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COORDINATED SEDIMENTARY AND BIOTIC CHANGE DURING THE PALEOCENE–EOCENE THERMAL MAXIMUM IN THE BIGHORN BASIN, WYOMING, USA

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INTRODUCTION

The Paleocene–Eocene Thermal Maximum (PETM) is established as a major, geologically rapid perturbation of the Earth's carbon cycle and climate, with global effects including significant dissolution of carbonate in the marine realm and a temperature increase of 4–8ºC (Kennett and Stott 1991; Zachos *et al.* 2005). The effects of the PETM on continents are less well documented than in marine systems, but include range change in animals (Gingerich 2003) and plants (Wing *et al.* 2005), regional drying (Kraus and Riggins 2007), and high seasonality of precipitation or more extreme rainfall events (Schmitz and Pujalte 2007).

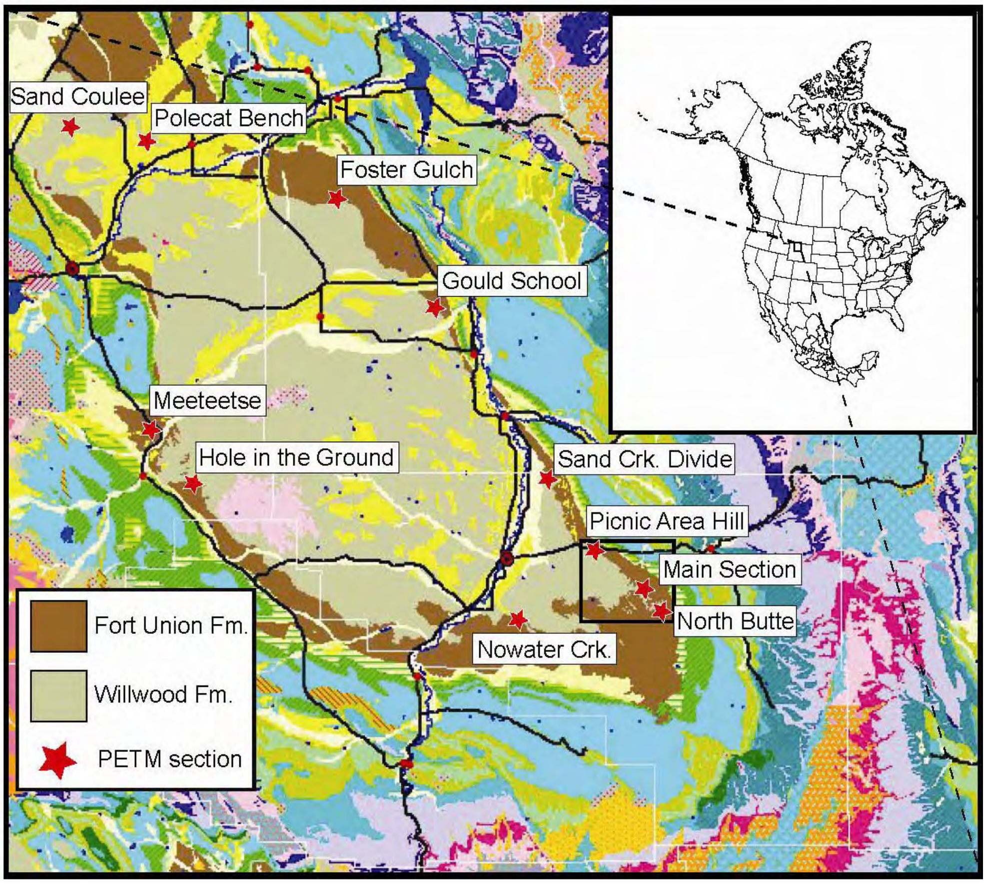

Figure 1. Location map of Bighorn Basin showing outcrop of PETM and study area in box.

PETM outcrops ring the margin of the Bighorn Basin (BHB) of northwestern Wyoming (Fig. 1), in most areas coinciding with the transition from the Fort Union Formation (Fm) to the Willwood Fm. Both formations are fluvial deposits, with the Willwood distinguished by red, variegated paleosols and the underlying Fort Union by drab, organic-rich rocks. We traced this contact across >35 km of badland exposures in the southeastern BHB, measured local lithological sections, described paleosols, collected fossils, and measured the $\delta^{13}C$ of various source materials. We attained stratigraphic precision of ±1 m within local areas using a jake staff and sighting level, and by taking coordinates with a differential GPS. We correlated local sections by recording bed traces with the GPS and reconstructing dip and strike from these measurements. We checked correlations with stable isotope and biostratigraphy, yielding a detailed stratigraphic framework for the study area.

