LETTER

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Fluvial response to abrupt global warming at the Palaeocene/Eocene boundary

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Climate strongly affects the production of sediment from mountain catchments as well as its transport and deposition within adjacent sedimentary basins[1–3]. However, identifying climatic influences on basin stratigraphy is complicated by nonlinearities, feedback loops, lag times, buffering and convergence among processes within the sediment routeing system[3,4]. The Palaeocene/Eocene thermal maximum (PETM) arguably represents the most abrupt and dramatic instance of global warming in the Cenozoic era and has been proposed to be a geologic analogue for anthropogenic climate change[5]. Here we evaluate the fluvial response in western Colorado to the PETM. Concomitant with the carbon isotope excursion marking the PETM we document a basin-wide shift to thick, multistoried, sheets of sandstone characterized by variable channel dimensions, dominance of upper flow regime sedimentary structures, and prevalent crevasse splay deposits. This progradation of coarse-grained lithofacies matches model predictions for rapid increases in sediment flux and discharge[1,3], instigated by regional vegetation overturn[5,6] and enhanced monsoon precipitation[7,8]. Yet the change in fluvial deposition persisted long after the approximately 200,000-year-long PETM[9] with its increased carbon dioxide levels in the atmosphere, emphasizing the strong role the protracted transmission of catchment responses to distant depositional systems has in constructing large-scale basin stratigraphy. Our results, combined with evidence for increased dissolved loads[10] and terrestrial clay export[5,11,12] to world oceans, indicate that the transient hyper-greenhouse climate of the PETM may represent a major geomorphic 'system-clearing event'[13], involving a global mobilization of dissolved and solid sediment loads on Earth's surface.

During the PETM, an extreme global warming event that occurred about 56 million years ago[5], mean annual temperatures increased by 5°–8° C, precipitation and vegetation patterns dramatically altered worldwide, and both atmospheric and oceanic circulation was perturbed[5,6,8]. The warming was associated with a massive exogenic pulse of isotopically light carbon into Earth's oceans and atmosphere, recorded as a major negative carbon isotope excursion in a suite of organic and carbonate substrates hosted in marine and terrestrial strata[5]. Although more than 4,000 petagrams of carbon (Pg C) were released in less than 10,000 years (10 kyr), a high atmospheric partial pressure of CO_2 (p_{CO_2} exceeding 1,200 p.p.m.; ref. 5) persisted for an additional 190 kyr or so before being sequestered[5,9].

Here we characterize shifts in the nature of fluvial deposition spanning the PETM within the intermontane Piceance Creek basin of western Colorado, USA (Fig. 1), which formed during the Laramide orogeny[14]. Palaeocene and early Eocene deposition[15–17] is represented by the Wasatch formation, and is separated from base to top into the Atwell Gulch, Molina and Shire members[16]. Our new $\delta^{13}C$ record using dispersed organic carbon documents an approximately 3.0‰ excursion from background values of about −23.0‰ (Vienna Pee-Dee Belemnite standard, VPDB) (Fig. 2; Supplementary Data), constrained between pollen and mammalian fossil localities characteristic of the latest Palaeocene and earliest Eocene epochs[15–17] (Supplementary Discussion; Supplementary Fig. 1). The beginning of the isotope excursion occurs within an approximately 10-m-thick sequence of crevasse splay deposits; the lowest values occur with the first laterally continuous sand-body, demarcating the onset of the deposition of the Molina member. The excursion persists for an additional 30 m or so of the Molina member (Fig. 2; Supplementary Fig. 1; Supplementary Data). The Molina member can be continuously traced in outcrop for about 40 km both east–west and north–south in the study area around DeBeque, Colorado[18]. Equivalent sand-rich PETM intervals crop out about 90 km north and about 50 km east of DeBeque, and are recognizable in well data in intervening areas[16,18].

The Atwell Gulch member is a mud-dominated succession of purple, orange and red palaeosols (Supplementary Figs 2 and 3). Fluvial sand-bodies are thin and laterally restricted (Fig. 3a, b). Estimates of bank-full flow depths and widths indicate that the rivers that deposited these sand-bodies were relatively shallow and narrow, and that the bedforms within channel-fills were dominated by trough cross-bedding (Fig. 3c–e). Levee complexes are commonly associated with these sand-bodies, but crevasse splay deposits are rare (Supplementary Figs 2 and 3). In contrast, fluvial sand-bodies are thick, laterally continuous, and sheet-like within the Molina member (Fig. 3a, b). Bank-full flow depths are deeper, channels wider, and both display a greater range than in the other members (Fig. 3c, d). Upper-plane bed laminations are the dominant bedform observed, with palaeosols typically purple in colour, levee complexes absent, and crevasse splay deposits ubiquitous (Fig. 3e; Supplementary Figs 2–4).

