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Fingerprinting enhanced floodplain reworking during the Paleocene–Eocene Thermal Maximum in the Southern Pyrenees (Spain): Implications for channel dynamics and carbon burial

Marine Prieur[1,*], Alexander C. Whittaker[2], Perach Nuriel[1], Rocío Jaimes-Gutierrez[1], Eduardo Garzanti[3], Marta Roigé[4], Tor O. Sømme[5], Fritz Schlunegger[6], and Sébastien Castelltort[1]

[1]Department of Earth Sciences, University of Geneva, 1205 Geneva, Switzerland
[2]Department of Earth Science and Engineering, Imperial College London, SW7 2AZ London, UK
[3]Dipartimento di Scienze dell'Ambiente e della Terra, University of Milano-Bicocca, 20126 Milan, Italy
[4]Departament de Geologia, Universitat Autonoma de Barcelona, 08193 Bellaterra, Spain
[5]Equinor, 1364 Fornebu, Norway
[6]Institute of Geological Sciences, University of Bern, 3012 Bern, Switzerland

ABSTRACT

The sedimentary record of the Paleocene–Eocene Thermal Maximum (PETM, ca. 56 Ma) allows the study of feedback mechanisms over the entire duration of a climatic event, from carbon release to the subsequent recovery phase. Clay sedimentation increase in the oceans during the PETM is linked to enhanced terrestrial erosion. Fluvial channel mobility has been invoked to explain this increase in fine sediment export based on more frequent transitional avulsions. In this study, we test whether the reworking of *Microcodium* (prismatic calcite concretions) from the floodplain to marine environments can serve to fingerprint floodplain reworking due to channel mobility. We quantified the abundance of floodplain-sourced *Microcodium* grains reworked in fluvial to marine sandstones pre-dating and coeval to the PETM in the Southern Pyrenees (Tremp Basin, Spain). Laser ablation–inductively coupled plasma–mass spectrometry U-Pb ages on calcite confirm the Thanetian age of the *Microcodium* grains. Our data show a four-fold increase in the export of floodplain sediments to the marine domain during the PETM. Moreover, we show that this is predominantly due to enhanced channel mobility, reworking channel banks and interfluves, with increased erosion in the hinterland as a secondary factor. This increase in floodplain reworking would correspond to an increase in biospheric carbon burial flux by a factor of 2.2. Therefore, enhanced channel mobility and fine-grain sediment transport to the oceans during a climatic perturbation such as the PETM may constitute an important negative feedback mechanism.

INTRODUCTION

The Paleocene–Eocene Thermal Maximum (PETM, ca. 56 Ma) is an ∼200-k.y. period during which temperatures rose globally by 5–6 °C in 5–20 k.y., marking a significant perturbation of the carbon cycle and climate (McInerney and Wing, 2011; Tierney et al., 2022). Sedimentary successions deposited during this period provide a rare opportunity to extract a concrete narrative of Earth's response to rapid global warming, which is informative in the context of current climate change (Pancost, 2017).

Several marine sedimentary records of the PETM across the globe show sedimentation rate increasing by factors of 2–10 (Schmitz et al., 2001; John et al., 2008; Carmichael et al., 2017; Sømme et al., 2023), which reflects enhanced delivery of fine-grained sediments sourced from the continent (John et al., 2008; Carmichael et al., 2017; Podrecca et al., 2021; Sharman et al., 2023; Vimpere et al., 2023). This enhanced supply potentially played a major feedback role in the PETM duration and recovery through the transport and burial of organic carbon (John et al., 2008; Galy et al., 2015; Lyons et al., 2019; Hilton and West, 2020).

Increases in clastic supply in both continental and marine environments during the PETM (Schmitz and Pujalte, 2007; Foreman, 2014) have been explained by enhanced flood discharge (Chen et al., 2018) and erosion due in part to increased seasonality (Carmichael et al., 2017; Tierney et al., 2022) and possibly amplified by declining vegetation and floodplain cohesiveness (Foreman, 2014).

