation and amalgamation (Chanvry et al., 2018).

The Chiriveta section, encompassing the Castissent Fm., is situated in a continental paleogeographic position prone to pedogenesis and slightly off-axis from the more "in-axis" amalgamated sand-rich type section of Mas de Faro (Fig. 2); for paleo-position and correlation see also Figs. 10 and 12 in Marzo et al. (1988).

In the Chiriveta location, stratigraphic constraints are limited to the identification of European Mammals zone MP10 (Badiola et al., 2009), which provides an age range of 50.73 to 47.4 Ma (GTS2012). This age span is refined by bio- and magnetostratigraphic data from the Castissent Fm. outcrops of the Campo location, about 40 km further west (Kapellos and Schaub, 1973; Tosquella, 1995; Bentham and Burbank, 1996; Tosquella et al., 1998; Payros et al., 2009) ~~Constraints on the age of the Castissent Fm in its upstream segment is the recognition of European Mammals zone MP10 (Badiola et al., 2009), which gives a broad age range of between 50.73 to 47.4 Ma~~

~~(GTS2012). However, most age constraints have been obtained through bio- and magnetostratigraphic studies in the downstream more marine-influenced segment of the Castissent Fm in the Campo area located 40km westward from the Chiriveta section~~ (fig. 3). ~~Thanks to its very prominent field expression~~Because of its outcropping extent, the Castissent Fm. has been ~~physically~~ mapped from west to east across these sections (Nijman and Nio, 1975; Nijman, 1998; Poyatos-Moré, 2014; Chanvry et al., 2018). 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. ~~and the stratigraphic constraints obtained in the west can thus be propagated eastwards to its more fluvial counterparts (Fig. 3).~~ In the Campo section, Kapellos and Schaub (1973) find the transition between the *D. lodoensis* and the *T. orthostylus* nannoplankton (NP) zones at *ca.* 200 m below the base of the Castissent Fm. and the transition between the *T. orthostylus* and the *D. sublodoensis* NP zones in the transgression *ca.* 100 m above the uppermost m~~M~~ember of the Castissent Fm. This indicates that the Castissent Fm. was deposited during NP13. Magnetostratigraphic data of the same section by Bentham and Burbank (1996) place the transition between the C22r and C22n magnetozones closely above the top of the Castissent Fm. We thus used the recent astrochronologic age models of Westerhold et al. (2017), which obtain numerical ages of 50.777±0.01 and 49.695±0.043 Ma respectively for the base and top of C22r, and obtain a numerical age of 50.534±0.025 Ma for the base of NP13 based on ODP site 1263. Considering the data available and their resolution, ~~We considered that~~ we suggest a depositional age span ~~these constraints give a maximal age extension of~~ between 50.5~~34±0.025~~ and 49.7~~695±0.043~~ Ma for the Castissent Fm. (reported in green on F~~f~~ig. 1). According to global isotopic records (Fig. 1), this period was marked by 4 hyperthermals labelled S/C22rH3, T/C22rH4, U/C22rH5 and V/C22nH1 (Cramer et al., 2003; Lauretano et al., 2016; Westerhold et al., 2017).

3 Material and methods

~~The Chiriveta section is situated in a continental paleogeographic position prone to pedogenesis and slightly off-axis from the more "in-axis" amalgamated sand-rich type section of Mas de Faro (Fig. 2); for paleo-position and correlation see also Figs. 10 and 12 in Marzo et al. (1988).~~

3.1 Sampling

A total of 74 samples were collected from the early-Eocene Chiriveta section for geochemical studies. All samples consist of floodplain material and were taken below the weathering depth (~50 cm), with an average resolution of 1 m. Resolution was increased by a factor of 2 in specific horizons such as red beds. When important sandbodies occurred, lateral equivalent floodplain material or intercalated paleosol horizons were sampled. Each sample was split in two aliquots, one for major and trace element analysis and the other for carbon and oxygen stable isotope analysis on pedogenic carbonate nodules. The carbonate nodules were extracted from the bulk paleosol material by sieving and then cleaned by repeated washes with deionized water in an ultrasound bath. From each cleaned nodules set, subsamples of 1 to 4 nodules were taken, leading to a total of 149 sub-samples of pedogenic carbonate nodules.

3.2 Carbon and oxygen stable isotopes

Pedogenic carbonate nodules were crushed and powdered in an agate mortar and analysed for stable carbon and oxygen isotope composition at the Institute of Earth Surface Dynamics of the University of Lausanne (Switzerland) using a Thermo Fisher Scientific (Bremen, Germany) carbonate-preparation device and Gas Bench II connected to a Thermo Fisher Delta Plus XL isotope ratio mass spectrometer. The carbon and oxygen isotope compositions are reported in the delta (δ) notation as the per mil (‰) isotope ratio variations relative to the Vienna Pee Dee Belemnite standard (VPDB). The analytical reproducibility estimated from replicate analyses of the international calcite standard NBS-19 and the laboratory standard Carrara Marble was better than ± 0.05 ‰ (1 sigma) for $\delta^{13}C$ and ± 0.1 ‰ (1 sigma) for $\delta^{18}O$.

3.3 Major and trace element composition

Fifty-two bulk paleosol samples were analysed for major and trace elements using X-r~~R~~ay fluorescence (XRF) spectrometry. Crushed bulk powders (<80 µm) were mounted in a plastic cup covered by a thin polypropylene film (4 µm~~-~~thick) and analysed in the laboratory with a Thermo Niton XL3t® portable XRF analyzer fixed on a test stand. Analyses were performed with a beam diameter of 8 mm, to determine the concentrations of 34 major and trace elements (from Mg to Au). Each measurement took 120 s, consisting of two 60 s cycles on four different filters (15 seconds on low, main, high, and light ranges), operating the X-ray tube at different voltage to optimize the fluorescence and peak/background ratios of the different elements. The limits of detection were of 10's ppm for most elements, except for Mg, Si, and Al which are at wt% level. ~~Na~~ Sodium is too light to be detected. The acquired spectra ~~of the measurements~~ were transferred to a computer using NDT software version 8.2.1. (Thermo Fisher Scientific, Waltham, Ma, USA). The same material has been analysed for ~~T~~twenty-three major and trace elements ~~were analysed~~ on fused and pressed ~~and fused~~ discs, respectively, ~~of the same material~~ using a PANalytical PW2400 XRF spectrometer with copper (Cu) tube at the University of Lausanne to cross-calibrate the compositions measured with the Niton XL3t® portable XRF analyzer.

3.4 Mean annual precipitation

The mean annual precipitation estimate (MAP) used in this study was estimated from the empirical relationship between MAP and CaO/Al_2O_3 ratio for Mollisols from a national survey of North American soils according to the following equation: MAP (mm) = $-130.9 \times \ln(CaO/Al_2O_3) + 467$ (Sheldon et al., 2002). CaO and Al_2O_3 concentrations were measured on bulk paleosol material. Climate linked to the MAP estimate was classified based on the following boundaries: arid to semiarid at 250 mm and semiarid to subhumid at 500 mm (Bull, 1991).

3.5 Grain-size estimation

The relative grain-size variation of the sediment samples was estimated from their major element compositions. Si, Ti and Zr are more concentrated in the coarse fraction of the sediment as they are found in larger mineral grains, whereas Al is more concentrated in the finer fraction of the sediment because is mostly linked to clay minerals (Lupker et al., 2011, 2012; Croudace and Rothwell, 2015). Grain size variation throughout the section was estimated using Si/Al, Ti/Al and Zr/Al ratios, therefore, an increase in these ratios suggests a relative increase in the proportion of coarser material in the sample.

3.6 Correlation with target curves

The measured $\delta^{13}C$ dataset was compared with a time-equivalent ODP 1263 global $\delta^{13}C$ record reported by Westerhold et al. (2017) using the Analyseries software (Paillard et al., 1996). The $\delta^{13}C$ record of site 1263 was favoured over those of ODP 1209 and 1258 covering the Castissent Fm. time-period, because it is continuous and has a higher resolution.~~-~~ Correlations between the $\delta^{13}C$ record of site 1263 and the $\delta^{13}C$ record of the Chiriveta section were performed in order to optimize the Pearson correlation coefficient (*r*) and by minimizing abrupt variations in sedimentation rates. Well-defined peaks in both $\delta^{13}C$ records were used as tie-points for the correlation and the number of tie-points was kept minimum (<10) so as not to force the correlations.

