

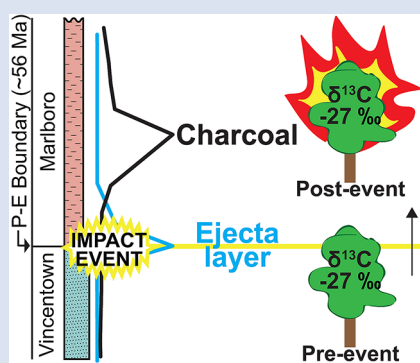
Widespread and intense wildfires at the Paleocene-Eocene boundary

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Abstract



Discovery of impact spherules associated with the onset of the Carbon Isotope Excursion (CIE) that marks the Paleocene-Eocene (P-E) boundary (~56 Ma) indicates that the P-E transition was coincident with an extraterrestrial impact. Charcoal abundances increase >20 times background immediately above the P-E spherule layer at two Atlantic Coastal Plain palaeo-continental shelf localities located >200 km apart. Individual charcoal shards (~100 µm long; 58–83 wt. % carbon) show charred plant features. The carbon isotope ratio of charcoal ($\delta^{13}\text{C}_{\text{charcoal}}$) through the peak shows that it originated from pre-impact vegetation that burned. We consider two scenarios to explain this widespread, synchronous increase in charcoal at the P-E boundary: 1) warming-induced, continental-scale drying; and 2) impact-induced wildfires. Differentiating between these two hypotheses depends critically on the observed sequence of events, which on the western North Atlantic margin is: the impact spherule horizon, followed by the peak in charcoal (derived from vegetation that grew before the CIE and impact),

and finally the nadir of the CIE. Importantly, the pre-excursion $\delta^{13}\text{C}_{\text{charcoal}}$ remains constant through the CIE onset, requiring a dramatic increase in sedimentation. This work clarifies our understanding of the timing and sequence of events following an extraterrestrial impact at the P-E boundary.

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Introduction

The P-E boundary is marked by a negative CIE in marine and terrestrial records and 5–8 °C global warming (Kennett and Stott, 1991; see McNerney and Wing, 2011, for review). Although the source(s) and magnitude of low $\delta^{13}\text{C}$ carbon released into the ocean-atmosphere system at the P-E boundary are debated, impact ejecta recently discovered at the CIE onset indicates that an extraterrestrial impact played a role. Glassy spherules are found in a discrete stratigraphic layer within the CIE onset on the U.S. Atlantic Margin at multiple sites spread over 1,000 km (Schaller *et al.*, 2016). The ejecta at Wilson Lake B (WL; Schaller *et al.*, 2016) and at Randall's Farm (RF; this study, Fig. S-1) are formed as either solidified melt-droplets or vapour condensates. On the palaeo-continental shelf, the CIE onset coincides with the base of the thick Marlboro Clay that extends from Virginia to New Jersey (Fig. 1).

In this study, we document unusually abundant microscopic (~100 µm) black charcoal shards near the base of the Marlboro Clay at WL and RF; these shards bear characteristics of well-preserved charred plant material and their distribution in the sediment column forms an abrupt peak immediately above the spherule level. SEM imaging – the most diagnostic

method of studying charcoalified plant material (Scott and Collinson, 1978) – reveals three-dimensional plant features with excellent preservation, including homogeneous cell walls and honeycomb structures (Figs. 2, S-2). This paper explores two hypotheses for the origin of the charcoal following the impact ejecta within the CIE: 1) warming-induced, continental drying and ecosystem change; and 2) as a direct consequence of the impact.

Evidence for Synchronous, Widespread Intense Wildfires

Charcoal is the most diagnostic artefact of wildfires (Belcher *et al.*, 2003). Overlying the P-E impact ejecta, we observe a 24-fold increase in charcoal pieces (>63 µm)/gram at WL, and 21-fold increase at RF, a remarkable change above a low but consistent background (Figs. 3, S-3). The material is typically brittle, black, opaque in thin section, and preserves anatomical detail. Raman spectroscopy is widely used to characterise carbonaceous materials (Ulyanova *et al.*, 2014; Wang *et al.*, 2014), and helps confirm the presence of charcoal (Fig. S-4). Wavelength dispersive X-ray spectroscopy (WDS) indicates that the black shards are 58–84 % carbon by weight. Charcoal

