High channel mobility sequesters coarse sediment in floodplain deposits

Eric Barefoot

# Abstract

# Introduction

The Paleocene Eocene Thermal Maximum (PETM) is the most severe climate perturbation known in the Cenozoic Era. The PETM is associated with altered hydrological cycling and precipitation extremes driven by rapid warming and accumulation of atmospheric carbon. As such, it serves as the best-known, and best-studied past analogue for contemporary anthropogenic climate warming. By studying paleo-environmental change during the PETM, we can better understand the mechanisms by which landscapes respond to rapid climate warming. Insights derived from the paleoenvironmental record of the PETM can be leveraged to guide and improve climate models and long-term hazard forecasts.

The stratigraphic record of the PETM generally indicates that altered hydrological cycling and temperature patterns impacted landscapes and sedimentary systems. Associated most often with a distinct, abrupt shift in sedimentary facies, the PETM has been identified to coincide with lithostratigraphic contacts globally. For example, the PETM is connected to increased terrestrial fine-grained flux to marginal marine environments , coarsening and braiding of fluvial environments , and

Overall, these globally-distributed observations suggest that terrestrial sediment transport systems responded to accommodate altered hydrological cycling, but mechanisms invoked for this response are ambiguous or inconclusive. Generally, previous studies suggest that increased discharge , transient increases in sediment flux , or fluvial steepening are responsible for changes in fluvial style and sediment transport. However, it has not been demonstrated that changes in total water and sediment flux are necessary conditions for sedimentological changes in fluvial systems during the PETM.

Previous work has generally relied on observations of sedimentary structures that correlate with channel and floodplain geometries, i.e. channel depths, channel widths, bedload grain size, and reach-averaged slope. Testing hypotheses of fluvial paleohydraulics with geometry-based methods is complicated by uncertainty inherent in the inversion relationships, as well as unknown variance fluvial geometries in the floodplain . Furthermore, geometric models for paleohydraulics require extrapolation to infer the dynamics of the fluvial system, introducing additional error and uncertainty. However, recent work has highlighted new methods to directly estimate relative rates of channel processes, or derive a proxy for relative rates of channel kinematics. When combined with geometric observations, indicators of fluvial paleokinematics may help to capture both the total scale of the system and its behavior as the system evolved through PETM time.

Therefore, we return to the Piceance Creek Basin, a field site previously studied as a case study of fluvial response to altered hydrological cycling during the PETM. Studies of the Piceance Basin to date have remained equivocal as to the precise mechanisms generating fluvial response at the PETM boundary. In particular, it is not clear whether fluvial systems experienced net changes in sediment and water flux during the PETM. Increased fluxes and floodplain diffusivity implies (increasing/decreasing) river gradients and more active channel kinematics, which should be expected to be preserved in the stratigraphic record. Nonetheless, these predictions have not been tested with paleohydraulic techniques developed in recent years since the initial studies on the Piceance Basin.

In particular, the model predicts that higher sediment and water fluxes generated deeper, coarser channels, and higher floodplain diffusivity with a lower gradient. As a result, river channel geometries would be expected to grow, and estimates of slope are expected to decrease, while kinematics, or reworking, is expected to increase with a transient increase in sediment flux. We also consider an alternative case, where mean sediment flux and water discharge is constant, but intra-annual variability in the flow conditions changes during the PETM.

Here, we deploy recently developed paleohydraulic techniques to evaluate hypothesized changes in fluvial geometries and kinematics and develop a new model for fluvial response to climatic perturbation.

# Study Site and Methods

To study the impacts of PETM-modulated changes in hydrological cycling, we turn to the Piceance Creek Basin, an intermontane Laramide depocenter active throughout the Paleogene and Eocene . Sedimentary fill of the Piceance Creek Basin is conformable across the Paleocene-Eocene boundary and records climate conditions integrated over approximately km of drainage area during the PETM . In the Piceance Creek Basin, the record of the PETM interval correlates with a distinctive sand-rich unit known as the Molina Member of the Wasatch Formation .