LITHOSTRATIGRAPHY

We recognize four lithological sequences around the PETM, though there is variation from site to site (Fig. 2).

I. Transitional Sequence

The uppermost 20–40 m of Fort Union Fm is similar to rocks below: drab mudstone paleosols, lenticular and tabular channel sandstones, and laterally extensive carbonaceous shales. The highest carbonaceous shale is 13 m below the base of the PETM. The Transitional Sequence differs from underlying Fort Union strata in having laterally discontinuous, reddish mudstone paleosols, suggesting locally better-drained floodplains. Near the eastern margin of the basin these reddish paleosols are more common and occur lower stratigraphically. In most of the study area the highest Fort Union unit is a laterally extensive fine to medium-grained, poorly-sorted sandstone from 2–10 m thick that weathers in a steep face. This tabular body is locally downcut <1 m; commonly its upper part is pedogenically altered.

II. Lower Red Sequence

We recognize the base of the PETM by a negative excursion in carbon isotope values (Fig. 2) and/or the first occurrence of the distinctive Wa0 mammalian fauna, though the latter is slightly later (Gingerich 2003). The base is marked lithologically by the first laterally persistent red paleosol, which typically contains small, pedogenic $CaCO_3$ nodules (<1 cm). The Picnic Area Hill section has 2–3 laterally extensive reddish paleosols in the lowest 5–10 m of the Willwood Fm and the lowest $CaCO_3$ nodules occur in a gray mudstone. In the middle of the study area a single red paleosol with $CaCO_3$ nodules marks the base of the PETM. We have traced this bed to North Butte at the eastern edge of Cenozoic basin fill, finding that it changes laterally to gray, and becomes the bed referred to by Yans *et al.* (2006) as "gray tracer."

III. Cut and Fill Sequence

Sequence III, the middle of the PETM section, has yellow or light-red, laterally discontinuous paleosols that contain large (>2 cm), irregular $CaCO_3$ nodules and burrow fills. Nodule lags in channel deposits are common. Abandoned channel deposits 2–3 m deep and filled with mud or interlaminated silt and sand are common, and some preserve plant fossils.

IV. Big Red Sequence

Throughout the area, the upper part of the PETM is marked by several to many, thick, laterally extensive, bright red and purple paleosols in close stratigraphic superposition (Fig. 2). Frequently the first of these paleosols is brick-red and contains abundant $CaCO_3$ nodules, but nodules are absent from the higher soils, many of which are purple. Large channel cuts filled with sandstone or interlaminated siltstone and sandstone are moderately common in the Big Red Sequence. In some areas (e.g. CAB10) these channels have removed >10 m of underlying paleosols, leaving only the lower part of the Big Red Sequence. The appearance of the Big Red Sequence is also influenced by the thickness of the intercalated gray-white siltstone/sandstone units. At the east margin of the basin the three lowest paleosols in the Big Red Sequence appear to merge in weathered outcrop, forming a single red bed more than 5 m thick.