4 Results

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 to red-brown mottled floodplain paleosols (Fig. 4A-B), corresponding laterally to thick, medium to coarse-grained quartz-rich channel-fill deposits (width/depth ratio = 20-50; Marzo et al. (1988)) and over-bank deposits flowing parallel to the main structures of the growing Pyrenean orogeny (Marzo et al., 1988). At the base of the section, the first marine incursion M0 is situated at the top of a 20 m-thick coarse-grained tidal bar deposit with herringbone cross-stratifications and oyster shells (Fig. 4C). In the Chiriveta section, the Castissent Member A is a 48 m-thick interval comprising two main medium-grained sandbodies of light coloration of 5.40 and 1.5 m in thickness respectively. Bedforms observed in the first sandbody have a mean height of 24 cm (n = 9). The second marine incursion M1 is located at 48 m just below the Castissent B Member and consists of a 2 m-thick grey interval interpreted by Marzo et al. (1988) brackish-lagoonal water facies (Fig. 4B-F). The Castissent B Member (Fig. 4G) is a 12 m-thick and laterally-extensive (width/depth ratio ≥ 250; Marzo et al. (1988)) amalgamated sandbody with a micro-conglomeratic erosive base. Grain size is overall larger than in Member A, and ranges from fine sand to large pebbles. Sandbody tops show a fining-upward trend and are capped by mottled siltstone packages. Mottled siltstone layers are interpreted as pedogenized over-bank deposits based on roots traces and their capping relationship with underlying sandbody deposits (observed at 26 m, 76 m, 89 m and 96 m in Fig. 4, Fig. 4H). More regular and sheet-like sandbodies interbedded with mottled siltstone layers are observed upwards. The section ends with a 23 m-thick, medium to very coarse tidally-influenced sandstone deposit interpreted as the equivalent M3 marine incursion by Marzo et al. (1988). Although Castissent Member C was not interpreted by Marzo et al. (1988) in this section, a 2m-thick fine-grained sandbody at ca 80 meters in our section could be the condensed lateral equivalent of it (Fig. 5)

4.2 Stable isotopic record

Carbon and oxygen isotope ratios from the carbonate nodules are presented in Fig. 5. The $\delta^{13}C$ values vary between -10.9 and -1.9‰ with a mean value and 1 SD of –7.7 ± 1.6 ‰. Six ~~NCIE~~CIEs (named A to F in Fig. 5 and colour coded in Fig. 6) are more negative than -9.3‰ (i.e., the mean value – 1 ~~SD~~ standard deviation) amongst which one (~~NCIE~~CIE D) is below 2 SDs. The values are –9.6, –9.8, –9.9, –10.9, –9.9 and –9.4‰ for ~~NCIE~~CIEs A to F respectively. At the bottom of the section, ~~NCIE~~CIE A is followed by a relatively constant interval of mean $\delta^{13}C$ values. ~~NCIE~~CIE B, situated in the first red bed, marks the beginning of a stepped $\delta^{13}C$ trend (around ±1 SD) leading to the minimum ~~NCIE~~CIE D. The second part of the section shows two more ~~NCIE~~CIEs separated by the highest δ^{13}C value at 74~~65~~ m. ~~NCIE~~CIE F is the ~~lowest~~ least prominent of all ~~NCIE~~CIEs. The δ^{18}O values vary between –7.0 and –5.0‰ with a mean value of –6.0 ± 0.4 ‰, which makes them less dispersed than the δ^{13}C record. Nine negative oxygen isotope excursions ~~(NOIEs)~~ are more negative than the mean value – 1 SD, amongst which one is below 2 SD reaching a minimum value of –6.8‰ at 19 m. The ~~NOIEs~~oxygen isotope excursions do not correspond with ~~NCIE~~CIEs described above.

4.3 Major and trace elements

Titanium (Ti), Aluminium (Al) and Zirconium (Zr) concentrations measured on bulk paleosols are plotted in Figure 5. These elements are commonly considered as immobile and are expected to concentrate in more weathered soils. Ti values vary between 0.18 and 0.52% with a mean value of 0.34% and a standard deviation of 0.08. Al values vary between 3.03 and 9.35% with a mean value of 5.85% and a standard deviation of 1.53. Zr values vary between 6~~6~~7 and 204 ppm with a mean value of 128 ppm and a standard deviation of 35. Mean annual precipitation (MAP) estimates values vary between 185 and 754 mm/y with a mean value of 376 mm/y and a standard deviation of 111. Ti, Al, Zr and MAP show a similar trend starting from the base of the section with a global increase of all values toward ~~NCIE~~CIE C and a decrease afterwards. All ~~NCIE~~CIEs show higher value of Ti, Al, Zr and MAP except ~~NCIE~~CIE F. Based on Bull (1991), an average value of 387 mm/y for the MAP in the Chiriveta section represent a semi-arid climate (Fig. 5). All ~~NCIE~~CIEs show an increase in MAP.

5 Discussion

5.1 Carbon and oxygen isotopic record

5.1.1 Identifying the CIE

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 δ^{13}C 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 (δ^{18}O), 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 δ^{13}C value of the atmospheric CO_2 and soil CO_2, which in turn is a function of the δ^{13}C of the atmospheric CO_2 ~~,~~and the overlying plants, as well as the soil respiration flux and the partial pressure of atmospheric CO_2 (Cerling, 1984; Bowen et al., 2004; Abels et al., 2012; Caves et al., 2016).

The δ^{13}C vs δ^{18}O diagram for the pedogenic carbonate nodules from the Chiriveta section (r = -0.26, n = 149) suggests a good preservation of the primary isotopic signal (Figure 6), with an average value of δ^{13}C = –7.7 ± 1.6 ‰ similar to mid-latitude late-Palaeocene to Eocene continental δ^{13}C values (excluding the PETM samples) observed elsewhere (e.g., McInerney and Wing, 2011; and references therein), and a spread comparable with δ^{13}C values from carbonate nodule analysed for the same period in the Bighorn Basin (Bowen et al., 2001). Fig. 6 emphasizes that early-Eocene carbonate nodules display overall more negative δ^{13}C values than the Holocene nodules, ~~that~~ which is consistent with a large compilation of~~global~~ data from eastern Eurasia (Caves Rugenstein and Chamberlain, 2018). Pre-PETM δ^{18}O values from carbonate nodules from the same area (–4.5 ± 0.4 ‰) (Hunger, 2018) show similar ~~range~~ values than ~~those measured in~~ the Chiriveta section's measurements (–6.0 ± 0.4 ‰). ~~Moreover,~~ Oxygen and carbon isotopes are not coupled during hyperthermal events in continental record as already observed by ~~(~~Schmitz and Pujalte, (2003), ~~(~~Bowen et al., (2001) for the PETM isotopic excursion. Though the precise mechanisms that produce stable δ^{18}O during CIE are still debated, mid-latitude precipitation δ^{18}O appears to be relatively insensitive to changes in atmospheric pCO_2 and warming, particularly in greenhouse climates (Winnick et al., 2015). In contrast, the stable δ^{18}O values of soil carbonates from the Pyrenean foreland basin ~~(excluding the PETM)~~ (–5.5~~3~~ ± 0.9 ‰) is likely additionally stabilized by its position close to the coast ~~indicate a more coastal-influenced isotopic signature (Cerling, 1984)~~ (Cerling, 1984; Kukla et al., 2019) compared for example to those of the Bighorn Basin (–9.0 ± 0.6 ‰). This is in line with a more continental paleogeographical position of the Bighorn Basin compared to the Tremp-Graus Basin at the time (Seeland, 1998).