However, Barefoot et al. (2022) recently reported on reduced fluvial bar preservation and increased frequency of transitional avulsions in the Wasatch Formation (Piceance Basin, Colorado, USA). They linked this to an intensification of channel mobility associated with higher discharge variability during the PETM. According to this mechanism, while coarse sediments are retained on the continent, fine sediments are preferentially remobilized and exported to the ocean. Because their data set shows no change in channel slope, Barefoot et al. (2022) hypothesize that enhanced channel mobility could explain the significant increase in fine-sediment accumulation in marine settings during the PETM without a marked increase in total fluvial water discharge and sediment flux.

To test the "Barefoot hypothesis," we take advantage of the abundance of *Microcodium* in the Paleocene floodplains of the Pyrenean fore-

Marine Prieur https://orcid.org/0009-0008-9539-7632
*marine.prieur@unige.ch

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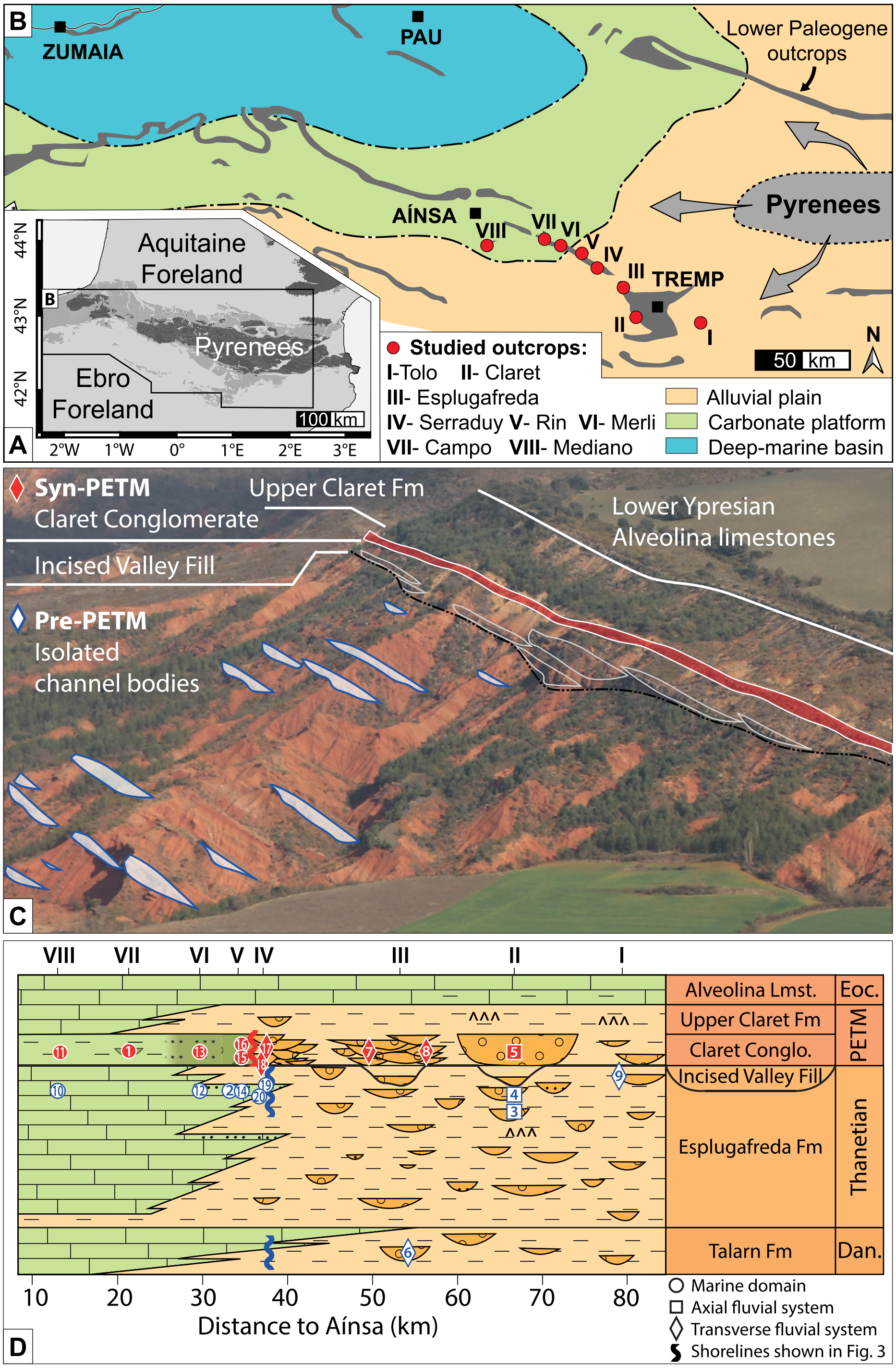

