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Delayed sedimentary response to abrupt climate change at the Paleocene-Eocene boundary, northern Spain

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ABSTRACT

Sediment routing systems (SRSs) are a critical element of the global response to ongoing climate change. However, SRS response to climate forcing is complex, fragmentary, and obscured when viewed over short, human time scales (10⁻¹–10⁻² yr). Over long time scales (10⁻²–10⁻³ yr), the aggregated, system-wide response of SRSs to climate forcing can be gleaned with more confidence from the sedimentary record, but the nature and time scales of this aggregated response to abrupt climate change are still poorly understood. Here, we investigate the aggregated temporal response of a SRS in northern Spain to abrupt climate warming at the Paleocene-Eocene thermal maximum (PETM). Our results show that terrestrial sites in northern Spain record a temporal lag of 16.5 ± 7.5 k.y. between the onset of the PETM, defined by an abrupt negative excursion in the δ¹³C profile, and the onset of coarse-grained deposition. Within the same SRS at a deep marine site 500 km to the west, we observe a temporal lag of 16.5 ± 1.5 k.y. using an age model that is independent of that used for the terrestrial sites. These results suggest that the aggregated, system-wide response of SRSs to present-day global warming—if we take the PETM as an appropriate modern-day analogue—may persist for many millennia into the future.

METHODS

To quantify the temporal relationship between the onset of the PETM climate perturbation and the response of the Spanish PETM SRS, we first assume that a close coupling existed between the onset of the PETM and the PETM climate perturbation. This is supported by high-resolution studies of expanded PETM sections from the New Jersey margin (USA) that find no significant lag between δ¹³C and δ¹⁸O records (Zeebe et al., 2016). Here we focus on quantifying the lag time (τₛ) between the onset of the PETM and the onset of coarse-grained detrital deposition (OCD) in a study section. To do this, we first calculate a mean sedimentation rate for each section using the latest estimates of PETM CIE duration (Westerhold et al., 2018) and the measured stratigraphic thickness of the CIE at each location. To account for uncertainty in the precise identification of the CIE “core” (~100 k.y. duration) versus “core and recovery” (~180 k.y.) in the study sections, we calculate lower and upper estimates for sedimentation rate using both of these durations (Westerhold et al., 2018).

Our approach should give minimum τₛ values for two reasons. First, sedimentation rates in most sections increase substantially during the
The calculated durations of the stratigraphic offset between the onset of the PETM CIE and the base of the Claret conglomerate is strong evidence for a temporal lag of SRS response. On this basis, the lag values calculated here are almost certainly minimum estimates. We note that, for our purposes, the calculation of $t_{lag}$ is not compromised by the Sadler effect (Sadler, 1981).

To further explore the stratigraphic response of SRSs to abrupt hydrological change, we utilize a one-dimensional (1-D) sediment transport model (see the GSA Data Repository1). The model solves for the change in topography due to the transport of sediment downslope, which is calculated to be a delay in sediment transport at the Esplugafreda section (0.1 m yr$^{-1}$) has led to a reduced level of stratigraphic completeness (Sadler, 1981; Straub and Esposito, 2013), inhibiting proxy record preservation and precluding the identification of a resolvable $t_{lag}$ (Foreman and Straub, 2017). We tentatively estimate the Campo $t_{lag}$ to be 20–36 k.y.

A new age model for the deep marine segment of this SRS at Zumaia (Fig. 1), alongside a record of detrital mass accumulation rate ($MAR_p$) (Dunkley Jones et al., 2018), allows for a unique comparison of the terrestrial and marine response to the same event. The $MAR_p$ data from the Zumaia section show an immediate response to the CIE, increasing from 1 g cm$^{-2}$ k.y.$^{-1}$ to 3 g cm$^{-2}$ k.y.$^{-1}$ over the first 5 k.y. (Fig. 2E). This elevated value is maintained for 10 k.y. before increasing abruptly to 7 g cm$^{-2}$ k.y.$^{-1}$ over a period of <4 k.y., an increase that lags behind the CIE by $t_{lag} = 15–18$ k.y., while maximum $MAR_p$ values are attained 25–30 k.y. after the onset of the CIE (Fig. 2E). The immediate response of $MAR_p$ to the CIE is due to the greater advective length scales or transportability of finer-grained material (Ganti et al., 2014). However, the synchronicity of the arrival of coarse material at the terrestrial sites and the increase in $MAR_p$ at the deep marine site suggests that a single causative mechanism is responsible for the observed time lag. The data presented above strongly suggest that SRSs may take $\sim$10$^3$ yr to respond to abrupt, large-magnitude climate change.