A hyperthermal event recorded in marine sediments is defined by a paired negative carbon and oxygen stable isotope excursions that are more negative than the mean value minus 1 SD (Kirtland-Turner et al., 2014). This definition may not be applicable to continental deposits, because continental systems respond differently than marine systems to the carbon cycle perturbations. Though the marine δ^{13}C record is thought to record the global CO_2 δ^{13}C, ~~Indeed,~~ the δ^{13}C value of the marine dissolved inorganic carbon is also influenced by dissolution of carbonates at depth (McInerney and Wing, 2011).~~,~~ ~~whereas~~ In contrast, δ^{13}C in pedogenic nodules varies~~y~~ with soil properties, atmospheric and soil pCO_2 and δ^{13}C, and~~,~~ the rate and nature of carbon input and/or output by soil respiration (Bowen et al., 2004; Sheldon and Tabor, 2009). These processes ~~may cause a misleading~~create complexities in estimating~~on of~~ CIEs in soil carbonate nodules and in marine carbonates (McInerney and Wing, 2011). Nevertheless, we used Turner et al. (2014)'s hyperthermal definition as a starting point to filter the high-resolution variations in the Chiriveta section. We identify 16 samples ~~were identified~~ with ~~NCIE~~CIE values more negative than the mean –1 SD. Among these 16 samples, we recognized 6 discrete ~~NCIE~~CIEs (named A – F in Fig. 5 and 7). Both marine incursion M1 and M2 show an abrupt shift from –9 to –10‰ ~~δ^{13}C values~~ in continental δ^{13}C values towards more (positive) marine values of –4 to –2‰; this point to a progressive higher contribution of seawater to the formation of the carbonate nodules.

Six correlation options with the global record were explored in the time-window of the Castissent Fm. (Figure S2~~1~~ and S3~~2~~ in the Supplement). The ~~C~~correlation presented in Figure 7A was favoured ~~for the following reason~~as it shows: i) ~~it shows~~ reasonable sedimentation rates variations, ii) a similar amplitude to~~is coherent with~~ the ~~NCIE~~CIE ~~amplitude of~~ in the global record, and iii) ~~it yielded~~ the highest correlation coefficient (r = 0.65, n = 71). Moreover, it plots on the same trend regarding hyperthermal ~~NCIE~~CIE amplitudes in marine and continental environments suggesting a common mechanism of global climatic change with ~~similar isotopic dynamic as~~ events I1, I2, H2 and ETM2 (Figure 7B). Based on these observations and ~~the resulting~~obtained correlation, we suggest that only hyperthermal U is preserved in the Chiriveta section and that it is correlated with ~~NCIE~~CIE D. Sedimentation rate obtained with the favoured correlation (Figure 7) varies between 0.1-0.29 mm/y, consistent with sedimentation rates reported for other Eocene floodplain successions (Kraus and Aslan, 1993). ~~and t~~The correlation coefficient of r = 0.65 suggests an overall good signal preservation in the studied continental section for a 40 kys climatic event.

5.1.2 Mechanisms causing the CIE

~~Soil organic matter sensitivity to a change in temperature is critical concerning today's global warming (Trumbore et al., 2006; Melillo et al., 2014), because it represents two-thirds of the terrestrial carbon pool and contains twice as much carbon as atmospheric CO_2 pool (Schimel et al., 1994; Carrillo et al., 2018).~~ An increase in temperature could ~~therefore~~ potentially release ~~important~~ significant amount of CO_2 into the atmosphere (Trumbore et al., 1996; Melillo et al., 2014). T~~As t~~he amplitude and duration of Eocene ~~NCIE~~CIEs are approximately 30% of the one~~s~~ recorded ~~in~~ for the PETM, we hypothesize that the climatic effects of smaller-scale hyperthermals can be linearly scaled to the PETM. Based on this assumption and in order to get a rough approximation without considering a non-linear sensitivity response, a smaller-scale hyperthermal would imply a release of approximately 500 to 1500 Gt of carbon to the ocean and atmosphere reservoir and a global temperature rise of about 1.5–2.5°~~ ~~C. This estimation correspond to the 1500 – 4500 Gt of carbon released during the PETM, causing a rise of 5–8°C (Bowen et al., 2006), and is in line with previous estimations of ~3 and ~2°C warming for ETM2/H1 and H2 events respectively (Stap et al., 2010). 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 $\delta^{13}C$ can however not fully explain the 3‰ shift in $\delta^{13}C$ observed in this study.

The $\delta^{13}C$ mean value in the Chiriveta section is –7.7 ± 1.6 ‰. This value reflects an overall equilibrium with a mean atmospheric CO_2 of –7‰ (Koch et al., 1995) and is coherent with pre-PETM $\delta^{13}C$ values of –7.1 ± 0.9 ‰ found in the same area (Hunger, 2018; Fig. 6). It is possible to calculate from the (small-scale) hyperthermal $\delta^{13}C$ excursions in the marine environment the shift to be expected in soil carbonate nodules by using known fractionation coefficients (Koch et al., 1995, 2003); the expected $\delta^{13}C$ value in carbonate nodules, only considering the respiration of organic matter, is ~~of~~ –11‰ (Fig. 8). This value is within the range of those measured ~~in~~ from the Chiriveta section, where some nodules reach values as low as -10.9‰. We suggest that the bacterial respiration of organic matter, enhanced by warmer temperatures (e.g.; Davidson and Janssens, 2006; Trumbore et al., 2006), may also have contributed to the lower $\delta^{13}C$ values of nodules during the ~~NCIE~~CIEs (Fig. 8). On geological timescales, soil organic carbon can be considered at steady state with equal organic carbon inputs and outputs from the soil (Koven et al., 2017). Respiration (carbon output after mineralization as CO_2) is thought to be more sensitive to global warming than gross primary productivity (organic carbon input as organic matter) leading to a depletion of the total soil carbon pool with time during transient global warming events; although the precise sensitivity of gross primary productivity remains poorly constrained (Davidson and Janssens, 2006). Large uncertainties remain about carbon dynamics and their timescale in the soils during climate changes. Parameters such as the vegetation type (Klemmedson, 1989), temperatures (Koven et al., 2017), soil geochemistry (Torn et al., 1997; Doetterl et al., 2015), and soil water content (Davidson et al., 2000) have been shown to be important controlling factors within historical timescales.

Considering these caveats, we estimate the maximum possible contribution of enhanced soil carbon respiration to negative $\delta^{13}C$ excursions during the ~~NCIE~~CIEs. Using typical values for the organic carbon reservoir comprising fast and slow cycling carbon in soils in arid to semi-arid ecosystems of 5.6–19.2 kgC/m^2 (Klemmedson, 1989; Raich and Schlesinger, 1992), respiration fluxes starting at a steady state value of 0.5 kgC/yr, and a respiration rate sensitivity *ca.* 5%/degree (Raich and Schlesinger, 1992) (Q_{10} = 1.5), we estimate that all of the organic carbon in soils would be consumed within 250 to 850 yrs., given an increase of 1°C and without changing the carbon input rate. Though there are a number of assumptions in this first-order estimate, the timescale of soil carbon depletion is substantially shorter than our estimate of the timescale of the ~~NCIE~~CIE (~36 kyrs) (Fig. 7). As evidenced by this calculation, an increase in soil respiration triggered by warmer temperatures cannot be the sole mechanism driving the ~~NCIE~~CIE shift over multi-millennial time-scales. Instead, we suggest that during these transient warmings, this mechanism is associated with a high primary productivity—resulting in a greater input of carbon to the soil—leading to an overall higher soil respiration of organic matter. Coupled with lower atmospheric δ^{13}C during hyperthermals, this mechanism caused a pronounced ~~NCIE~~CIE in soil carbonate nodules.