Figure 1. Study area. (A) Location map of the Pyrenees, Spain. (B) Reconstructed paleogeography (modified from Pujalte et al., 2015) with outcrop locations. (C) Continental Esplugafreda outcrop showing clear differences in floodplain preservation between pre- and syn-PETM (Paleocene–Eocene Thermal Maximum) intervals. Fm—Formation. (D) Lithostratigraphy with location of the samples (modified from Pujalte et al., 2014). Lmst.—Limestone; Conglo—conglomerate; Eoc.—Eocene; Dan.—Danian. Red samples are syn-PETM; blue samples are pre-PETM.

land (Cuevas, 1992; Basilici et al., 2022) to fingerprint the reworking of floodplain material to the ocean. *Microcodium* is a form of calcite concretion developing in soils, in association with roots (Košir, 2004; Kabanov et al., 2008). The primary productivity of *Microcodium* in Pyrenean floodplains is argued to be constant across the PETM because more diverse and abundant terrestrial palynomorphs were exported to the ocean (Schmitz et al., 2001), which is inconsistent with the hypothesis of a drop in their primary production due to less abundant vegetation (McInerney and Wing, 2011). When transported, *Microcodium* grains are found in fluvial to marine sandstones (Pujalte et al., 2019). Therefore, quantifying the amount of reworked *Microcodium* is a straightforward method to constrain floodplain reworking, allowing us to test for postulated changes in channel mobility during the PETM.

GEOLOGICAL SETTING

The PETM negative carbon isotopic excursion has been extensively described over the Tremp Basin in the South Pyrenean Foreland Basin (Spain; Fig. 1), where a direct correlation is drawn from continental to marine deposits (Pujalte et al., 2014). In the fluvial domain, the pre-PETM (Paleocene) Talarn and Esplugafreda Formations (Figs. 1C and 1D) are characterized by conglomeratic alluvial channel bodies isolated in extensive floodplain paleosols with abundant *Microcodium* and soil nodules (Cuevas, 1992; Dreyer, 1993; Schmitz and Pujalte, 2007; Colombera et al., 2017; Arévalo et al., 2022; Basilici et al., 2022) developed in a semiarid precipitation regime (Schmitz and Pujalte, 2007; Basilici et al., 2022). After a short episode of incision and filling of a fluvial valley network (Pujalte et al., 2014), sedimentation during the PETM onset is represented by the laterally extensive Claret Conglomerate (Fig. 1C), interpreted as a vast braid plain of amalgamated fluvial channels with limited preservation of floodplain deposits (Cuevas, 1992; Dreyer, 1993; Schmitz and Pujalte, 2007; Colombera et al., 2017; Arévalo et al., 2022; Payros et al., 2022). In the marine domain, syn-PETM siliciclastic deposits replace Paleocene carbonate platforms (Pujalte et al., 2014). The abrupt increase in fluvial channel-body amalgamation and the siliciclastic input to coastal and deeper marine environments have been linked to enhanced erosion and sediment supply from the hinterland due to the PETM warming and associated extreme flooding events (Schmitz and Pujalte, 2007; Chen et al., 2018; Arévalo et al., 2022). The amalgamated nature of the Claret Conglomerate and channel architectures in the Esplugafreda section (e.g., Colombera et al., 2017; Arévalo et al., 2022) are also suggestive of increased lateral channel migration during the PETM similar to that postulated for the Piceance Basin by Barefoot et al. (2022).