Juxtaposed between mud-rich units, the Molina Member exhibits starkly different sedimentological characteristics as opposed to the underlying Atwell Gulch Member and the overlying Shire member of the Wasatch Formation. While the Atwell Gulch and Shire members are composed largely of isolated channel sand bodies confined within a matrix of fine-grained overbank deposits, the Molina member comprises interconnected, sheetlike amalgamated sand bodies with relatively thin intervening layers of floodplain fines. The distinctive sand enrichment in the Molina member has been attributed to a fluvial response to climate-induced changes to hydrological cycling during the PETM.

However, the precise mechanisms underlying the interpreted fluvial response remain unclear. The current accepted model invokes a transient increase in water and sediment flux to generate the selective deposition of coarse channel facies in the Molina member . It is difficult to distinguish between this scenario and alternative depositional histories though, because the equivalent signal could feasibly be generated through increased channel dynamics, independent of the net increase in sediment or water supply . More detailed and precise paleohydraulic methods may shed light on the relative importance of sediment supply and channel dynamics in the Piceance Basin, as these different sources of sedimentological change are predicted to alter the geometrical and kinematic properties of fluvial channels in dinstinctive ways.

The Piceance Creek is a uniquely suited locale for testing hypothesized landscape responses to climate perturbation using fluvial paleohydraulics. While climate is expected to influence basin dynamics significantly, other key allogenic forcing parameters such as tectonic uplift/subsidence and base level fluctuations have been previously shown to be either negligible or invariant through the PETM interval. Detrital zircon analysis and formation geometries argue against a sediment supply increase due to tectonic uplift or unroofing of sand-rich units in the hinterland. Additionally, the great distance of the paleo-shoreline (km) and a lack of evidence for temporally-variable subsidence indicate that neither of these allogenic mechanisms are likely to have influenced sedimentary stacking in the Piceance Creek Basin.

A climate-induced change in hydrological cycling, therefore, is the most parsimonious explanation for observed facies changes and enrichment of sand in the Molina member. However, to better understand how the mechanisms by which fluvial systems responded to altered hydrological cycling, it is necessary to distinguish between a scenario involving increased sediment and water flux and a scenario where average sediment supply and discharge were constant, but channel dynamics were different. We will distinguish between these scenarios by employing detailed paleohydraulic reconstructions of Molina fluvial systems as contrasted with Atwell Gulch and Shire alluvial systems. The main geometric attribute that is hypothesized to distinguish between these two scenarios are the size of channel deposits (particularly depth) and the reach-averaged slope of channels.

Our paleohydraulic toolkit for this study includes two methods to reconstruct bankfull channel depths, one method to reconstruct paleoslope, and a new technique for estimating reworking by avulsions and lateral migration. The main considerations for choosing paleohydraulic inversion techniques included a robust accounting of uncertainty in the model framework, and simple application to ancient deposits. 3D models of outcrops were derived from drone imagery and used to map bar clinoform structures, channel-fill structures, and bedding surfaces. We estimate paleo-flow depths primarily by measuring the total relief of fully preserved bar clinoforms . When outcrops lacked fully preserved bar strata, we estimate flow depth by measuring the distribution of cross-stratification thicknesses, and using empirical relations to convert dune cross-stratification to flow depth, with associated uncertainty. Flow depth estimates, and grain size information for interpreted bedload deposits are combined in an empirical relation from to derive an estimate of paleoslope. Finally, the relative proportions of fully-preserved, partially preserved, and truncated bar strata were estimated to derive an index of fluvial reworking.

This model takes as parameters fluvial sediment flux, grain size distribution (sand v mud), basin geometries, and subsidence rate. Floodplain sediment composition is determined in this model by the relative proportion of channel deposits vs overbank sediments, each of which have a predetermined sand concentration, where channels have a higher enrichment in sand. Channel sand-bodies rework overbank sediments, replacing them with channel deposits. By varying channel geometries and kinematic rates relative to subsidence rates, channel deposits occupy more or less of the morphodynamic reworking zone. In this way, based on observations of the total enrichment in sand, the abundance of channel deposits, and the frequency of cross-cutting relationships, inferences are made of channel geometries and kinematic rates as a function of floodplain parameters.