5.2 Geochemical signature of hyperthermal events

Major and trace elements compositions of floodplain sediments is a function of river dynamics, climate, and sediment grain-size (Lupker et al., 2012; Turner et al., 2015). Based on the ~~NCIE~~CIEs ~~described above~~, we defined six intervals ~~in the Chiriveta section. Each interval~~ show~~s~~ing a relative enrichment (up 10 to 30% compared to the average value) in immobile elements such as Ti, Al and Zr (Fig. 5). To ensure that major and trace concentrations are not grain-size biased, we plotted grain-size proxies Si/Al, Ti/Al and Zr/Al (Lupker et al., 2012; Turner et al., 2015), which all exhibit a relatively stable trend, not ~~correlated~~ connected with the immobile element concentrations (Figure S4~~3~~ in the Supplement). The enrichments in Ti, Al and Zr suggest mature paleosols with potential intense weathering due to enhanced humid climatic conditions; but may also correspond to a longer exposure time on a stable floodplain, allowing leaching of mobile elements and relative enrichment of immobile elements (Sheldon and Tabor, 2009). Pedogenic nodules are frequent in well-drained soil profiles associated with a climate regime where the potential evapotranspiration is greater than the mean annual precipitation rate (Slessarev et al., 2016) and with a mean annual precipitation < 800 mm/year (Cerling, 1984; Retallack, 1994; Sheldon and Tabor, 2009). These conditions correspond to climate ranging from arid to sub-humid conditions (Hasiotis, 2004; Prochnow et al., 2006; Hyland and Sheldon, 2013). This agrees with MAP values obtained for the paleo-precipitation estimate (Fig. 5) and with a smectite/kaolinite >1 assemblage dominating some of the studied soils (Nicolaides, 2017, Table S2~~1~~ in the Supplement); all ~~fitting well with~~suggestive of a semi-arid to sub-humid ~~contrasted~~ climate with seasonal humidity (Arostegi et al., 2011). Associated with ~~NCIE~~CIEs C and D in red bed deposits, sub-milimetric iron-oxide and hydroxides nodules made of concentric hematite and goethite were found together with carbonate nodules (Fig. S1). This suggest a ~~contrasted~~ seasonal climate as hematite forms under more arid soil condition than goethite (Kraus and Riggins, 2007). Together, these observations are in line with an acceleration of the hydrological cycle and a higher seasonality, as has been ~~already~~ observed during the PETM, H1, H2; I1 and I2 hyperthermals (Bowen et al., 2004; Nicolo et al., 2007; Slotnick et al., 2012; Dunkley Jones et al., 2018). Therefore, combined with ~~NCIE~~CIEs, we suggest that small scale hyperthermals in continental records can be recognized by an increase in the weathering index (Hessler et al., 2017) and by an increase in the immobile element concentrations, both related to an increase in precipitation intensity.

5.3 High-resolution hyperthermal signal

The high-resolution isotopic and elemental record of the Chiriveta profile allow us to highlight the dynamics and variability of a hyperthermal event. We do not observe a unique peak in δ^{13}C, but rather a stepped isotopic signal suggesting, together with above-discussed geochemical data, a climatic oscillation alternating with variably intense precipitations and leaching conditions during a climax spanning *ca.* 150 kyrs (interval ~~NCIE~~CIE B to D). Such a climatic behaviour, ~~already~~ was already described for the PETM, during the pre-onset ~~PETM~~ excursion (Bowen et al., 2015) and in the core CIE of the PETM (Giusberti et al., 2016)~~, may indicate a back and forth climatic response to carbon cycle perturbations~~. Moreover, the δ^{13}C climax (~~NCIE~~CIE D) does not correspond ~~neither~~ to the highest concentrations of immobile elements nor maximum MAP estimates, which we estimate occur ~~happening~~ during ~~NCIE~~CIE C, ~~since it~~which predates ~~from~~ by *ca.* 50 kyrs the ~~NCIE~~CIE D (Fig. 7). The minimum δ^{13}C value therefore does not seem to be coeval with the most extreme climatic response, suggesting a complex environmental response. However, because sedimentation in floodplain depositional settings is a function of the channel position and flood frequency, the relative concentration of elements ~~only likely~~may reflects the changes in river dynamics instead of climatic variability, which could explain the mismatch between minimum values in ~~NCIE~~CIE and the climatic response. More high-resolution hyperthermal studies in coeval continental sections are needed to better understand the relationships between proxies.

5.4 Possible implication for the ~~P~~preservation potential of hyperthermals in continental sections

~~Since the first studies that applied sequence stratigraphy concepts onto continental deposits, the preservation of environmental signals in the continental stratigraphic record has been considered incomplete, especially during falling sea-level (Shanley and McCabe, 1994; Wright and Marriott, 1993). Even at higher-resolution timescales, floodplain deposits are still considered as fragmentary and discontinuous in nature due to non-continuous flood, avulsion, and channel migration sedimentation processes and the irregular depositional thickness relative to the position of the channel (Turner et al., 2015). This potential incompleteness of the sedimentary record (Barrell, 1917; Sadler, 1981) and the capacity of a sedimentary section to document a continuous paleoclimatic signal has probably led many workers to prefer the deep-marine records.~~ Major events such as the PETM ~~event~~ ha~~s~~ve 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), ~~is~~ may be more difficult to detect~~somewhat uncertain~~ (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, ~~assess in a quantitative matter the preservation potential of a hyperthermal event with a generic 40 kyr duration (Sexton et al., 2011),~~ we calculated the compensation time scale (Tc) of the Castissent Fm. Tc is a ~~characteristic~~ time-scale characteristic of ~~in~~ an alluvial basin below which stratigraphic signals with shorter durations may be of autogenic origin, thereby giving a scale below which allogenic forcing should be interpreted carefully (Wang et al., 2011; Foreman and Straub, 2017; Trampush et al., 2017). In other words, an external forcing signal with a duration smaller than Tc will be challenging to identify from background variability; the external forcing must be therefore of a ~~longer~~ duration longer than Tc and optimally twice Tc (Foreman and Straub, 2017). Tc max can be calculated by dividing the topographic roughness or maximum channel depth by the average subsidence or deposition rate (Wang et al., 2011). ~~Based on preserved channel fills in La Roca and Chiriveta sections, we estimated a maximum channel depth to be 6 m with an average of 3.75 m (fitting previous measurements of maximum 7 m). With a thickness of 150 m for the Castissent Fm in the La Roca section (Marzo et al., 1988) and of 101 m in the Chiriveta section (this study) and using the maximum and minimum age extension of the Formation, we obtain sedimentation rates between 0.1 and 0.29 mm/yr. These values are within sedimentation~~

~~rates of Eocene floodplain succession (Kraus and Aslan, 1993).~~ Using an average sedimentation rate of 0.17 mm/~~k~~yr and an average channel depth of 3.75 m, we obtained a mean Tc of 22,000 yrs, which means that~~. A~~ hyperthermal events of 40 kyrs duration (time-scale of hyperthermal U and preceding CIE)~~, being approximately twice as long as the estimated Tc,~~ have the potential to~~should~~ be recorded despite fluvial system dynamics. 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 (Marriott and Wright, 1993; Bowen et al., 2015; Kraus et al., 2015). 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° (Farrell et al., 1987; Nijman, 1998; Clevis et al., 2004; 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.

~~There are five Eocene hyperthermal events (PETM, ETM2/ELMO/H1, H2, I1, I2) identified worldwide (e.g.; Abels et al., 2016; Schmitz and Pujalte, 2003). If we add the data from this study (U event), we can estimate a mean thickness for hyperthermal events of *ca.* 27 m for continental and 1.3 m for deep-marine succession, respectively (Abels et al., 2016; Bowen et al., 2001; Lauretano et al., 2015; Lourens et al., 2005; Nicolo et al., 2007; Schmitz and Pujalte, 2003; Slotnick et al., 2012; Westerhold et al., 2018). Thus, regarding the hitherto studied sections, terrestrial strata recording hyperthermals are potentially one order of magnitude thicker with resolutions likely higher than deep-marine sections. Therefore, continental strata, which are directly linked to environmental conditions occurring at the time of their formation, might preserve a better record of past climatic events (Sheldon and Tabor, 2009). The continental record of past climatic events might have been overlooked; if such record can be proved complete, the potential climatic events preservation is higher and likely of high resolution.~~

6 Conclusions

A new high-resolution isotopic record from the paleosol-rich deposits at the Chiriveta section ~~succession allows to~~ identified~~y~~ a prominent negative carbon isotope excursion (~~NCIE~~CIE) in continental settings. ~~deposits that w~~We suggest that the CIE recorded in fluvial succession of the early Eocene Castissent Formation is ~~to be~~ the “U” event, identified for the first time in continental deposits. ~~providing new insights into the climate and carbon cycle dynamics during a hyperthermal event.~~ This climatic event~~, identified for the first time in continental deposits~~, reaches $\delta^{13}C$ values of 2 sigma (standard deviation) below the mean and is ~~preceded~~ heralded and followed by several smaller-scale stepped ~~NCIE~~CIEs, which are interpreted as moments of enhanced primary productivity, leading to an overall higher soil respiration. We show that all these ~~NCIE~~CIEs are relatively enriched in immobile elements (i.e., Ti, Zr and Al) and display an increase in MAP estimates. These observations coupled with the presence of iron-oxide nodules on an overall weathered succession, suggest ~~a contrasted climate and~~ an increase in precipitation rates during these events. The data presented in this study suggest~~s~~ a period of *ca.* 150 kyrs of ~~oscillating~~ contrasted climate alternating average and above background weathering conditions. Finally, the results of this ~~study provide support to the recognition and~~demonstrate the importance of hyperthermal events in continental successions as well as in the preservation potential of such deposits.