MATERIAL AND METHODS

We sampled pre-PETM (i.e., Paleocene) and syn-PETM sections outcropping along a 70-km-long transect (Fig. 1B). A total of 20 samples were collected from coarse-to-medium sandstones deposited in channel fills or shallow-marine environments (Fig. 1D). Thin sections were prepared for each sample and studied under natural and polarized light, point-counting 400 elements per slide. The classification includes (1) *Microcodium* grains, (2) catchment-sourced carbonate clasts, (3) catchment-

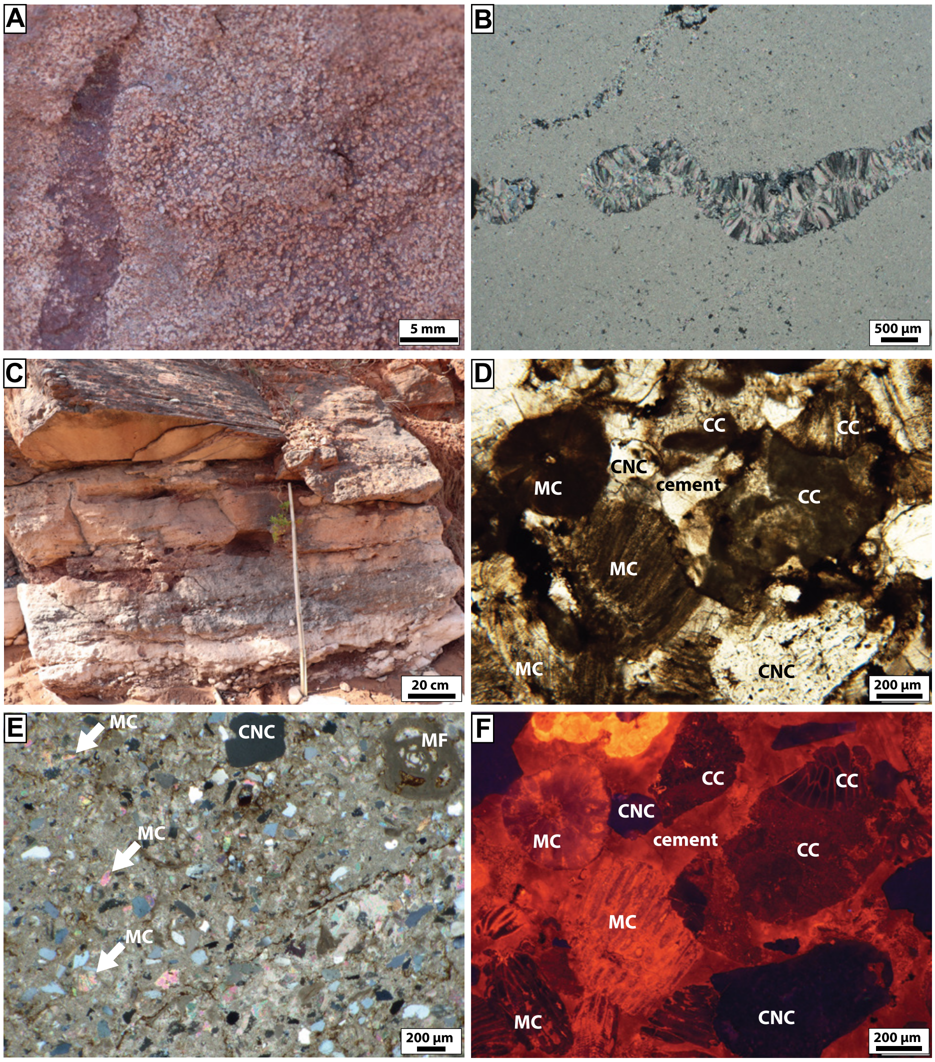

Figure 2. *Microcodium* grains as seen in the field and in microscope images. (A) Floodplain deposit made of *Microcodium* remains (white spherules) with root trace, Thanetian, Esplugafreda section (South Pyrenean Foreland Basin, Spain). (B) In situ *Microcodium* in a Danian calcrete, Rin section. (C) A fluvial channel, Thanetian, Esplugafreda section. (D) Reworked *Microcodium* grains observed in C. (E) Reworked *Microcodium* grains in a marine sandstone, Thanetian, Serraduy section; cross-polarized light. (F) Cathodoluminescence image of D, with the example of a *Microcodium* grain included in a clast. CC—catchment-sourced carbonate clast; CNC—catchment-sourced non-carbonate clast; MC—*Microcodium*; MF—marine fauna.

