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# Evidence for enhanced fluvial channel mobility and fine sediment export due to precipitation seasonality during the Paleocene-Eocene thermal maximum

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## ABSTRACT

**The Paleocene-Eocene thermal maximum (PETM) was the most extreme example of an abrupt global warming event in the Cenozoic, and it is widely discussed as a past analog for contemporary climate change. Anomalous accumulation of terrigenous mud in marginal shelf environments and concentration of sand in terrestrial deposits during the PETM have both been inferred to represent an increase in fluvial sediment flux. A corresponding increase in water discharge or river slope would have been required to transport this additional sediment. However, in many locations, evidence for changes in fluvial slope is weak, and geochemical proxies and climate models indicate that while runoff variability may have increased, mean annual precipitation was unaffected or potentially decreased. Here, we explored whether changes in river morphodynamics under variable-discharge conditions could have contributed to increased fluvial sand concentration during the PETM. Using field observations, we reconstructed channel paleohydraulics, mobility, and avulsion behavior for the Wasatch Formation (Piceance Basin, Colorado, USA). Our data provide no evidence for changes in fluvial slope during the PETM, and thus no evidence for enhanced sediment discharge. However, our data do show evidence of increased fluvial bar reworking and advection of sediment to floodplains during channel avulsion, consistent with experimental studies of alluvial systems subjected to variable discharge. High discharge variability increases channel mobility and floodplain reworking, which retains coarse sediment while remobilizing and exporting fine sediment through the alluvial system. This mechanism can explain anomalous fine sediment accumulation on continental shelves without invoking sustained increases in fluvial sediment and water discharge.**

## INTRODUCTION

Increasing global temperatures are predicted to impact the hydrological cycle. The consequences of this can be understood by reconstructing hydrological conditions during past climate change (e.g., Slotnick et al., 2012). The Paleocene-Eocene thermal maximum (PETM) is the most prominent climate perturbation known in the Cenozoic (Zachos et al., 2008), and is considered to be one of the best geologic analogs for contemporary warming (Dickens et al., 1997; McInerney and Wing, 2011).

Identified in strata by a negative carbon isotope excursion (CIE; Kennett and Stott, 1991), the PETM often manifests as drastic sedimentological changes, interpreted to be the result of significant climate-driven changes to landscape dynamics. For example, a terrigenous clay deposit marks marginal marine PETM sections worldwide (e.g., Nicolo et al., 2007). These deposits are attributed to elevated sediment flux from continents as a result of (1) enhanced hillslope weathering and mobilization (Lyons et al., 2019), and/or (2) large-scale sediment-transport "system-clearing" events (Jerolmack and Paola, 2010; Foreman et al., 2012). Both scenarios necessitate enhanced sediment transport capacity to drive sediment flux.

Studies from terrestrial basins assert that the signature of enhanced transport capacity and hillslope supply is evident in fluvial PETM deposits, which are generally channel-dominated, and enriched in sand relative to surrounding Paleocene and Eocene strata (e.g., Pujalte et al., 2015). In particular, paleochannel depth (Foreman et al., 2012) and slope reconstructions (Chen et al., 2018) are interpreted to show that channel-forming water discharge increased because of enhanced intra-annual water discharge variability. However, the paleohydraulic techniques used to estimate these parameters carry substantial uncertainties (Trampush et al., 2014), and the connection between enhanced water discharge variability during the PETM and an overall increase in sediment transport capacity or supply is unclear.

Moreover, even without adjustments in sediment supply, water discharge variability in isolation can significantly impact fluvial morphodynamics and sediment storage in alluvial deposits. For example, Esposito et al. (2018) showed experimentally that intense flooding caused channels to migrate and avulse rapidly, as compared to channels that were supplied with the same time-averaged volume of water and sediment, but at a constant rate. Elevated channel mobility led to floodplain reworking, and this resulted in preferential preservation of channel facies in the strata, demonstrating that changes in total time-averaged water and sediment flux are not required to affect basin architecture. Thus, if evidence for enhanced mobility

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exists in the absence of change in channel geometry, it does not parsimoniously follow that a change in sediment flux from erosive catchments should be invoked. We used sedimentological evidence in the Piceance Basin, Colorado, to test whether an increase in sediment discharge during the PETM was the primary driver of global changes in sediment accumulation patterns, or whether increased discharge variability alone could be sufficient.