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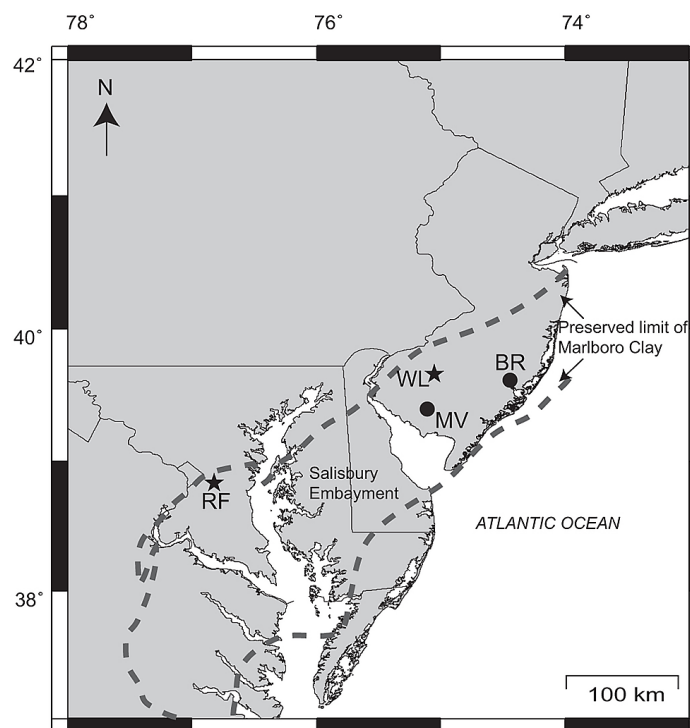


Figure 1 Location map of Wilson Lake (WL), Randall's Farm (RF) and other sites discussed in text; Millville (MV), Bass River (BR). Modified after Self-Trail (2017).