sourced non-carbonate clasts, (4) marine fauna, and (5) matrix (Fig. 2). Undetermined grains constitute 5%, on average, of the counted elements. For each sample, we calculated the number of *Microcodium* grains over all counted elements ($[\mu c]^{bulk}$), and the number of *Microcodium* grains over all transported grains (*Microcodium* debris and hinterland-sourced clasts) ($[\mu c]^{clasts}$). Additionally, the size of the *Microcodium* grains and clasts were measured (see Supplemental Material[1]).

In the sandstones, *Microcodium* is observed either as isolated grains or encased in carbonate clasts (Fig. 2). We suggest isolated *Microcodium* grains (Fig. 2) come from unconsolidated floodplain deposits of Paleocene age, in which they are abundant (Cuevas, 1992; Dreyer, 1993; Schmitz and Pujalte, 2007; Colombera et al., 2017; Arévalo et al., 2022; Basilici et al., 2022; Payros et al., 2022), and *Microcodium* encased in clasts are sourced from older deposits eroded in the hinterland. To test this assumption, we selected 65 *Microcodium* grains and clasts using cathodoluminescence and dated them through 496 spot analyses using U-Pb on calcite by laser ablation–inductively coupled plasma–mass spectrometry (detailed analytical procedure and data are provided in the Supplemental Material). The weighted mean ages are 52.9 ± 15.1 Ma for isolated *Microcodium* grains, consistent with the late Paleocene–Eocene, and 72.0 ± 11.0 Ma for *Microcodium* encased in carbonate clasts, sourced from late Cretaceous rocks in the hinterland (Díaz-Molina et al., 2007). We note that while Pujalte et al. (2019) postulated Jurassic bedrock-related soil for the source of *Microcodium* reworked in Paleocene–Eocene turbidites in the Betics (southern Spain), the isolated *Microcodium* grains in fluvial to marine sandstones in the Tremp Basin result from the reworking of floodplain deposits associated with late Paleocene channel banks and interfluves.

RESULTS AND DISCUSSION

The concentration of floodplain-derived *Microcodium* grains entering the sea increases significantly, by a factor of four, during the PETM (Fig. 3A), from 6.5% (blue in Fig. 3) to more than 25% (red in Fig. 3) in the marine sandstones. This result directly suggests a significant increase in remobilized floodplain sediments during the thermal maximum, coherent with the high amalgamation rate of the Claret Conglomerate. Our observation is also consistent with the three-fold increase in the proportion of clay and silts observed in PETM marine sediments by Podrecca et al. (2021) in the New Jersey (USA) coastal plain, and with the many records of increased terrestrial input (Podrecca et al., 2021; Sharman et al., 2023; Vimpere et al., 2023).

In the fluvial domain, the percentage of *Microcodium* grains per sample is highly variable. The average varies from 26.9% in pre-PETM samples to 16.4% during the PETM (Fig. 3A) with no statistical difference (see Supplemental Material). Because it is independent of grain size (see Supplemental Material Fig. S1) and of the nature of the fluvial system (Fig. 3), this variability seems inherent to fluvial depositional processes that may relate to different channel architectures (Colombera et al., 2017; Arévalo et al., 2022).

We questioned whether our results relate to a step change in lateral channel mobility at the PETM, reworking floodplains (Barefoot et al., 2022), or whether they can solely be explained by an overall increase in sediment flux (including *Microcodium* grains) in the channels and sourced from hinterland catchments (Pujalte et al., 2015). To test this, we compared the concentration of *Microcodium* grains ($[\mu c]^{bulk}$, Fig. 3A) with the ratio of *Microcodium* debris over all transported clasts ($[\mu c]^{clasts}$, Fig. 3B). We expect $[\mu c]^{clasts}$ to remain relatively unchanged across the PETM compared to $[\mu c]^{bulk}$ if the increased sediment flux is derived from hinterland catchments only. In the marine domain, $[\mu c]^{clasts}$ increases by a factor of three during the PETM (Fig. 3B), which is slightly less than the four-fold increase in $[\mu c]^{bulk}$. This suggests

[1]Supplemental Material. Point-count and grain-size data, method, and LA-ICP-MS U-Pb dating data. Please visit https://doi.org/10.1130/GEOL.S.25829587 to access the supplemental material; contact editing@geosociety.org with any questions.