## STUDY LOCALITY

The Wasatch Formation (Piceance Basin, Colorado, USA; Fig. 1) is a >500-m-thick conformable succession of fluvial sediments within which the PETM CIE has been shown to coincide with an abrupt increase in sand content and channel amalgamation (Foreman et al., 2012). This PETM interval occurs in the Molina Member, which consists of interconnected, sheet-like amalgamated sand bodies with relatively thin intervening layers of floodplain mud (~40% channel). In contrast, the underlying Atwell Gulch and overlying Shire Members of the Wasatch Formation consist predominantly of muddy floodplain paleosols encasing isolated channel sand bodies (~20% channel; Donnell, 1969). The fluvial sediments studied here accumulated in a Laramide basin, within 100 km of the surrounding uplifts. The composition and uplift rate of the adjacent sediment sources remained the same throughout deposition (Johnson and Flores, 2003; Foreman et al., 2012). Larger channel sand bodies and upper-stage plane bed structures observed in the Molina Member (Foreman et al., 2012), as well as in coeval strata from neighboring basins (Foreman, 2014; Birgenheier et al., 2020), generally support a regional increase in water discharge seasonality (Plink-Björklund, 2015; Fielding et al., 2018) that is interpreted to have enhanced sediment flux across the region.

Evidence for a corresponding change in mean annual precipitation (MAP) from other methods, however, appears equivocal. Paleosol geochemical and paleofloral records in the Piceance Basin (Erhardt, 2005) and the nearby Bighorn Basin (Wing et al., 2005; Kraus and Riggins, 2007) suggest an ~40% decrease in MAP. Yet, ichnofossils and paleosol sedimentology suggest highly variable floodplain drainage conditions (Smith et al., 2008; Adams et al., 2011), more consistent with hydrologic variability. Climate model simulations predict minor drying conditions across the North American interior during the PETM, but with a significant change in seasonal distribution of rainfall and increased occurrence of the most extreme precipitation events (Carmichael et al., 2018). This suggests that the proxy records may be biased toward recording drier summer conditions. While future work may find an absolute decrease in MAP, we proceeded under the assumption that the change in rainfall variability during the PETM was the dominant effect on fluvial dynamics.

An increase in sediment supply would, by necessity, decrease the time-averaged water-to-sediment ratio and require enhanced sediment transport capacity. Without an increase in water discharge, changes in sediment supply have a limited impact on channel width (Bufe et al., 2019), so enhanced transport capacity should manifest as an increase in fluvial slope (e.g., Paola, 2000). Thus, in this basin, evidence for a increase in fluvial slope would be diagnostic of enhanced sediment supply.