# Results and Interpretations

Paleohydraulic estimates from the Piceance Creek indicate that measured channel geometries were across the PETM boundary. Our estimates of paleoflow depth and paleoslope show no differences between the Molina Member and the bounding Atwell Gulch and Shire members . Despite clear differences in sedimentology between the three members, these results suggest that within the resolution of current methods, rivers during the PETM were than before or after the climate perturbation. This implies that rivers in the Piceance Basin did not necessarily carry an increased sediment flux or higher discharge as a result of changes to regional climate and hydrological cycling.

Paleohydraulic estimates are, however, difficult to constrain in outcrop with high confidence, as the techniques rely on empirical relations developed from modern systems with associated uncertainty. Statistical inference for paleoslope, for example, is limited in resolution to a factor of 10 . It is therefore feasible that paleoslope in the Piceance Creek Basin could have changed by less than a factor of ten, and the current state of the art methods would not be able to detect the change. The poor resolution of techniques based on channel geometries alone limits inference in the ancient record, and prompts the refinement of existing paleohydraulic models and the development of new ones.

It is important to note that the poor resolution of paleohydraulic methods only preclude interpretation that the paleoslope in the Piceance Basin did not increase by more than a factor of ten. Previous work suggested that increased sediment flux due to hillslope clearing and vegetation overturn could changed slope in the Piceance Basin. This remains a possibility, however, as a substantial increase of even a factor of two or five in fluvial slope to accomodate increased sediment supply would go undetected using current methods. Similarly, even amongst rivers with comparable depth, discharge can vary by up to a factor of 5, suggesting that inferences based on paleo-depths in the stratigraphic record are likely insensitive to even doubling of discharge. A change in channel kinematics is therefore the most likely primary agent for changing sediment partitioning in the Piceance Basin because there is affirmative evidence for this process. However, it is feasible that adjustments in total discharge and sediment flux occurred in the Piceance Basin, but they cannot presently be detected with confidence.

With no strong evidence for increased total fluxes of water or sediment in channel geometries, we turn to the complimentary question of interpreting channel paleokinematics. We employ a newly developed technique that quantifies the interrelationship and reworking of fluvial structures, thereby the kinematics of fluvial channels during the PETM in the Piceance Basin. Drone imagery was collected from outcrops throughout the Shire, Molina, and Atwell Gulch members of the Wasatch Formation and was processed using photogrammetry to generate 3D models of outcrops. This drone imagery was interpreted using and barform structures identified and mapped. geometric information was collected for all barforms, as well as their interrelationships and degree of preservation.

Mapping of meso-scale sedimentary structures shows that barforms in the Molina member intersect each other more often, crosscut each other more frequently, and are overall less well preserved than in either the Shire or Atwell Gulch members. The geometries of fully-preserved barforms indicate that channels were not substantially deeper, , but rather that channel forms revisited locations frequently, cross-cutting previously deposited structures and reworking the floodplain surface. These data imply that while channel morphology and geometries were very similar before, during, and after the PETM, channels were more laterally mobile or avulsed more frequently, causing increased reworking of the floodplain surface.

Through avulsion and more rapid channel migration, fluvial kinematics recombed the floodplain surface in the Piceance Creek Basin during the PETM. We mapped large-scale structures by stratigraphic surfaces and classified channel-forms by their avulsion style, data for which indicate that there were more avulsions in the PETM interval. These results too suggest more rapid channel kinematics, and more frequent incisional avulsions relative to subsidence rates. As a result, the average residence time of sediment in floodplain deposits would have decreased, exposing fine sediments to more frequent transport in alluvial channels. In this way, channels excavated previously deposited overbank material, which preferentially deposited channel bodies in the floodplain.