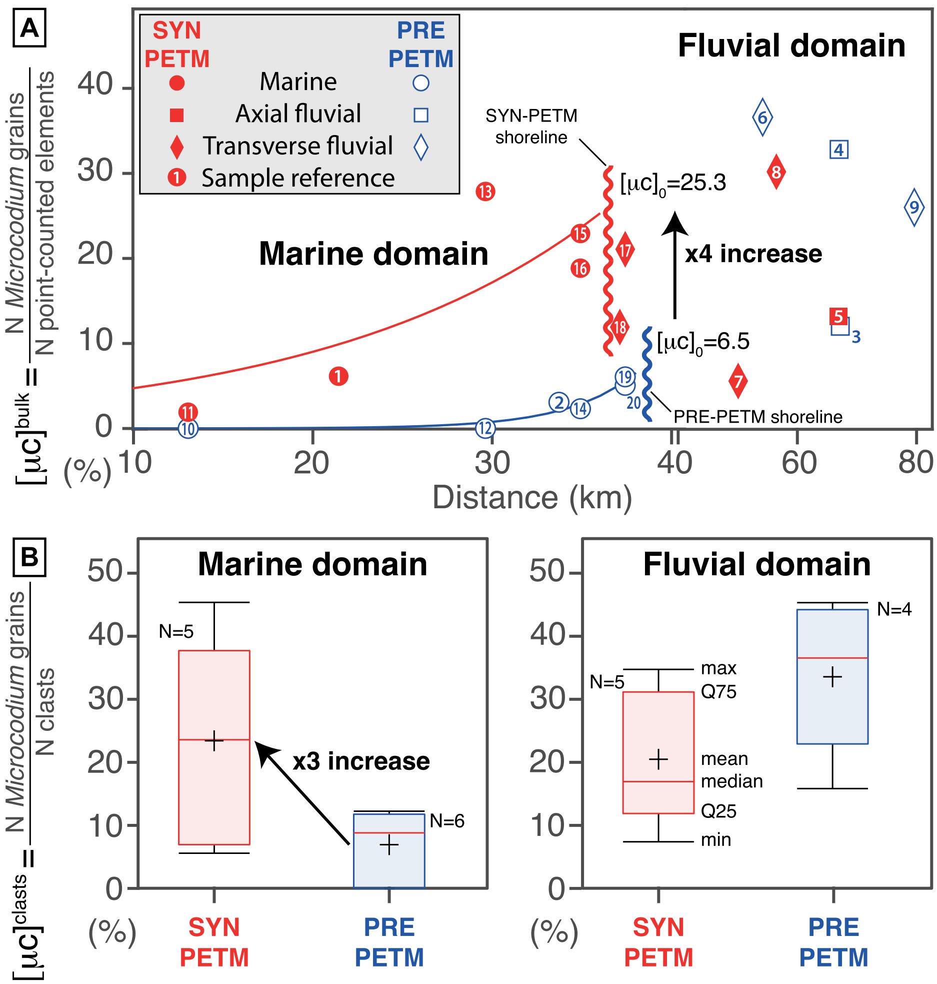

Figure 3. Abundance of *Microcodium* grains in sandstones deposited prior to (blue) and during (red) the Paleocene–Eocene Thermal Maximum (PETM) in fluvial to marine domains in the South Pyrenean Foreland Basin, Spain. The shoreline retrogrades slightly during the PETM. (A) Number of *Microcodium* grains point-counted from 400 elements per thin section plotted with radial distance to Aínsa village. Error bars are smaller than the point size, and solid lines are exponential fits. (B) Ratio of the amount of *Microcodium* grains over all clasts (N—number of samples per boxplot).