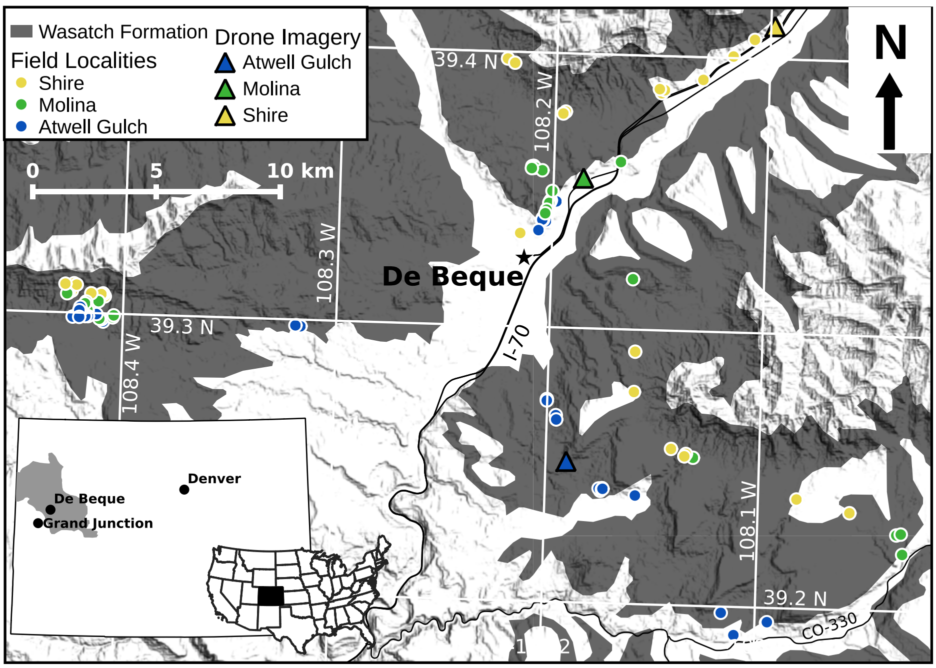


**Figure 1. Study area map showing outcrop extent of the Wasatch Formation (dark gray) in the Piceance Basin, Colorado, USA. Outcrops analyzed for new paleodepth and paleoslope estimates are indicated by circles. Bar preservation estimates were collected from outcrops indicated by triangles. Location data for all outcrops and measurements are included in the Supplemental Material (see footnote 1).**

## METHODS

Estimates of paleoflow depth through the Wasatch Formation were obtained by measuring the relief on fully preserved fluvial bar forms and channel-fill structures (following Ethridge and Schumm, 1977) for a total of 114 flow depth estimates. Paleoflow depths from bar clinoforms were combined with collocated measurements of bed-material sediment size, interpreted using a hand lens and grain-size card, to estimate paleoslope via the empirical scaling (Eq. S1 in the Supplemental Material[1]) of Trampush et al. (2014).

To identify changes in paleochannel mobility, avulsion style and bar preservation were estimated through the Wasatch Formation. The basal contact of a fluvial sand body represents an avulsion event that is either preceded abruptly (without crevasse splays) or transitionally (with splays) (Jones and Hajek, 2007). Transitional-style avulsions in an alluvial basin indicate more active crevassing in the channel-floodplain system (Hajek and Edmonds, 2014). In contrast, stratigraphically abrupt avulsions indicate less crevasse-splay deposition. We classified avulsions from field observations in all three members of the Wasatch Formation using criteria in Jones and Hajek (2007).

To reconstruct channel mobility, drone imagery was collected for three outcrops in the Piceance Basin, and bar preservation was assessed following Chamberlin and Hajek (2019), where low preservation indicates higher channel-deposit reworking (and thus higher channel mobility, under constant-subsidence conditions). Photogrammetry was used to construct three-dimensional (3-D) digital models of the outcrop surface, and bar clinoforms were mapped on the 3-D digital outcrops. Bar forms

[1]Supplemental Material. A more-detailed explanation of the field methods used to collect the data for this study, and the statistical tools used to analyze the data, in addition to a description of how the data file is organized. This information should be applied in conjunction with the data and code if readers are interested in using these data for future work. Please visit https://doi.org/10.1130/GEOL.S.16674220 to access the supplemental material, and contact editing@geosociety.org with any questions. All data needed to replicate the study is available in the Supplemental Material, and code to analyze the data is available in a GitHub repository (https://doi.org/10.5281/zenodo.4067055). Photographs used to construct three-dimensional models are available in a Zenodo repository (https://doi.org/10.5281/zenodo.5079782).