As channel deposits are generally composed of coarser material, the effect of more rapid channel kinematics was to change the overall composition of the floodplain. Whereas before and after the PETM, floodplain deposits were composed of approximately 20% coarse material, during the PETM, far more coarse material (up to 40%) was partitioned to floodplain deposits.

We interpret the increased floodplain coarse fraction of the Molina member to be due to increased reworking, and not a general increase in sediment supply or discharge. This inference is supported by a lack of observable change in channel geometries indicative of changing flux conditions, like adjustments to channel depth or slope. In contrast, many indicators exist for a substantial shift in rates and character of channel kinematics. Therefore we offer here a new interpretation of landscape response to shifting hydrolgical regime, whereby increased seasonality of discharge during the PETM weakened channel banks, allowing more rapid channel migration and altered in-channel sedimentation shortened avulsion timescales.

\*these prob belongs in the next section. An individual parcel of floodplain material therefore had a higher likelihood of being reworked, which likely increased the exposure frequency of floodplain organic matter to oxidation The converse of this assertion is sand is preferentially bypassed during Atwell and Shire time, likely due to stable channels that act as conduits for coarse sediment.

# Conclusions and Implications

Changes in paleodischarge and sediment flux has been previously invoked to explain sedimentological differences in the Piceance Creek Basin, as well as other localities. However, in the Piceance Basin, we do not find this interpretation to be strictly supported by paleohydraulic estimates of fluvial channel geometries. Our results suggest that sedimentological shifts during the PETM are instead driven by changes in channel kinematic rates. We propose that increased seasonality of precipitation during the PETM is responsible for sequestering more channel sediment in floodplain deposits by varying the lateral migration rate and avulsion timescales of the channel system.

Before the PETM, the hydrological regime favored meandering channels that seldom avulsed and laterally migrated through bar accretion. The outcome of this style of fluvial system is the preferential deposition of channel-derived sand bodies in thin ribbons. Low precipitation seasonality corresponds to low flooding intensity in the river system, a condition thought to induce strong, confining river banks that promote low width-to-depth ratio channels that migrate slowly an avulse seldomly. A low width-to-depth ratio induces high shear stresses on the bed, ensuring that coarse sediment is transported primarily in the thalweg, and low Froude numbers promote . Accordingly, with high bank strength, due both to vegetation density and cohesive material, channels would have migrated laterally at reduced rates, and increased shear stress year-round on the bed would have reduced in-channel sedimentation, forestalling superelevation of the riverbed, and therefore forcing less frequent avulsions.

In contrast, as a result of the PETM, an more intense flooding regime and peakier hydrograph increased channel activity, driving more channel sediment to be deposited in floodplains. The primary mechanisms for increasing channel kinematic rates is through destabilized banks. It is thought that decreased riparian vegetation density via seasonal drying and more intense flood peaks worked in tandem to increase the width-to-depth ratio of PETM rivers in the Piceance Creek Basin. Higher width-to-depth ratios in PETM rivers probably raised local Froude numbers of flows, potentially into critical, or even super-critical flows during flood stages. This increases the potential for significant in-channel sedimentation during low flows, and less confining ability for the channel during high flows. Both the infilling of channels during low flow, and low confinement during high flow, increase the likelihood of avulsion, thereby increasing avulsion frequency.

Our integrated observations of paleohydraulics favor a scenario where Piceance river systems were slow-moving and confined by strong banks during Atwell Gulch and Shire time, before and after the PETM. In contrast, during the PETM Piceance river systems had weak banks and moved rapidly across the floodplain surface during Molina time. The result of this see-saw change in fluvial system dynamics across the PETM was a change in the relative partitioning of coarse and fine sediment into floodplain deposits.