Acknowledgements. The authors would like to acknowledge the lifetime work of Josep Serra Kiel, whose research and scientific contributions in the Pyrenees have been fundamental to this work and much beyond. This study has benefited from scientific discussion and field work with M. Perret, A. Nowak, C. Läuchli, T. Hunger, J. Vernier, K. Thomson, M. Odlum, A. Le Cotonnec and T. Maeder. Work supported by an Augustin Lombard grant from the SPHN Society of Geneva. Field work was supported by an Equinor grant to SC.

Isotopic, majors and trace data and tie points used for correlation can be found in the supporting information (Table S3~~2~~ and S4 in the Supplement)

Author contributions. LH led the field work, sampling, sample preparation, data interpretation and writing. TA contributed to field work, sampling, data interpretation, discussion and writing. JES performed stable isotope analysis, data interpretation and writing. JKCR interpreted the data and writing. MPM and EC contributed to fieldwork, sampling, discussion and writing. CP, JC and AF supervised the fieldwork, discussions and writing. EV led discussions on the paleosols. KK and MH performed the XRF analysis. SC supervised the project and writing.

The authors declare that they have no conflict of interest

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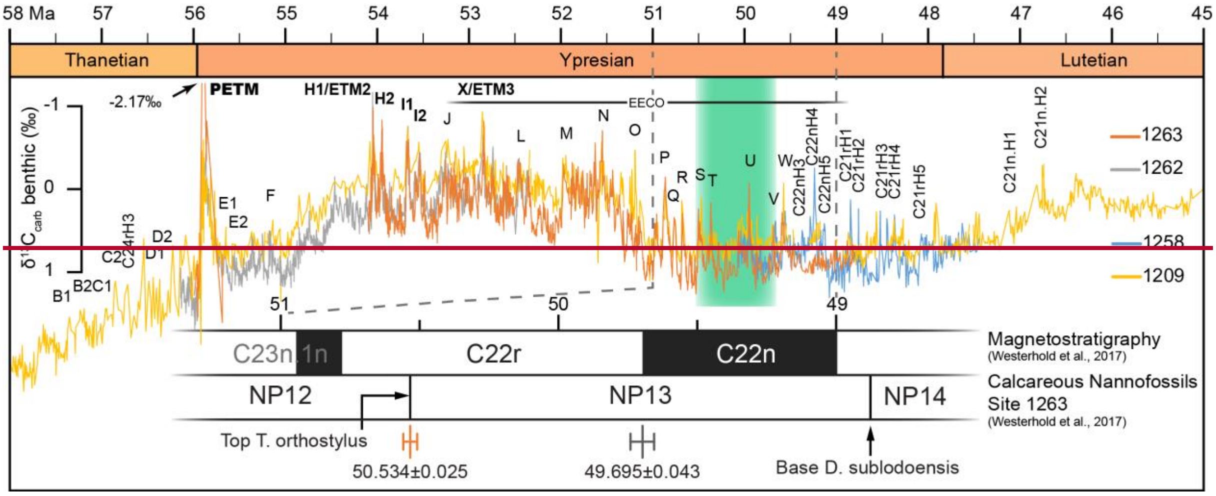

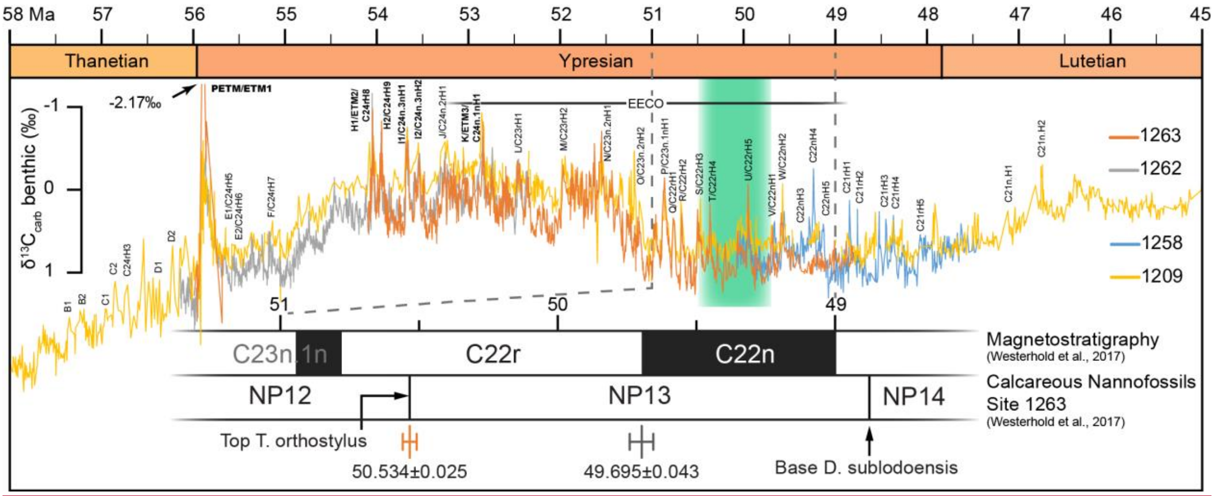

Figure 1: Late Paleocene and early-Eocene benthic carbon isotope record from Sites 1209, 1258, 1262 and 1263. Top of Chron C22r and top of T. orthostylus zone from site 1263 from Westerhold et al. (2017). Hyperthermal nomenclature from Cramer et al. (2003), Lauretano et al. (2016) and Westerhold et al. (2017). Castissent Fm. extension in green.