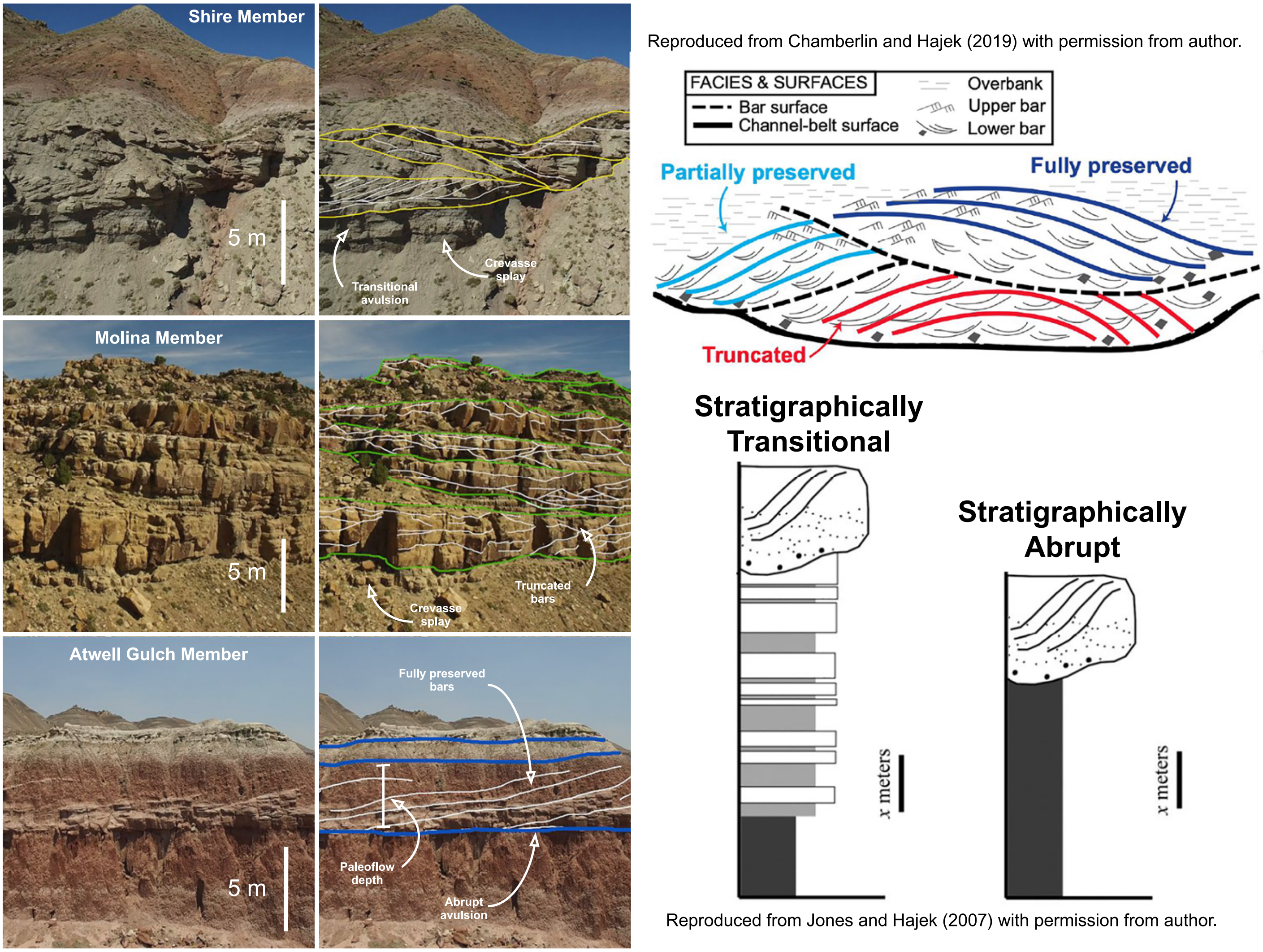


**Figure 2. Example outcrops showing key sedimentological features in each member of Wasatch Formation (Piceance Basin, Colorado, USA). Colored lines indicate bounding surfaces between channel stories. White lines in each photograph indicate bar and scour surfaces. Locations for photographs correspond to drone imagery locations in Figure 1. Line drawings show criteria used to determine bar preservation and avulsion style.**

were then classified within channel belts as either fully preserved, partially preserved, or truncated (see example interpretations in Fig. 2).

More detailed descriptions of methods, analysis, data format, and sources are given in the Supplemental Material.

## RESULTS

Paleoflow depths and bed-material grain sizes were statistically indistinguishable throughout the Wasatch Formation at a 95% confidence level (using a Kruskal-Wallis test; Table 1; Fig. 3A). Consequently, estimates of paleoslope in the Piceance Basin indicate no difference between the Molina Member and the bounding members at a 95% confidence level (Fig. 3B). Together, these results demonstrate that within the resolution of currently available paleohydraulic methods (Trampush et al., 2014), rivers were not likely to be substantially steeper during the PETM (Molina) as compared to the intervals before (Atwell Gulch Member) or after (Shire Member).