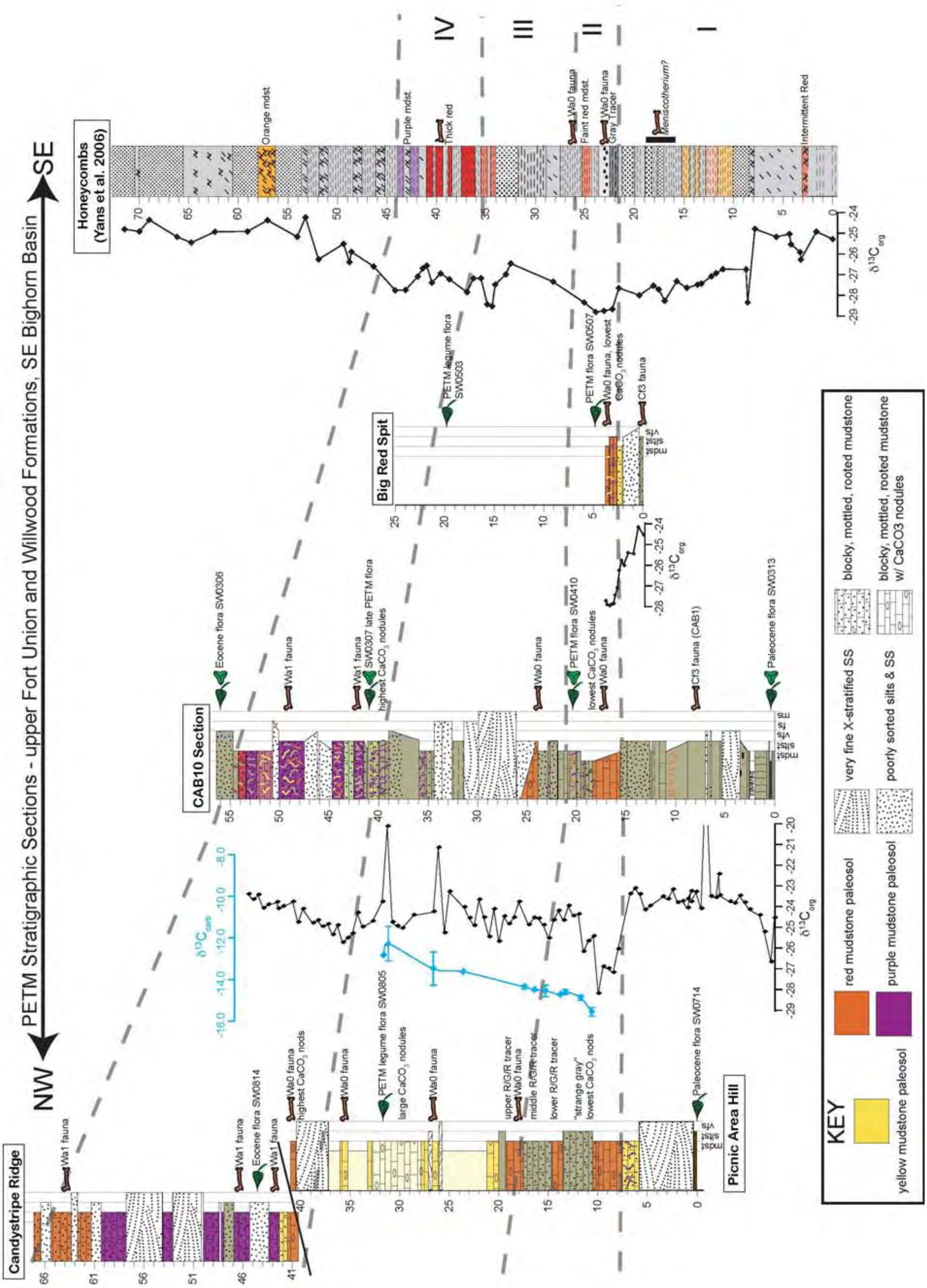

Figure 2 PETM sections in the southeastern Bighorn Basin showing lithology, key fossil localities, and isotope stratigraphy. Colours in lithologic columns approximate paleosol colors in weathered outcrop.

PALEONTOLOGY

The Transitional Sequence has abundant fossil plants in both carbonaceous shales (wet floodplain habitats) and interlaminated siltstone/sandstones beds (near-channel habitats). The highest plants in the Fort Union Fm are 8 m below the first laterally extensive red paleosol and 18 m below the lowest Wa0 mammals in the Picnic Area Hill section (Fig. 2). Uppermost Fort Union floras are dominated by temperate deciduous groups such as Betulaceae, Platanaceae, Cercidiphyllaceae, Fagaceae, Sapindaceae (*Aesculus*), *Ginkgo*, and taxodiaceous conifers (*Metasequoia* and *Glyptostrobus*). Probable evergreen taxa include Lauraceae, palms and cycads. Most of the deciduous genera are common throughout the Late Paleocene and across the Holarctic region (Collinson and Hooker 2003). Palynofloras are also typically Late Paleocene, dominated by Taxodiaceae, Juglandaceae, and Betulaceae. Although leaf and pollen assemblages of Sequence I are compositionally similar to other Late Paleocene floras, the absence of some common leaf types with toothed margins causes leaf margin estimates of mean annual temperature to be higher than for any other Paleocene level in the BHB (Wing and Currano 2008). Vertebrate fossils are rare in the uppermost Fort Union Fm of the study area, with the exception of an iron-cemented, sand-granule conglomerate that outcrops locally at the base of the tabular sandstone at the top of the formation. A vertebrate locality ~6 m below the base of the CIE has produced >200 specimens. The fauna includes champsosaurs, *Aletodon gunnelli*, *Apheliscus nitidus*, *Haplomylus simpsoni,* and *Copecion brachypternus*, lacks *Plesiadapis cookei,* and has a high relative abundance of *Phenacodus* and *Ectocion*. The presence of *Copecion* and absence of characteristic Eocene species indicates a latest Clarkforkian age (Cf3) (Secord *et al.* 2006). An *in situ* jaw of the Clarkforkian species *Coryphodon proterus* was found just 2.5 m below the base of the tabular sand at Big Red Spit (Fig. 2). Yans *et al*. (2006) reported a single specimen of the PETM index mammal, *Meniscotherium*, 3–4 m below the "gray-tracer" bed, which we have traced into a laterally extensive red paleosol that marks the base of the CIE in four other sections. We think this specimen is likely to have washed down slope, a common occurrence in this area because the steep-faced tabular sandstone underlying the base of the PETM facilitates downslope movement of abundant Wa0 vertebrate fossils into the sparsely fossiliferous Fort Union Fm below.