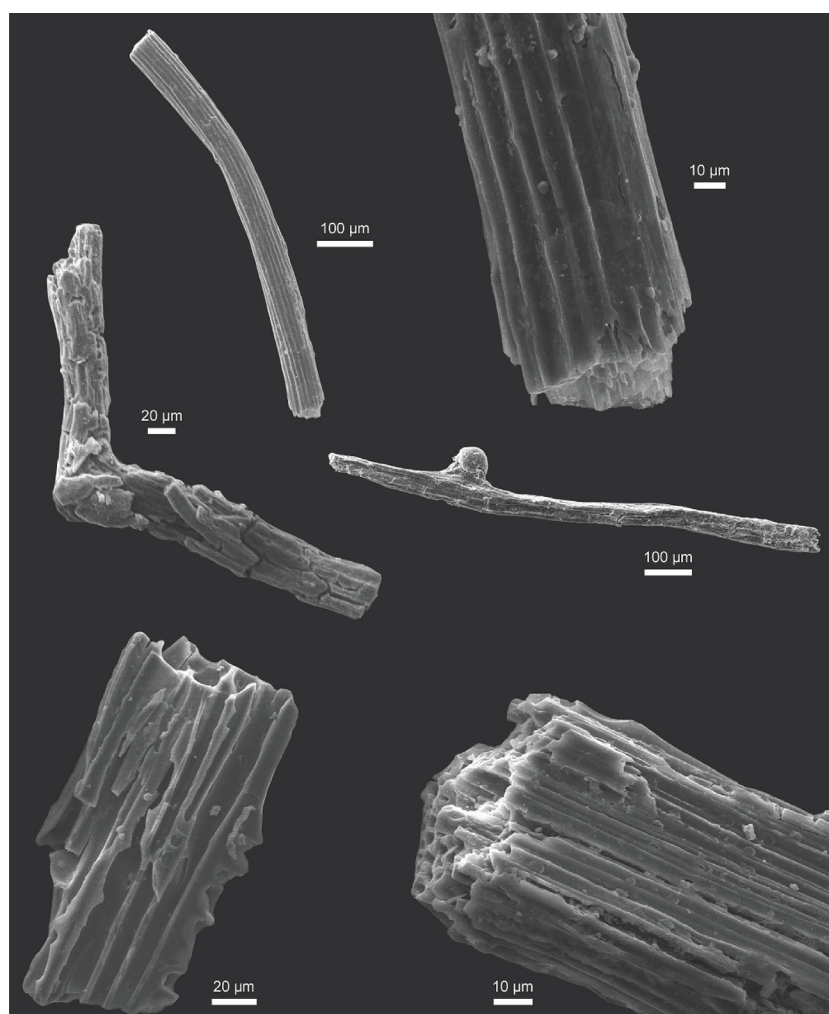


Figure 2 SEM images of charcoal fragments from WL and RF.

exhibits high reflectance (R_0) compared to other maceral groups as the result of heating; higher reflectance indicates higher combustion temperatures (Scott and Jones, 1991). Samples yield average R_0 values between 0.38 % and 2.99 %, corresponding to temperatures between 340–550 °C (Scott and Jones, 1991) (Table S-1). Lowest R_0 values indicating vitrinite (uncharred plant material) are found below the boundary; highest R_0 values occur within the charcoal peak at both RF (1.24 %) and WL (2.99 %), and decrease above; this distribution of R_0 values supports a widespread and intense singular wildfire event.

The ejecta found at the base of the Marlboro Clay, have all the characteristics of instantaneous air-fall deposit (Schaller *et al.*, 2016), and have been dated by K-Ar to 54.9 ± 3 Ma (Schaller and Fung, 2018). Because the depositional and cooling ages of the spherules appear to be indistinguishable, the impact ejecta may provide a time-equivalent marker and baseline for the start of the CIE across the mid-Atlantic Salisbury Embayment. The charcoal peak at both localities occurs stratigraphically above both the spherule layer and the start of the CIE; based on this sequence, we infer that: 1) the charcoal was deposited after the impact; and 2) synchronous wildfires produced the charcoal.

Several lines of evidence indicate that the charcoal-rich layers are neither artefacts of reworked older sediments nor simply due to sedimentation change. (1) The charcoal peak lies 12 and 104 cm above the ejecta layer at WL and RF, respectively, indicating that the charcoal is not older burned material reactivated by the impact event. (2) The charcoal increases substantially above the change from sands to clayey silts, and decreases to near-background levels well within the clay. (3) There is a single observed pulse of charcoal, not multiple peaks as would be expected from reworking of charcoal.

There is a stratigraphic and causal link between our charcoal observations and an unusual and widespread abundance of magnetic nanoparticles in the Marlboro Clay (Lanci *et al.*, 2002), which resulted from soil pyrogenesis (Kent *et al.*, 2017). The stratigraphic level of the charcoal increase at RF and WL coincides with this unique change in magnetisation (Kopp *et al.*, 2009 and Kent *et al.*, 2017, respectively; Fig. 3), indicating that they share a common origin and were deposited contemporaneously. The unique magnetisation is observed in ten sites spanning ~400 km in the Salisbury Embayment (Kopp *et al.*, 2009), providing an independent line of evidence indicating that the wildfire activity was regionally extensive (See SI). Elevated fern spores and charred plant material within the CIE at the Mattawoman Creek-Billingsley Road site in the southern Salisbury Embayment (Self-Trail *et al.*, 2017) provides further evidence that the wildfires were widespread and contemporaneous (within the level of resolution possible). The dramatic increase and dominance of fern spores in the Marlboro Clay is consistent with the opportunistic nature of ferns immediately following wildfire (Ainsworth and Kauffman, 2009).

We use the nadir of the CIE onset as a tie point to correlate the sequence of events recorded at WL and RF (Fig. 3). Remarkably, the highest charcoal abundance occurs prior to the CIE nadir, highlighting the following sequence of events: 1) impact event (deposition of spherule layer); 2) widespread wildfires (significant increase in charcoal); and 3) CIE nadir. The significant increase in charcoal invites the obvious question: what triggered the intense, widespread wildfires that produced the charcoal spike? Here, we consider two scenarios to explain the elevated charcoal abundance at the P-E boundary: 1) continental drying and subsequent wildfires; and 2) impact-induced wildfires.