The results of the 1-D sediment transport model demonstrate that a $t_{lag}$ can be reproduced (Fig. 3). The greater the precipitation increase over the 5 k.y. onset duration, the shorter the value of $t_{lag}$ (Fig. 3). The truncation of individual grain size profiles (e.g., Fig. 3B) signifies sediment bypass and non-deposition (i.e. a time gap) of the coarsest grain-size populations. We suggest that this phase of bypass is recorded in northern Spain as a 20–30-m-thick succession of fine-grained floodplain sediment that directly overlies the Claret conglomerate. The model predicts $t_{lag}$ values of 0 k.y. at 50 km distance from the origin, 10–35 k.y. at 100 km, and 45–85 k.y. at 150 km (Fig. 3D), which is not dissimilar to the field estimates of $t_{lag}$. We acknowledge that these model results are approximations.
As a comparison, $t_{lag}$ values were calculated for two well-studied sections in the Piceance Creek basin of western Colorado (Foreman et al., 2012) and the Bighorn Basin of Wyoming (Foreman, 2014), giving values of $t_{lag} = 22$–40 k.y. and 14–25 k.y., respectively (see the Data Repository). The presence of a $t_{lag}$ in PETM sections in the United States and in northern Spain might suggest a common mechanism of generation. However, we advise slight caution on this because the value of $t_{lag}$ will depend on the input grain size of the sediment supply, location within the basin, and local basin and earth-surface conditions that dictate the degree of stratigraphic completeness (Foreman and Straub, 2017).

Given the lag times present in many of the studied PETM sections, our results suggest that it may take up to 15 k.y. for SRS to achieve a total and aggregated, system-wide response to modern abrupt climate forcing. This time scale probably represents an upper estimate given that anthropogenic carbon release rates are an order of magnitude greater than that associated with the PETM CIE (Zeebe et al., 2016). The aggregated, system-wide response time scale described here is akin to the time scale necessary for "system clearing" (Jerolmack and Paola, 2010; Foreman et al., 2012) to occur in an individual SRS following abrupt climate forcing. This temporal and spatial character of SRS response is a function of the nature of climate forcing and the size and sensitivity of the SRS (Jerolmack and Paola, 2010; Knight and Harrison, 2013). From a stratigraphic perspective, accurately decoding past climate from sedimentary caliber or type alone is problematic given the observed complex response of SRSs, where sedimentary layers may well be recording an event that took place 10^4 yr earlier. From the perspective of modern global change, it is clear that the response of SRSs to anthropogenically induced climate change has only just started. Based on the available PETM data, dramatic changes in sediment erosion, sediment flux, and sediment accumulation rates across both terrestrial and marine segments of SRSs are likely to evolve and persist for millennia to come.

**CONCLUSION**

A linked terrestrial to deep marine sediment routing system in northern Spain records a stratigraphic offset between the abrupt onset of warming and hydrological change at the PETM, and the onset of deposition of greater amounts of detrital grains at both the terrestrial and deep marine sections. The calculated duration of this stratigraphic offset ($t_{lag}$) is on the order of 16.5 ± 7.5 k.y. for terrestrial sites and 16.5 ± 1.5 k.y. for the deep marine site, each using independent age models. This SRS-wide response and $t_{lag}$ value range are reproduced using a 1-D sediment transport model, which supports the mechanism of delayed sediment transport from the sediment source area to locations down-system. Our data provide new field and modeling constraints on the response of SRSs to abrupt climate change and highlight the protracted response of our landscape to current global warming, which may take millennia.

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Figure 3. Model results of time delay as function of distance from source. A: Four “increased precipitation” scenarios. $\Delta p$—positive change in precipitation from initial value of 0.5 m yr$^{-1}$; $\Delta p = 0.25$ m yr$^{-1}$; $\Delta p = 0.50$ m yr$^{-1}$; $\Delta p = 1.00$ m yr$^{-1}$; $\Delta p = 1.00$ m yr$^{-1}$. B, C: Chronostratigraphic plots showing grain-size response of each precipitation scenario at two locations: at 50 km and 100 km from source. PO—Paleocene-Eocene thermal maximum (PETM) onset; OCD—onset of coarse detrital deposition; SBP—sediment bypass. Time difference between PO and OCD is time delay ($t_{lag}$). D: Model $t_{lag}$ results (white-filled symbols) and field data results (gray-filled symbols) plotted as function of distance. T—Tendry section; CL—Claret section; C—Campo section; Z—Zumaia section; $\text{MAR}_{\text{max}}$—Maximum detrital mass accumulation rate at Zumaia (Dunkley Jones et al., 2018).

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