The Lower Red Sequence (II), representing the first part of the PETM, has produced plant fossils in only two locations. Both are minor siltstone channel-fills 1–3 m thick and <10 m in lateral extent; they occur 2–5 m above the base of the CIE. These floras are poorly preserved, and the deposits have abundant fusain (fossilized charcoal) Eight taxa have been recognized, including *Sabalites* (the only taxon surviving from Fort Union floras), a previously unknown member of the Fabaceae, and *"Artocarpus" lessigiana*, a pinnately lobed leaf of uncertain botanical affinity that is widespread in Paleocene floras of the southern U.S. (Brown 1962). Hundreds of vertebrate fossils have been recovered from the Lower Red Sequence, including characteristic Wa0 mammals (*Arfia junnei, Copecion davisi, Sifrhippus [=Hyracotherium] sandrae, Ectocion parvus,* and *Diacodexis ilicis*). The lowest occurring Wa0 vertebrate fossils come from paleosols and mudclast accumulations in sandstones within 3 m above the base of the CIE and ~3 m above the highest Clarkforkian vertebrate localities.

The Cut and Fill Sequence (III) in the middle of the PETM section has no organic-rich lithologies, but plant fossils are preserved as ferric-iron compressions in two siltstone channel fills, separated by 11 km, but each 15–20 m above the local base of the PETM. The two localities have similar composition and together have 35 taxa. The most striking feature of this flora is that it shares only two taxa with latest Paleocene and earliest post-PETM floras: leaves of the palm, *Sabalites*, and winged fruits probably belonging to the family Polygalaceae. Numerically the flora is dominated by fabaceous (legume) leaflets belonging to at least six morphotaxa. There are three types of fabaceous fruits. Two PETM plant types are common in late Early Eocene floras of the BHB, during the Early Eocene thermal maximum. The abundance and diversity of Fabaceae in these floras is unique among Paleocene and Early Eocene floras of the northern Rocky Mountains, and implies changes in climate (higher temperature and greater seasonality of precipitation) or atmospheric composition (higher CO_2) that favored a group of plants that today has many dry tropical, nitrogen-fixing lineages. Mammalian faunas from the Cut and Fill Sequence are generally preserved with the brown/tan tooth enamel seen in other Wa0 faunas, and include the "dwarf" species of *Sifrhippus, Cantius, Diacodexis, Ectocion, Copecion* and *Arfia* that are observed in Wa0 faunas from elsewhere in the BHB (Gingerich 2003).

Fossils from the Big Red Sequence record a rapid transition away from the distinctive PETM biota. A single plant locality near the base of the Big Red Sequence in the CAB10 section has a mixture of taxa known only from the PETM and long-ranging ones such as *Macginitiea*. Channel-fill deposits 5–10 m above the base of the Big Red Sequence near Candystripe Ridge lack the distinctive PETM taxa, but do have long-ranging species of Cercidiphyllaceae and Taxodiaceae, and the earliest occurrence of the Eocene index *Platycarya*. Palynofloras from this level contain Eocene indices *Platycarya* and *Intratriporopollenites instructus* (Wing *et al*. 2005). Faunas from the lowest Big Red Sequence are assignable to Wa0, and include the first occurrence of Euprimates *Cantius toressi* and *Teilhardina brandti*, but the Wa1 index fossil *Cardiolophus,* and other species not restricted to Wa0, occur just above, within 5 m of the base of the Big Red Sequence.