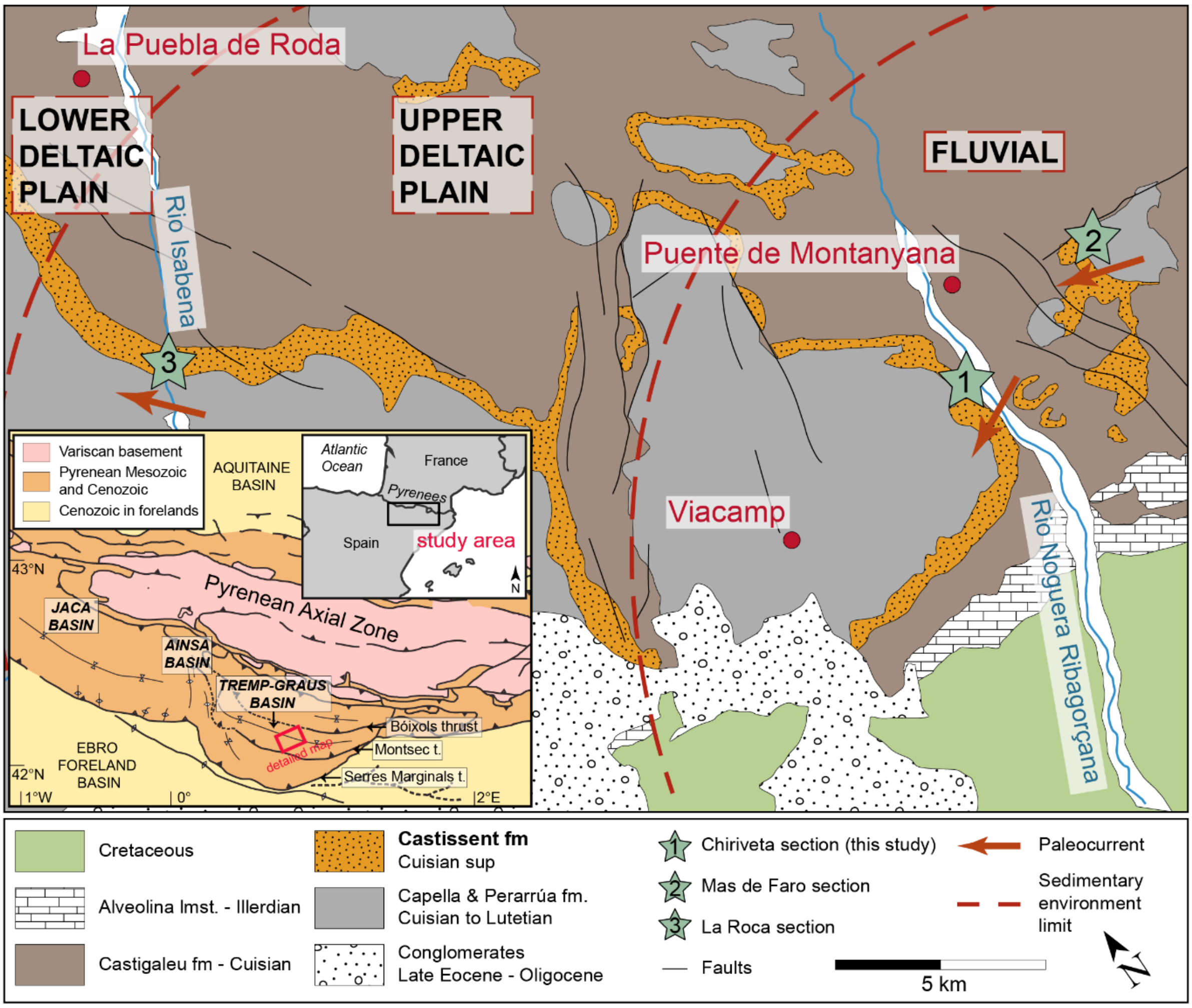

Figure 2: Simplified situation and geological map of the study area with main depositional paleo-environments (e.g., Nijman, 1998). The Castissent Fm. is a prominent fluvial unit particularly well-exposed in the Noguera Ribagorçana and Isabena river valleys. (1) Chiriveta section (2) Mas de Faro (3) La Roca section. Main paleoflow directions indicated in orange (from Nijman and Puigdefabregas, 1978). Regional map after Teixell (1998).

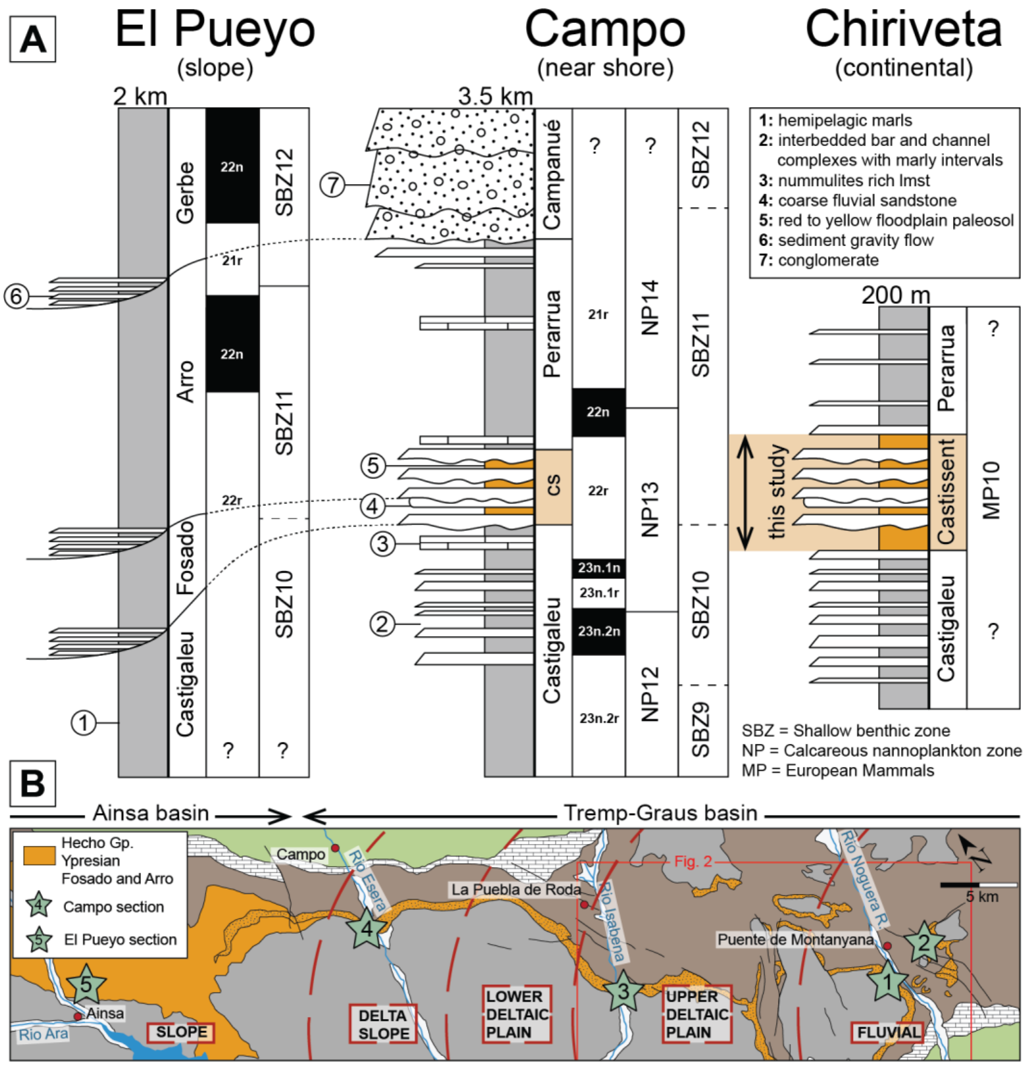

Figure 3: A - Time constraints on the Castissent Fm. MP zone from the continental section from Checa-Soler (2004) and Payros and Tosquella (2009). SBZ and NP in the Campo section from (Schaub, 1966, 1981; Kapellos and Schaub, 1973; Tosquella, 1995)**, magnetostratigraphy from Bentham and Burbank (1996). SBZ in El Pueyo section from Payros and Tosquella (2009). Magnetostratigraphy in El Pueyo from Poyatos-Moré (2014). B – Extended map of the study area. For map legend and references, see Fig. 2.**