When river banks were strong, i.e. in Atwell Gulch and Shire times, low intensity flooding in Piceance rivers allowed only fine-grained silt and mud to be transported over levees to the floodplain. Coarser sand was insead transported in the thalweg, and low lateral migration rates relative to subsidence rates meant that thalweg deposits constitute a smaller fraction of the overall deposit. The result was that during Atwell Gulch and Shire time, river channels were most likely long-lived stable conduits conveying coarse material through the system without depositing it in the floodplain. In this way, we can consider Atwell Gulch and Shire rivers to be efficient transporters of sand, preferentially retaining mud and silt in the floodplain while allowing sand to bypass the depocenter.

Correspondingly, during Molina time, weak river banks and rapid channel kinematics relative to subsidence rates ensured that channels visited locations across the floodplain surface frequently, and that flood-stage flows could transport coarse sediment more effectively to the overbank environment. More frequent visitation of the river across the floodplain surface likely meant that deposits were re-excavated more frequently than during Atwell Gulch or Shire time, and fine silt and mud deposits were more likely to be re-mobilized during Molina time and replaced by coarse sand. Additionally, a higher incidence of crevasse splays and overbank coarse deposition preferentially sequestered coarse material in non-channel deposits. The integrated effect of these accelerated processes was that coarse sandy sediment was retained more often in the floodplain. As such, Piceance rivers during Molina time were inefficient transporters of sand, preferentially bypassing fine-grained silt and mud to downstream basins.

These results imply that hydrologically-modulated channel dynamics affect the distribution of sediment grain-size fractions retained in continental depocenters in unintuitive ways. Accelerated rates of lateral migration, for instance, have traditionally been thought to increase the diffusivity of floodplains, allowing coarser facies to prograde further into the basin system. Accordingly, lower rates of channel kinematics would be expected to inhibit the transport of coarse facies to distal portions of the basin. In fact, our finding suggest that the opposite may be true, and during periods of dampened channel kinematics, coarse sediment is actually preferentially bypassed through the system, and deposited even more distally than with active channels.

The preferential partitioning of grain-size fractions due to channel kinematic rates could have implications for understanding carbon cycling. As recent studies have highlighted , the PETM is associated with a sustained period of -depleted carbon release, which they hypothesize could be due to increased export of fossil carbon from soils. The primary evidence for this claim is the increased accumulation of fossil carbon and increased accumulation of fine-grained sediment in marine sequences. However, do not invoke a precise mechanism for the increased reworking of soil fossil carbon, only stating that by some process, floodplain material is reworked to expose fossil soil carbon to respiration. Our observations suggest that increased seasonality of precipitation is a viable mechanism to promote increased reworking of fossil carbon reservoirs. In the process of excavating fine-grained silt and sand reservoirs, Molina rivers would have also reëxposed carbon stored in those floodplain deposits to respiration. We propose that a global increase in precipitation seasonality may be the mechanism driving the excess flux in soil carbon after the initial PETM onset.

In certain circumstances, the impact of climate modulation on channel dynamics may adjust conventional notions of where petroleum reservoirs are emplaced along the source-to-sink continuum. For example, a system under a highly seasonal hydrology would be expected to partition sand preferentially in the proximal parts of the source-to-sink system, and off-shore deposits would be expected to be rich in mud. As a result, knowledge of climate conditions during exploration could indicate that most reservoir-forming deposits may be located in terrestrial reservoirs during that interval. Additionally, reservors emplaced by laterally mobile systems like Molina river systems will exhibit greater reservoir connectivity due to the frequent interaction of sand bodies in the formation.

The absolute timing of fluvial response as it relates to the onset of the PETM is difficult to constrain in the stratigraphic record. However, it is clear that channel dynamics in the Piceance Basin adjusted rapidly to new hydrological conditions. As humanity prepares for environmental impacts due to anthropogenic climate change, it will be important to consider the medium and long-term consequences for infrastructure situated on floodplains. Higher-intensity flooding in some regions may drive significant increases in channel mobility, threatening adjacent floodplain communities. Increased risk of avulsions due to changes in hydrological cycling would also present a threat to communities.