a small increase in the export of hinterland-sourced clasts to the ocean during the PETM compared to the marked increase in the export of *Microcodium* grains. Therefore, *Microcodium* grains are predominantly sourced from the alluvial domain, and their reworking must result from channel mobility. This directly reconstructed increase in channel mobility during the PETM in the Southern Pyrenees supports the inferences drawn by Barefoot et al. (2022) in the Piceance Basin. The triggers of the increase in channel mobility may be extreme flooding events due to increased discharge variability (Carmichael et al., 2017; Barefoot et al., 2022), increased sediment flux (Bryant et al., 1995; Wickert et al., 2013; Pujalte et al., 2015), and increased bank erodibility due to vegetation change (Schmitz et al., 2001; Foreman, 2014).

In the marine domain, the abundance of *Microcodium* grains decreases exponentially from the shoreline in pre- and syn-PETM sandstones (R^2 of 0.93 and 0.64, respectively) (Fig. 3A). The maximum transport distance of *Microcodium* grains increases from 16 km to more than 35 km during the PETM. Nevertheless, no *Microcodium* grains are reported in the deep-water Zumaia succession, located more than 230 km farther west (Fig. 1B), sometimes reconstructed as the ultimate sink for the Claret system (e.g., Duller et al., 2019). The sequestration of *Microcodium* grains to the shelf questions the extent to which reworked floodplain deposits fed deep-water sedimentary systems during the PETM. However, the size of *Microcodium* grains (100–1300 μm; see the Supplemental Material) is bigger than the silt and clay sediments that compose 80% of the floodplain in which *Microcodium* formed (Basilici et al., 2022) and from which they were eroded. We propose that during the PETM, a four-fold increase in the reworking of floodplain deposits from the alluvial domain to the ocean led to the deposition of *Microcodium* grains on the shelf, whereas finer grains were transported in more distal environments due to the faster transport of fine-grained sediments (Tofelde et al., 2021). Moreover, the differential transport modes based on grain sizes explain the rapid arrival of clastic sediments in Zumaia within 15–30 k.y. (Duller et al., 2019).

Such an increase in the export of terrestrial fine-grained sediments leads to carbon cycle feedback through organic matter burial (Bains et al., 2000; Galy et al., 2015). Based on modern river systems, Galy et al. (2015) scaled biospheric carbon fluxes (Y_{bios}) to suspended sediment yields (Y_{sed}) with the following equation: $Y_{bios} = 0.081\ Y_{sed}^{0.56}$. According to this equation, a four-fold increase in floodplain reworking would result in an ~2.2-fold increase in carbon burial flux from the biosphere. This preliminary estimation illustrates the importance of channel dynamics in modulating the interaction between surface processes and climate. Moreover, enhanced export of fine-grained sediments to the ocean impacts nutrient fluxes and marine biodiversity (Salles et al., 2023).

Therefore, increased channel mobility and the subsequent floodplain reworking may have significant implications for carbon budgets and biodiversity in a warming world.

CONCLUSIONS

We use *Microcodium* grains formed in floodplain settings and transported to coastal sandstones in the Tremp Basin (Southern Pyrenees) to fingerprint the increase in floodplain reworking during the PETM. Our data show a four-fold increase in reworked floodplain deposits entering the sea during this period. Dating the reworked *Microcodium* grains confirms their origin from late Paleocene overbank deposits and interfluves. Therefore, the reworking of floodplain deposits to marine environments results from fluvial channel mobility, which increased during the PETM as observed in the Piceance Basin (USA) by Barefoot et al. (2022). Although sediment flux from the hinterland increases as well, we show that channel mobility and the subsequent reworking of floodplain material is the primary driver of enhanced export of fine sediments to the ocean during the PETM. According to empirical models, multiplying floodplain reworking by four would increase organic carbon burial by at least two, potentially acting as a negative feedback mechanism. These results highlight the importance of channel dynamics in the interplay between climate and surface processes. In the context of anthropogenic climate change, our findings provide an important perspective on the complex links between human-influenced landscape dynamics, floodplain degradation, and the carbon cycle.

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