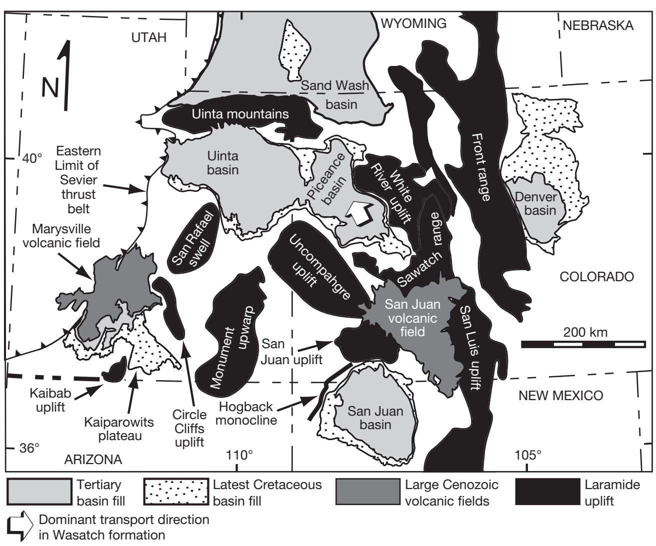

Figure 1 | Generalized geologic map showing major Laramide structures and associated basins. The Uinta and Piceance Creek basins were separate during the Palaeocene and the earliest Eocene epochs, and Cenozoic volcanic fields substantially post-date the deposition of the Wasatch formation.

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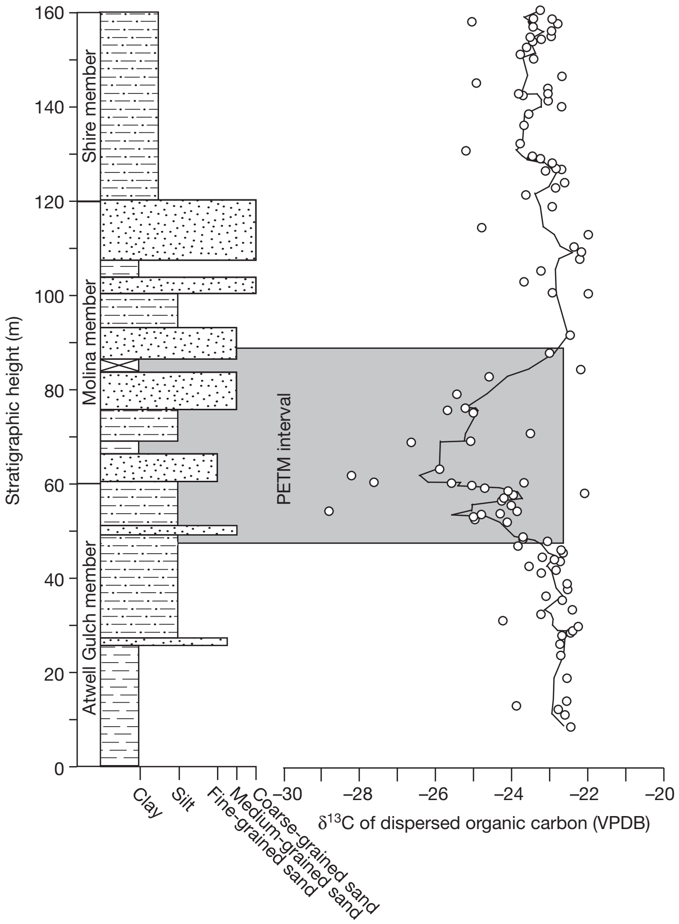

Figure 2 | Stratigraphic section through the middle portion of the Wasatch formation east of the town of DeBeque in Colorado, and the $\delta^{13}C$ record from dispersed organic carbon. The black line shows the five-point running average, and the width of individual data points represents analytical precision (about 0.1‰). Replicate analyses are ±0.3‰ of average values at a given stratigraphic height.

The strata of the overlying Shire member are similar to the Atwell Gulch member, except that the palaeosols are dominantly red and pink, and sand-bodies tend to be slightly thicker (Fig. 3; Supplementary Figs 2 and 3).