ISOTOPE STRATIGRAPHY

The $\delta^{13}C$ of bulk organic matter ($\delta^{13}C_{org}$) in BHB rocks varies up to ~1‰ within single beds across lateral distances of ~1 km, reflecting differences in floral input, organic preservation, and/or microbial processing (Diefendorf *et al*. 2007). Differences in $\delta^{13}C_{org}$ between the two main isotope sections in the southeastern BHB (CAB10 and Honeycombs; Fig. 2) are 2–3‰, and must reflect additional sources of variability. In spite of the discrepancy in absolute values, $\delta^{13}C_{org}$ used to identify the CIE in multiple BHB sections (Magioncalda *et al.* 2004; Wing *et al.* 2005; Yans *et al.* 2006). Lithostratigraphic correlation of the Honeycombs Section with CAB10, Big Red Spit, and two other sections (CAB1 and CAB3, not in Fig. 2) show that the base of the CIE in the Honeycombs Section coincides with an excursion of only -1‰. This suggests caution in identifying the PETM from $\delta^{13}C_{org}$ without good biostratigraphic control.

In four sections where we have biostratigraphic control the lowest Wa0 fossils coincide with a negative excursion of 3–4‰ in $\delta^{13}C_{org}$, and with the first laterally extensive, red paleosol containing $CaCO_3$ nodules. Values of $\delta^{13}C_{org}$ are at a nadir in the first 5 m of the Lower Red Sequence, but become ~2‰ more positive (though variable) through the rest of the Lower Red and the Cut and Fill Sequences. The $\delta^{13}C$ values of $CaCO_3$ nodules in the same section show gradually increasing values, the expected pattern for the plateau phase of the CIE, and are too light to be in equilibrium with the non-PETM atmosphere (Fig. 2; Bowen *et al*. 2006). We hypothesize that the irregular and positive $\delta^{13}C_{org}$ reflects variable mixing of old organic matter into fluvial channel deposits during the PETM, especially during deposition of the Cut and Fill Sequence. Beginning near the base of the Big Red Sequence $\delta^{13}C_{org}$ slowly becomes more positive, but as in other isotopic records the CIE does not end sharply.

CONCLUSIONS

Lithological, isotopic and paleontological features define four PETM intervals in the southeastern BHB.

- Transitional Sequence (10–20 m): latest Paleocene, decreased soil wetness, higher temperatures, but little change in biotic composition or carbon isotope values.
- Lower Red Sequence (3–5 m): onset of PETM, further decrease in soil wetness, increased temperature, sharp decline in carbon isotope values, major biotic transitions.
- Cut and Fill Sequence (15–20 m): middle PETM, seasonal precipitation, high temperature, low stability of floodplains, unique faunal and floral composition, carbon isotope values remained low.
- Big Red Sequence (15–20 m): late PETM, precipitation increased, floodplains more stable, faunas and floras of typical Eocene composition, and carbon isotope values gradually becoming more positive.

The distinctive character of these four intervals may be manifestations of global phenomena. The Transitional Sequence may reflect climatic warming and/or drying that was a precursor to the onset of the PETM (Sluijs *et al.* 2007). Depositional rates in our sections imply that warming began 40–50 000 years before the PETM, consistent with estimates of pre-PETM warming by Secord *et al*. (2007). The next three sequences in the southeastern BHB may correspond to the three phases of the PETM outlined by Bowen *et al*. (2006) — initiation, alternate semistable state, and recovery. They described initiation as the first 15–30 000 years of the PETM, during which most of the carbon was emitted, climate changed rapidly, and ecosystems responded to changing climate and atmospheric composition. We equate this with the Lower Red Sequence. The alternate semistable state corresponds to the ~60 k.y. "plateau" phase of the CIE during which marine and terrestrial ecosystems and the carbon cycle were maximally different from their prior state. This phase is represented by the Cut and Fill Sequence. The recovery phase, our Big Red Sequence, lasted for ~70 000 years, during which temperatures fell, marine carbonate burial increased, and the pulse of carbon released at the onset of the PETM was withdrawn from the exogenic pool (Bowen *et al.* 2006). Correspondence between sedimentary sequences in the BHB and global changes in the carbon cycle and climate imply that local changes on the continents are strongly influenced at a fine temporal scale by global events.

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