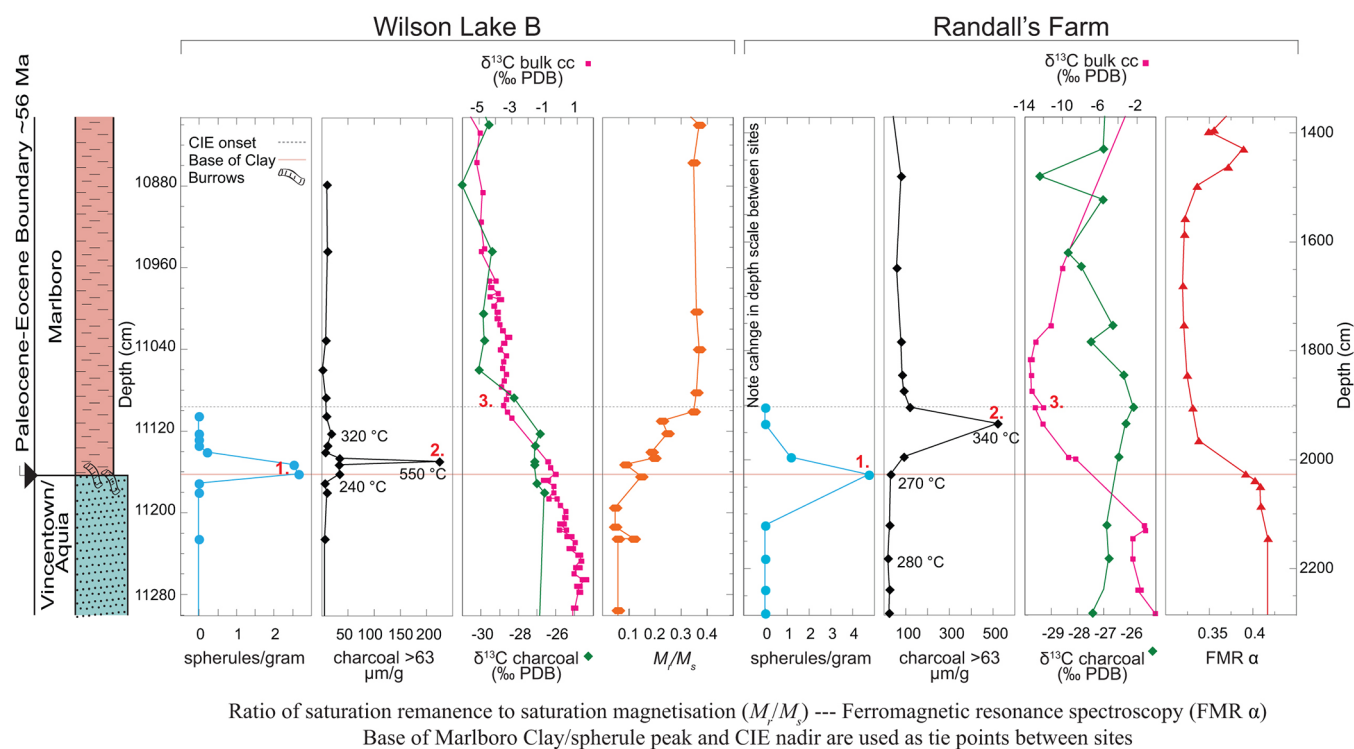


Figure 3 Charcoal abundance ($\# > 63 \mu\text{m/g}$) and $\delta^{13}\text{C}_{\text{charcoal}}$ (this study) plotted with $\delta^{13}\text{C}_{\text{bulk carbonate}}$ and spherules/gram discovered at WL (Schaller *et al.*, 2016) and RF (this study). Total depth range at RF is ~2 times WL, allowing for direct comparison. Note difference in isotope scale between WL and RF. R_0 measurements, M_r/M_s at WL (Kent *et al.*, 2017), and FMR α at RF (Kopp *et al.*, 2009) are shown.