The sand-body and channel measurements are non-normally distributed based on Lilliefors statistical tests at the $\alpha = 0.05$ level. Non-parametric Kruskal–Wallis tests reject the null hypothesis that Molina member sand-body thickness (degrees of freedom, d.f. = 2; $\chi^2 = 46.1982$; $P \ll 0.001$), sand-body width (d.f. = 2; $\chi^2 = 35.1015$; $P \ll 0.001$), bank-full flow depth (d.f. = 2; $\chi^2 = 6.0541$; $P = 0.0485$), and flow width (d.f. = 2; $\chi^2 = 9.5330$; $P = 0.0085$) have the same median values as other members (Supplementary Data).

Previous authors ascribed the abrupt sedimentologic transition of the Molina member to either unroofing of Permian/Jurassic-aged aeolianites in the hinterland[18] or to a tectonically induced increase in sediment supply generated from surrounding Laramide uplifts[16] (Fig. 1). Sea level influences were probably unimportant given that western Colorado was separated from the palaeo-shoreline by around 1,000 km and several mountain ranges[14,19].

The unroofing hypothesis argues for a coarsening of the grain-size probability density function of flux from eroding mountain catchments[18]. We tested the hypothesis by assessing provenance changes within the Wasatch formation using U–Pb detrital zircon age spectra and their similarity to age spectra of the Glen Canyon group aeolianites[20], the proposed source for the Molina member[18]. All the major peaks and cumulative curves of the age spectra are nearly identical among the three members, indicating no major changes in sediment source during deposition (Fig. 4a; Supplementary Discussion). None show peak ages characteristic of older aeolianite sources from the Colorado plateau and the Uncompahgre uplift[20] (Fig. 4a). Furthermore, sandstone compositions are lithic arenites in all three members, unlike the quartz arenite composition of the aeolianites[21].

The tectonic hypothesis invokes simultaneous uplift events and corresponding increases in flux from the Uncompahgre and White River Laramide structures flanking the southwest and east of the study area, respectively[16] (Fig. 1). Constant subsidence rates (though limited in resolution) in the basin[22] and uniform palaeocurrent dispersal patterns (Fig. 4b) suggest that there were no periods of new or renewed rapid surface uplift and attendant flexural loading of the basin[23], nor deflection of rivers as a result of increased sediment flux from these margins. Moreover, the Molina member thins towards the proposed source areas[16], the opposite geometry of syntectonic deposits, which thicken towards the sediment source[23]. Alternatively, the Molina member could record a period of slowed subsidence with constant sediment flux, in which reduced accommodation causes progradation and denser amalgamation of coarse facies[23]. Existing subsidence histories[22] do not support this scenario either, but owing to age uncertainties neither tectonic scenario can be definitively disproved. However, we find them less parsimonious given the Molina member's correlation with the PETM and its sedimentologic coherency with proposed climatic changes.

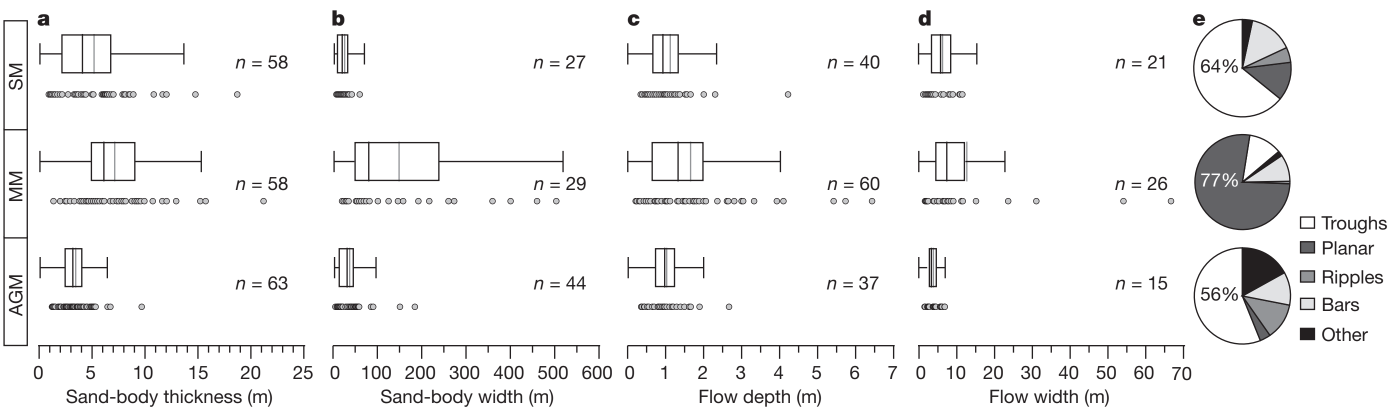

Figure 3 | Box and whisker plots of fluvial data from the Atwell Gulch, Molina and Shire members. AGM, Atwell Gulch member; MM, Molina member; SM, Shire member. Edges of boxes denote bounding quartiles, the black vertical lines represent median values, the grey vertical lines represent mean values, and whiskers denote the lower fence and upper fence (that is, 1.5 times the interquartile range). Grey circles denote individual data points. **a**, Sand-body thickness. **b**, Sand-body width perpendicular to local flow direction. **c**, Bank-full flow depth. **d**, Channel flow width perpendicular to mean local flow direction. **e**, Relative abundance of different bedform structures and bar clinoforms within sand-bodies.