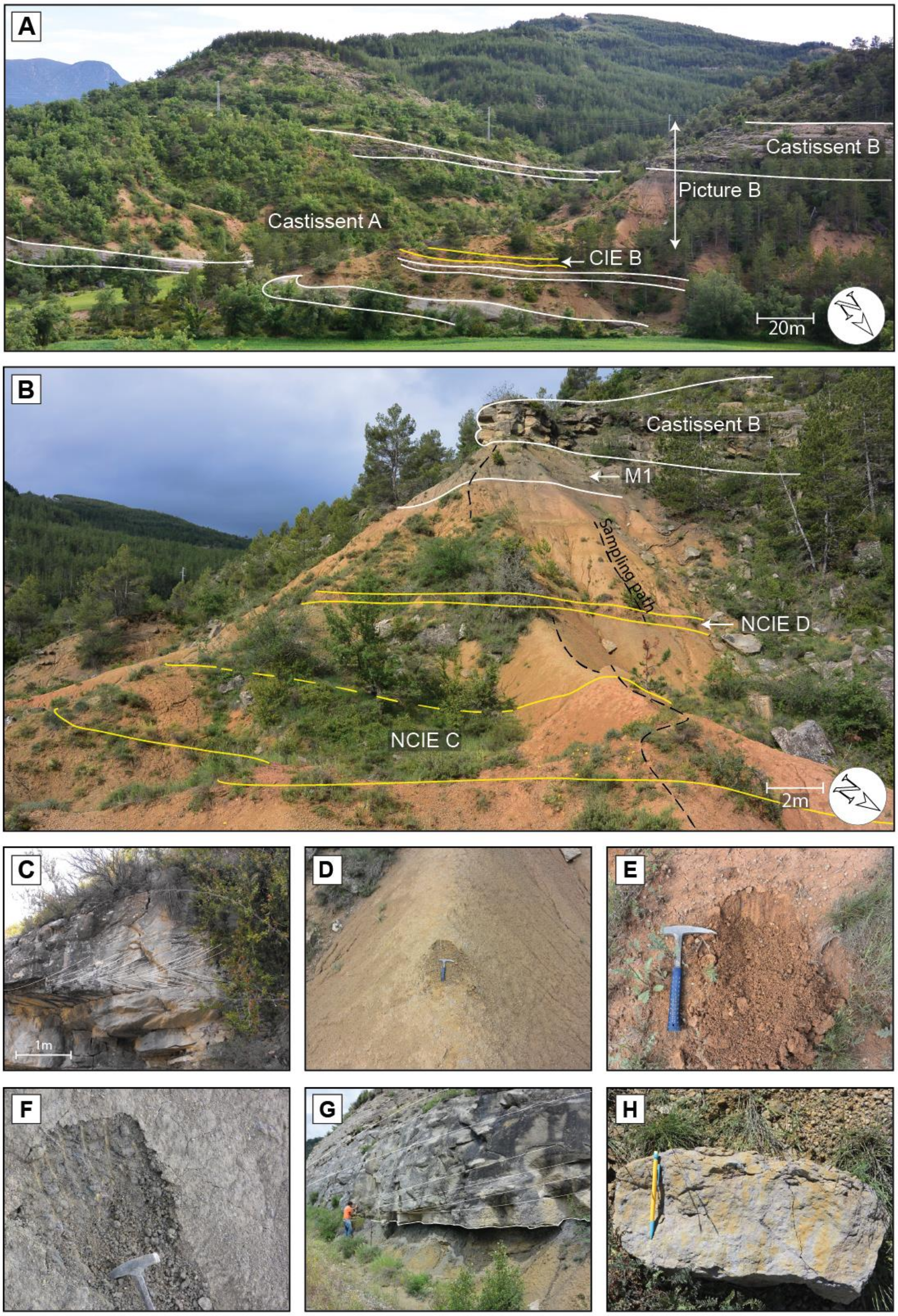

Figure 4: Field images of the Chiriveta section (42°7'56.57"N, 0°41'19.45"E). A – Outcrop view of Members A and B of the Castissent Formation. B – Close-up view of the upper part of Castissent A Member. Fluvial channel-fill deposits, intercalated in reddish floodplain and overbank deposits and regional marine incursions (M1). C – M0, first marine incursion at the base of the Castissent Fm. described by Marzo et al. (1988) expressed in the Chiriveta section by a tidal-influenced coarse sandstone with herringbone cross-stratification. D – Yellow mottled paleosol between ~~NCIE~~CIE C and D. E – Redfloodplain interval equivalent of the ~~NCIE~~CIE C. F – 2 m-thick grey interval interpreted as poorly drained brackish water facies and equivalent to the marine incursion M1. G – ~6m thick laterally extensive Castissent B sandbody incised in the underlying floodplain deposits. H – Mottled silt, interpreted as pedogenetic fluvial channel overbank deposits.

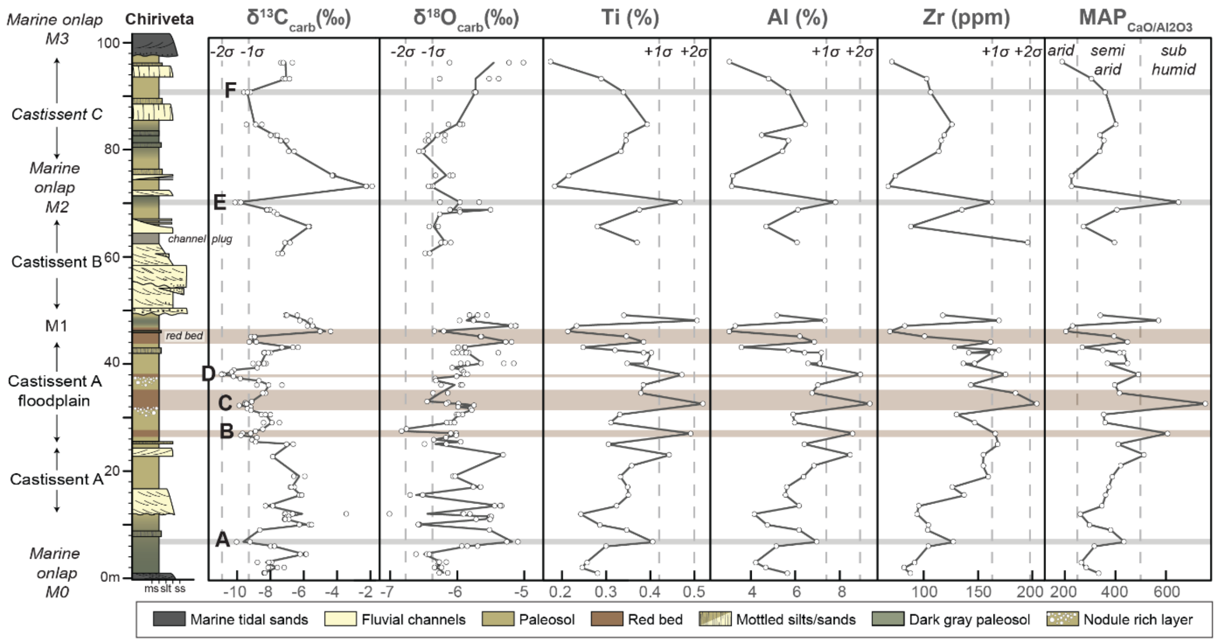

Figure 5: Isotopic and geochemical data from the Chiriveta section. For the isotope dataset, the curves passes through the mean values at each sample position. Samples with minimum in δ^{13}C values below 1 and 2 standard deviation are labelled A to F. Mean Annual Precipitation (MAP) was estimated from the empirical relationship between MAP and CaO to Al_2O_3 ratio (Sheldon et al., 2002).