Bar clinoform mapping showed that 14.8% of bar forms in the Molina Member are fully preserved, whereas in the Atwell Gulch and Shire Members, 37.0% and 38.3% of bar forms are fully preserved, respectively (Fig. 3C). A $\chi^2$ test showed that there are significantly fewer fully preserved bar forms in the Molina Member ($\chi^2$ [1, $n$ = 141] = 7.55, $p$ = 0.006 [2-tailed]),

TABLE 1: PALEOHYDRAULIC RESULTS

| | Stratigraphic member* | Depth ± σ (m) | Slope ± σ (–) | Median bed-load grain size ± σ (μm) | Fully preserved bars ± σ (%) | Transitional avulsions ± σ (%) |
|---|---|---|---|---|---|---|
| Parameter estimates | Shire | 1.48 ± 0.954 | $7.03 \times 10^{-4}$ ± 65.4% | 247 ± 72.9 | 38.3 ± 7.02 | 22.4 ± 5.98 |
| | Molina | 1.72 ± 1.43 | $7.54 \times 10^{-4}$ ± 61.6% | 174 ± 102 | 14.8 ± 5.06 | 81.6 ± 4.97 |
| | Atwell Gulch | 1.68 ± 1.34 | $6.54 \times 10^{-4}$ ± 82.5% | 248 ± 85.6 | 37.0 ± 9.66 | 17.2 ± 4.42 |
| Statistical test results | | $p = 0.973^{\dagger}$ | $p = 0.676^{\dagger}$ | $p = 0.963^{\dagger}$ | $p << 0.006^{\S}$ | $p << 0.001^{\S}$ |

*Data for Wasatch Formation in the Piceance Basin.
†Significance values for Kruskal-Wallis tests comparing flow depths and slope between different Members of the Wasatch Formation.
§Results from $\chi^2$ tests for the proportion of fully preserved bars and abundance of avulsion styles.

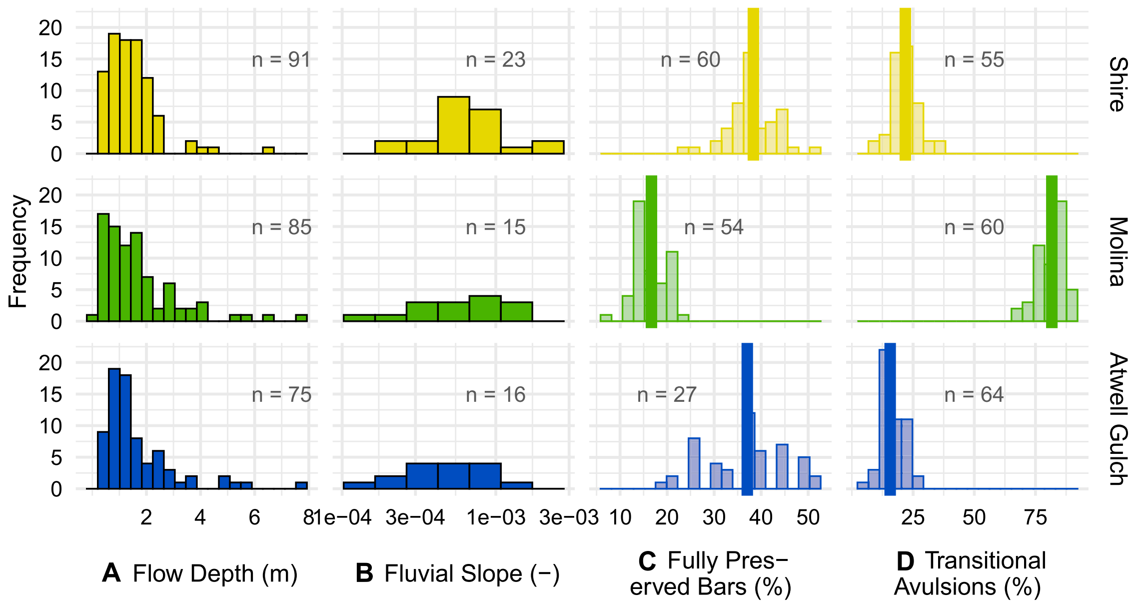


**Figure 3. Reconstructed Wasatch Formation (Piceance Basin, Colorado, USA) paleohydraulic parameters. Paleoflow estimates represent new data collected in this study aggregated with published sources. Paleoslope measurements were derived from subset of paired paleoflow depth and grain-size data. Bar preservation estimates were derived from three-dimensional outcrops. Avulsion style was mapped in field. Vertical lines represent measured proportion of fully preserved bars and transitional avulsions in panels C and D. Shaded histograms represent bootstrapped values to visualize standard error. Statistics and values may be found in Table 1.**

indicating that bar forms in the Molina Member crosscut each other within channel belts more frequently than those in either the Shire or Atwell Gulch Members.