Scenario 1: Warming-induced, continental drying and subsequent wildfires

Large scale continental drying associated with Paleocene-Eocene Thermal Maximum (PETM) warming could put vegetation at risk for wildfires. These wildfires could be triggered by lightning strikes and be regionally widespread. The first of these many fires would burn extensively, probably contemporaneously, over a wide area, be very intense, and lead to deposition of the large charcoal peak we observe in the sedimentary record. This would likely be followed by subsequent smaller wildfire events producing repeated charcoal pulses, which we do not observe.

Under this scenario, continental interiors experienced aridification. Studies from the U.S. western interior indicate rainfall decreased by ~40 % near the PETM onset, but do not conclude if this aridification was more than regional (Wing *et al.*, 2005). Palaeosols in Wyoming also indicate decreased precipitation at the onset (Kraus and Riggins, 2007). Conversely, modelling results from northern and mid-latitudes (including Wyoming) indicate a 20–25 % increase in soil and atmospheric moisture during the PETM (Bowen *et al.*, 2004), and Kopp *et al.* (2009) speculated on an “Appalachian Amazon” in Eastern North America. The latter is consistent with the apparent runoff increase responsible for the *Apectodinium* acme at the P-E onset in the Marlboro Clay (Sluijs *et al.*, 2007). Hydrologic studies on the PETM thus have not provided clear evidence for a pattern of dryer or wetter conditions, but observations suggest the mid-Atlantic margin was wet.

Scenario 2: Impact-induced wildfires

The charcoal peaks at WL and RF occur stratigraphically above the ejecta layer; therefore, the wildfires could have been ignited by the P-E boundary impact. In this scenario, the massive thermal energy of an impact vapour plume and subsequent ejecta fallout (Melosh *et al.*, 1990) ignited widespread wildfires, producing abundant charcoal that was transported to the shelf *via* the next major hydrologic event, resulting in the observed depositional sequence. Wildfires following the Cretaceous-Paleogene boundary impact event (see SI for review) provide a model for the P-E boundary impact and potential ignition mechanism, though we note that the P-E boundary impact was smaller.

The $\delta^{13}\text{C}_{\text{charcoal}}$ at WL and RF provides insight into our two proposed wildfire ignition scenarios and sequence of events (Fig. 3). The $\delta^{13}\text{C}_{\text{charcoal}}$ from the charcoal peak exhibits pre-excursion values, and $\delta^{13}\text{C}_{\text{charcoal}}$ remains constant through the start of the CIE onset in bulk carbonate. Pre-excursion $\delta^{13}\text{C}_{\text{charcoal}}$ values indicate that: 1) the charcoal peak resulted from biomass that grew prior to the impact event and climatic perturbation; and 2) there was no vegetation growth within the time represented by the section of steady $\delta^{13}\text{C}_{\text{charcoal}}$ values through the CIE onset and charcoal peak. If the vegetation had grown during the CIE onset, as expected during a millennial-scale event, the $\delta^{13}\text{C}_{\text{charcoal}}$ would display excursion values because new plant growth would record the changing atmospheric $\delta^{13}\text{C}$. In contrast, our $\delta^{13}\text{C}_{\text{charcoal}}$ decreases above peak charcoal abundance and above the start of the CIE onset in bulk carbonate. At WL, two low charcoal abundance samples above the peak exhibit pre-excursion $\delta^{13}\text{C}_{\text{charcoal}}$ values, hence the pre-excursion $\delta^{13}\text{C}_{\text{charcoal}}$ values in the charcoal peak do not represent a mixture of pre-excursion and excursion carbon, diluted by an over-abundance of pre-excursion vegetation that burned along with it. Because there was apparently no time for new plant growth, we conclude that sediment deposition between the impact ejecta and the $\delta^{13}\text{C}_{\text{charcoal}}$ excursion was relatively fast (no more than centennial scale).

Climate Change or Impact Event?