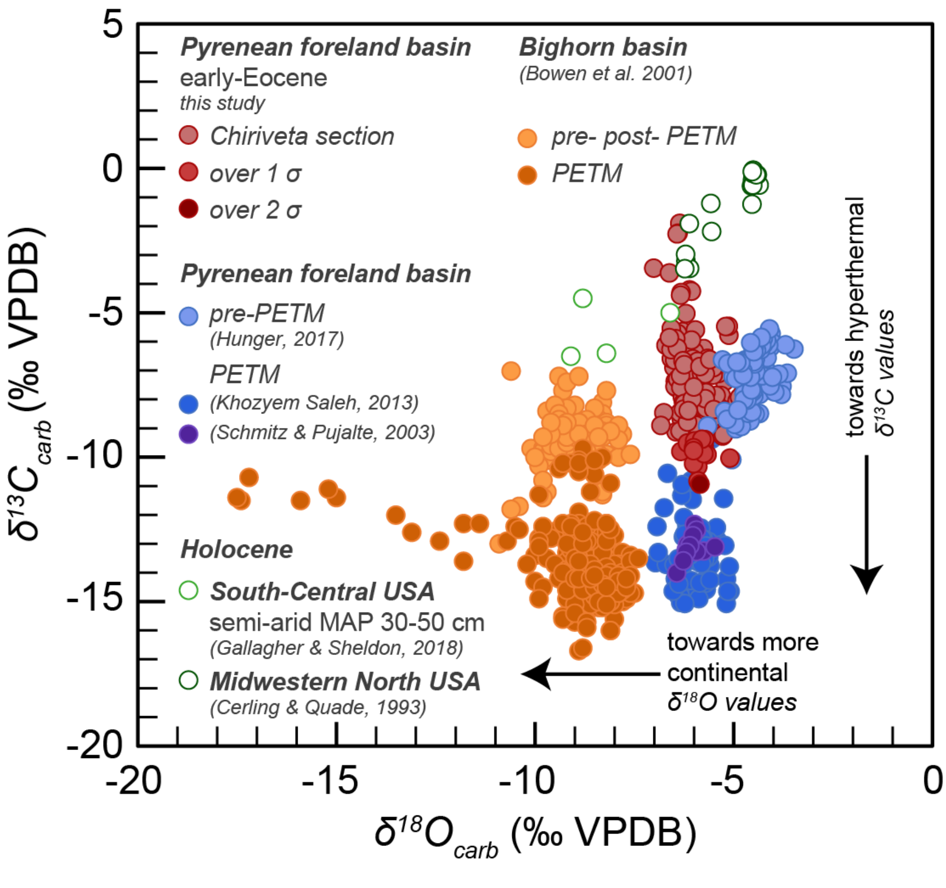

Figure 6: Continental δ^{13}C and δ^{18}O values from the early Eocene Castissent Fm. in the Chiriveta section (this study) plotted with pre- and syn-PETM δ^{13}C and δ^{18}O values from the same area (Khozyem Saleh, 2013; Hunger, 2018) **and Pre-, syn and post-PETM values from the Bighorn Basin (Bowen et al., 2001) as well as recent pedogenic carbonate isotopic values (Cerling and Quade, 1993; Gallagher and Sheldon, 2016).**

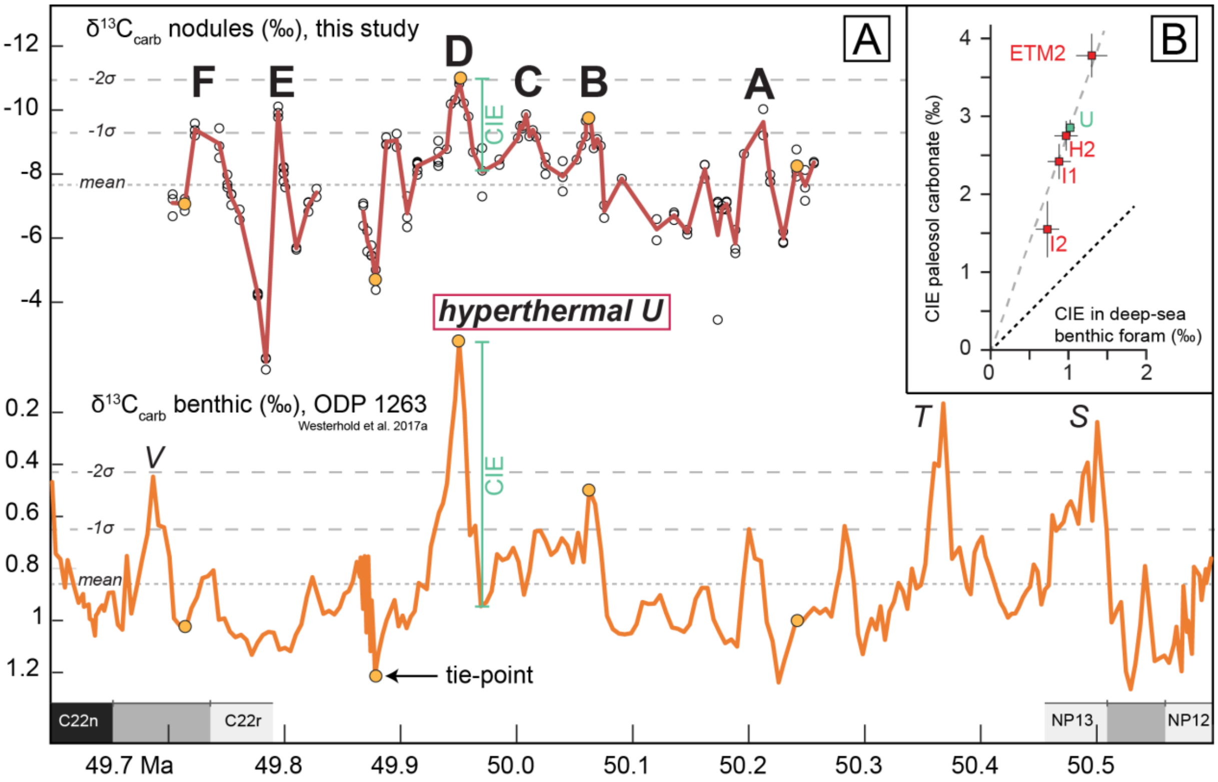

Figure 7: A - Scaling of the Chiriveta isotopic section with the time equivalent interval of site 1263 (Westerhold et al., 2017). The correlation was calculated using the Analyseries software (Paillard et al., 1996) and centred on ~~NCIE~~CIE D and hyperthermal U. Mean, minus 1 and 2 SD lines on the global record were calculated sets over the selected time period. The correlation coefficient (*r*) between the two curves is 0.65. B - Hyperthermal U amplitude in paleosol carbonate and benthic foraminifera (inset B after Abels et al. (2016))

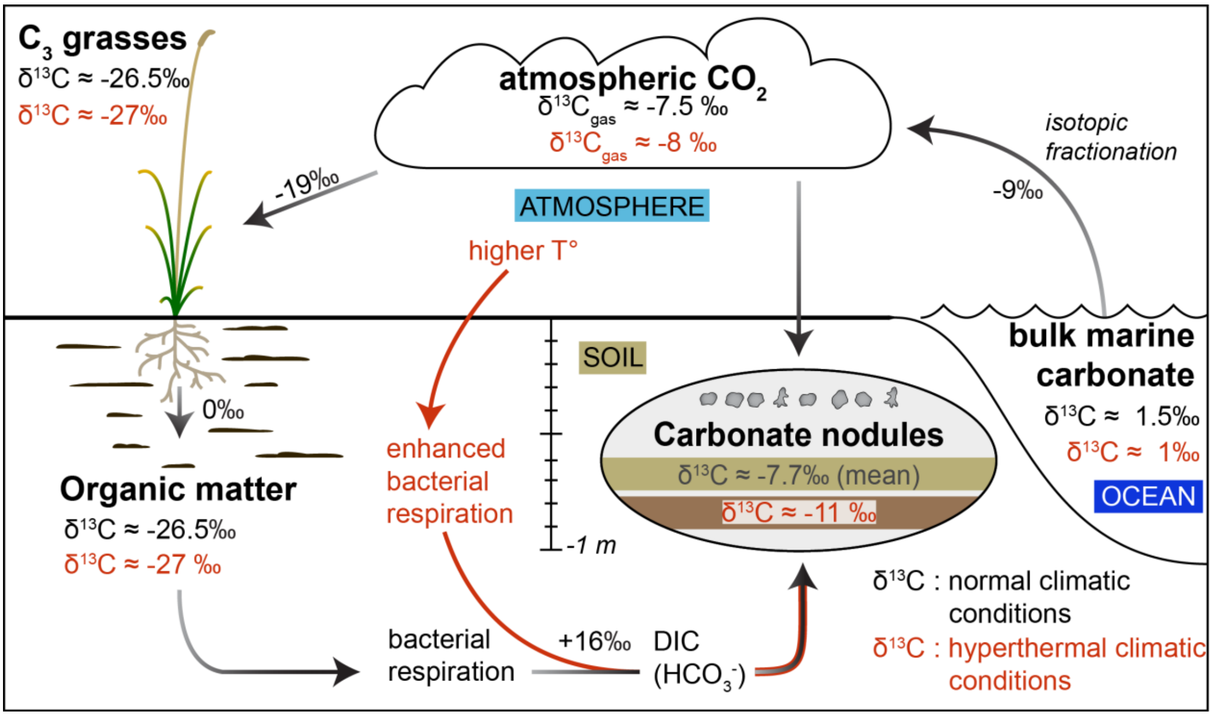

Figure 8: Components influencing the $\delta^{13}C$ values of pedogenic carbonate nodules. Mean early Eocene bulk marine carbonate and small scale hyperthermal (all except PETM) are from Westerhold et al. (2018). Fractionation value between organic matter and carbonate nodules are based on Sheldon and Tabor (2009). All other fractionation values are based on Koch et al. (1995). Mean carbonate nodule values come from this study.