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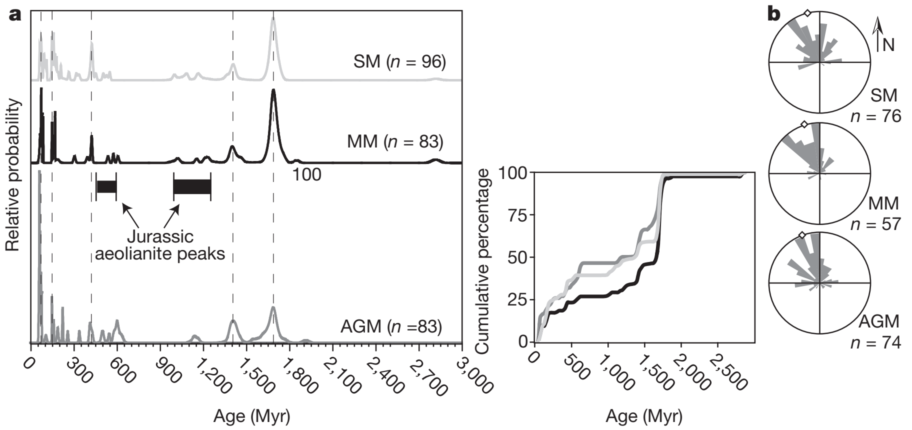

Figure 4 | Comparison of provenance and palaeodrainage patterns in the Atwell Gulch, Molina and Shire members. **a**, Normalized U–Pb age-distribution curves for detrital zircon populations (*n* is the number of grain ages determined). Key age peaks shared amongst the members are marked with dashed vertical lines. Age range of Jurassic aeolianite peaks are from ref. 20. Right, the cumulative distribution function incorporating errors. **b**, Rose diagrams showing uniform palaeocurrent direction throughout the Wasatch formation. Black diamonds represent vector means and *n* is the number of measurements.

Deeper and wider channels in the Molina member, assuming similar slopes, imply greater discharges and potentially higher mean annual precipitation. The greater range of values displayed in bankfull flow depths within the Molina member suggests larger variability in the channel-forming discharges, which may correlate with greater variability in the severity and intensity of rainfall events. Preservation of upper-flow-regime sedimentary structures, such as upper-plane bed laminations and climbing dunes (Supplementary Fig. 4), within channel deposits require either a peaked hydrograph or high in-channel sedimentation rates, or else they would have been reworked by waning flow stages[18,24]. Alternatively, such upper-flow-regime structures can occur in unusually shallow flows; however, this is difficult to reconcile with deeper flows indicated by bar clinoforms and would require sustained steepened river gradients to transport coarser sediment. The abundance of crevasse splay deposits and lack of well-developed levee complexes suggests that channel-breaching and flooding were common occurrences. Finally, a shift to purple palaeosols suggests less well drained conditions[25].

The high p_{CO_2} conditions of the PETM potentially instigated increased atmospheric humidity and intensified the hydrologic cycle[26]. Within the western interior of the USA, circulation models suggest the increased importance of convective atmospheric circulation off the palaeo-Gulf of Mexico, leading to enhanced monsoons[7,8]. Larger channels and preservation of upper-flow-regime structures are broadly consistent with the hypothesis, possibly with periods of higher runoff and greater channel-forming discharges associated with summer monsoonal rains. Yet increases in mean annual precipitation are more uncertain because channel-forming discharge will not necessarily reflect mean flow conditions. Overall, the monsoon hypothesis needs further testing at sites in other Laramide basins, especially since proxies in the Bighorn basin of Wyoming, around 500 km north, suggest drying trends during the PETM[6,25].