Under the drying scenario, the climate must have become hotter and drier as a result of the carbon cycle event. The environmental perturbation and warm temperatures associated with the PETM created conditions favourable for wildfires, yet peak charcoal occurs within the start of the onset and before the nadir of the excursion, which coincides with most observations of environmental perturbation. This suggests that the PETM climate perturbation did not cause the widespread wildfires and charcoal deposition; rather, wildfires were the consequence of an earlier event. The drying scenario is also inconsistent with the apparent massive increase in sedimentation rate at Salisbury Embayment shelf sections, which would have required an accelerated hydrologic cycle and increased precipitation and runoff, although we note that wildfires would result in significant soil loss. Interestingly, fern spikes of up to 90 % within the Marlboro Clay in the southern Salisbury Embayment suggest warm, wet environments (Self-Trail *et al.*, 2017) because ferns need moist environments to complete their lifecycle (Mehltreter *et al.*, 2010), making them particularly rare in arid climates (Aldasoro *et al.*, 2004). If drying were the source of the P-E boundary wildfires, then there should be evidence of fires during subsequent Early Eocene Hyperthermal events, yet charcoal studies through the Early Eocene Climatic Optimum in Germany do not indicate any increase in fire activity (Robson *et al.*, 2014).

Although our findings are most consistent with impact-induced wildfires at the P-E boundary, either ignition scenario is feasible. Importantly, both continental drying and impact-induced wildfires are in agreement with a fast scenario (Wright and Schaller, 2013), supported by $\delta^{13}\text{C}_{\text{charcoal}}$ analyses. In contrast, a 4 kyr onset (Zeebe *et al.*, 2016) requires the absence of plant growth or wildfires in the hinterlands for thousands of years; this is unlikely because fire has a revitalising effect on ecosystems and vegetation growth is quickly renewed following wildfires (Ahlegren, 1974). A sustained period without vegetative growth or wildfires for millennia is highly improbable (Bond and Wilgen, 1996) when the lifetime of a typical large woody plant is less than a few centuries; therefore, we would expect resumption of at least background charcoal flux with post-CIE $\delta^{13}\text{C}$ values during those millennia, which is not observed (Fig. 3). The charcoal record could consist of a mixture of charcoal that burned over a number of years; decades seem feasible, yet thousands of years is extremely unlikely, because we would expect to see multiple pulses of charcoal in the record (especially in proximal site RF), which we do not. The charcoal is so well preserved and displays such delicate features that we find it unlikely the material remained exposed on the landscape for thousands of years before being aggregated by floods.

A more realistic explanation of the charcoal record is that the P-E boundary sediments were deposited relatively rapidly during the start of the CIE onset. This explanation is consistent with mechanics of charcoal production and transport (see SI). Extremely high sedimentation rates are common in response to widespread landscape clearance by forest fires, resulting in massive post-wildfire debris flows and deposition of large volumes of sediment (Wells, 1987). Modern fires increase soil erosion rates by ~30-fold compared to pre-fire levels (Swanson, 1981). In addition, rapid mud accumulation rates are observed in the modern Amazon shelf (Kuehl *et al.*, 1986), demonstrating that high sedimentation rates during the CIE onset are plausible, especially during an enhanced hydrologic cycle (Kopp *et al.*, 2009) with ample sediment supply. Effects of wildfires in coastal California show a significant increase in sediment yield, and up to ~35 times greater than average during the subsequent wetter year (Warrick *et al.*, 2012). These studies

highlight how an increase in sedimentation and erosion rates occurs during the next major hydrologic event and is therefore an immediate (decadal scale) consequence of wildfires; this provides a framework for our fast sedimentation model. Regardless of the trigger mechanism, burnt terrestrial plant matter and eroded forest soils were transported to continental shelves in a sediment deluge during the next storm event, producing the base of the Marlboro Clay (see SI).

To summarise, a synchronous, more than twenty-fold increase in charcoal abundance is identified at the P-E boundary in two locations, indicating that intense widespread wildfires occurred during a climatic warming event. We consider two hypotheses to explain the source of the wildfires: 1) warming-induced, continental drying during the PETM; and 2) thermal radiation and/or ejecta fallout from the P-E boundary impact event. Although we cannot definitively rule out either scenario, our data strongly support the impact-induced wildfire hypothesis. Regardless of the trigger mechanism, a critical finding of this study is that the carbon isotope composition of individual charcoal grains exhibit pre-excursion values and remain constant through the onset of the carbon isotope excursion, indicating a rapid onset of the CIE that challenges the rate paradigm for the very early stages of the event by thousands of years.

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Additional Information

Supplementary Information accompanies this letter at <http://www.geochemicalperspectivesletters.org/article1906>.



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