Our data also indicate that avulsion style changed during the Molina Member interval. Stratigraphically transitional avulsions were more abundant than abrupt avulsions in the Molina Member, as compared to the Shire and Atwell Gulch Members ($\chi^2$ [1, $n$ = 179] = 61.9, $p < 0.001$ [2-tailed]). This indicates that avulsions were more likely to occur via progradation and channel building by crevasse-splay deposition, rather than by incision into the floodplain (Hajek and Edmonds, 2014).

## DISCUSSION

The preponderance of truncated and partially preserved fluvial bar deposits observed in the Molina Member indicates enhanced fluvial reworking by mobile channels during the PETM as compared to the intervals before (Atwell Gulch) and after (Shire). Channel mobility is sensitive to a change in sediment supply if it impacts the water-to-sediment ratio (Bryant et al., 1995). Because time-averaged water discharge appears to have been largely constant during the PETM, if channel mobility were enhanced by an increase in sediment supply, an adjustment to channel gradient would be expected to handle the additional load. Our estimates did not resolve an adjustment in channel gradient. This indicates that, within uncertainty, Piceance rivers did not steepen to convey elevated sediment discharge from catchments during the PETM (Table 1).

The abundant evidence of enhanced channel mobility is therefore most parsimoniously explained simply as a consequence of increased water discharge variability during the PETM without invoking an increase in sediment supply (Esposito et al., 2018). Mechanistically, intervals of high-intensity flow would have exerted higher shear stress on channel banks, promoting enhanced erosion and accelerated lateral migration (Konsoer et al., 2017). This mechanism may have caused channels during the PETM to have widened or become braided, but given the available exposure and existing paleohydraulic techniques, a change in planform morphology cannot be distinguished from a simple change in channel mobility. Elevated bed shear stress during intensified flooding would have also enhanced bed-material entrainment (Rouse, 1939); higher bed-material entrainment would have enhanced crevasse-splay deposition and increased the tendency for progradational avulsions during the PETM (Millard et al., 2017). Altogether, the channel-dominated strata and lack of bar preservation in the Molina Member parallel observations from studies in a number of modern rivers with highly variable flow, summarized in Fielding et al. (2018), as well as from experimental studies (Esposito et al., 2018), and they favor a scenario where discharge variability increased, but overall sediment supply remained stable.

The consequence of increased lateral mobility and crevasse-dominated avulsions was to enrich Piceance floodplain strata with coarse bed sediment. Bar preservation estimates imply that mobile channels reworked near-surface deposits, preferentially entraining fines and transporting them downstream, while a change in avulsion style partitioned suspended bed material into floodplain deposits. Because an increase in sediment supply cannot be inferred, and fluvial slope was unchanged through the PETM, sediment mass balancing dictates that within a source-to-sink framework, increased reworking and stratigraphic sand concentration in the Piceance Basin should have occurred in conjunction with increased fine sediment flux downstream. If this model of fluvial response to changing hydroclimate during the PETM bears out in similar basins, it has the potential to explain broad trends across depositional environments without requiring a sustained, continent-scale increase in sediment and water flux.

## CONCLUSIONS AND IMPLICATIONS

We applied paleohydraulic techniques in the Piceance Basin of western Colorado to constrain changes in channel-floodplain processes connected with abrupt climate change during the PETM. The analyses indicated that fluvial channel geometries, including depth and slope, remained constant across the PETM boundary. However, fluvial structures were more often truncated and crosscut during the PETM interval, and avulsions became transitional in nature. Taken together with experimental and observational studies of discharge variability and paleoclimate evidence from the region, the most plausible explanation of these findings from the Piceance Basin is that, all else being equal, terrestrial floodplains subjected to seasonally intense precipitation experienced accelerated channel dynamics. In this way, mud bypassed floodplain storage through morphodynamic reworking, while sand was retained in both channel and floodplain deposits in the basin. This framework emphasizes that changing hydrological regimes under global warming can induce morphodynamic sorting, even in the absence of long-term changes in water or sediment discharge. Moreover, these results suggest that if global warming enhances precipitation seasonality in the future, this may drive enhanced suspended sediment flux to oceans, threatening coastal ecosystems that depend on low turbidity.


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