Numerical models predict extensive progradation of coarse-grained lithofacies due to increased discharge and sediment flux, reducing the rate of down-stream fining via selective deposition of coarser grains[1,3,4]. Greater rainfall leads to increased discharge (seasonal or otherwise), causing higher diffusivity and the capacity to transport coarse sediment in rivers[1,3]. Additional sediment flux to rivers will also cause progradation[1]. Continental-scale overturn of vegetation regimes during the PETM[5,6] undoubtedly remobilized sediment from basin hillslopes and floodplains. Similarly, greater hinterland catchment efflux is predicted during periods of vegetation overturn, precipitation increases and heightened storm intensity that together act to cleanse catchments of colluvium, enhance bedrock erosion by expanding drainage channel networks, increase bedrock channel incision rates, and accelerate sediment provision via landslides and other threshold-dependent hillslope processes[2,4].

Assuming these geomorphic processes led to increased sediment flux during the PETM, coupled with constant basin subsidence[22], the observed stratigraphic pattern implies the preferential bypass of fine-grained sediment through the basin towards the north (Fig. 1). The shift to sand-rich deposits is a consequence of selective deposition by alluvial rivers filling the basin[1,3]. Analogously, during the PETM in the Tremp-Graus basin of Spain, a vast conglomeratic braid-plain prograded owing to enhanced seasonal precipitation[27] with correlative shelf and bathyal marine sediments recording greater terrestrially derived clay accumulation[28]. Indeed, many marginal marine settings around the world record an increase in terrestrial clay deposition during the PETM[5,11,12]. The well-studied Bighorn basin may record the reverse scenario, in which basin-wide, enhanced palaeosol formation during the PETM[25] reflects reduced sediment supply due to lower diffusivity of basin rivers and catchment efflux brought on by decreases in precipitation by up to 40% (refs 6 and 25).

While increases in dissolved loads[10] and clay export[5,11,12] to oceans are restricted to the PETM interval, which implies fast response times in step with the climate change, the fluvial response in western Colorado persists 30 m beyond the isotope excursion (Fig. 2). Hysteresis effects such as this result from the dynamic coupling of hinterland erosional and basin depositional regimes and relate to how the perturbation is propagated (for example, a kinematic wave versus diffusion, respectively), the length scales they are transmitted over, and relaxation times for the reattainment of 'equilibrium' slope conditions[1–4]. Even in simplified two-dimensional models these effects may combine to maintain perturbed states for around 500 kyr (ref. 3). The likelihood of nonlinear sedimentation rates and imprecise age control precludes an accurate estimate for the relaxation time in western Colorado, though conservatively we suggest it was on the timescale of 10^5 years. More importantly, we emphasize the overall coherency in western Colorado with simplified and scaled-down model and experimental predictions, and that we expect future studies to find similar responses in other terrestrial sequences. If the pattern bears out, the high p_{CO_2} concentrations of the PETM did not only have far-reaching consequences for the evolution and ecology of biotic systems[5], but may also represent a global-scale 'clearing event' for geomorphic systems[13].

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METHODS SUMMARY

U–Pb detrital zircon ages. Medium-grained sandstone samples were obtained near the base of fluvial sand-bodies (see Supplementary Discussion for stratigraphic positions). Samples were disaggregated, and zircons removed using standard water table, magnetic and heavy-liquid separation techniques. U–Pb determinations (about 100 unknown and about 35 standards per sample) were performed at the University of Arizona's LaserChron facility using a laser-ablation multicollector inductively coupled plasma mass spectrometer, measurement error is around 1–2% (2-sigma level). A 10% discordance filter was applied to the generated ages. See ref. 29 for detailed description of analytical methods.

Carbon isotope analyses. Samples for isotopic analysis were obtained by trenching until fresh rock was exposed. Approximately 40 mg of powdered sample were loaded into glass vials and loaded into a dry bath held at 50 °C. Then, 100 μl of 6 N HCl was added incrementally each day to the samples over the course of three days. Dried samples were weighed into tin capsules before introduction to the Thermal Finnigan Delta Plus XP elemental-analyser isotopic-ratio mass spectrometer housed at the University of Wyoming Stable Isotope Facility. Results are reported in δ notation with reference standard VPDB. Analytical error is around 0.1‰, and replicate analyses are ±0.3‰ of average values at a given stratigraphic height.

Stratigraphic data. Over 175 sand-bodies were examined during the course of this study across about 1,200 km^2. Fluvial data were obtained using a Jacob's staff and laser range finder. The accuracy of the laser range finder is ±0.1 m, and its precision is better than ±0.2 m. Flow depths were determined from relief on bar clinoforms and mud plugs. Flow widths were estimated from 1.5 times the toe-to-crest horizontal distance of bar clinoforms and mud-plug widths[30], corrected for local palaeocurrent direction relative to outcrop orientation. These estimates should be viewed as minimums because bar clinoform deposition may be oblique to the flow direction.

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Supplementary Information is available in the online version of the paper.

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