Floral Indicators of Late Paleocene-Eocene Thermal Maximum Climate Change in the Bighorn Basin, Wyoming

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ABSTRACT:

The Paleocene-Eocene Thermal Maximum (PETM) is one of the best analogs to modern climate change and is an important event in the evolution and dispersal of modern flora and fauna. It was a period marked by a rapid rise in global temperature due to the release of greenhouse gasses. I examined a particular time interval towards the end of the PETM in the Bighorn Basin, which showed a decrease in mean annual temperature to 16.4(±5.4)°C, from 19.8(±3.1)°C of the early PETM. I also analyzed carbon and nitrogen isotopes in order to place the temperature change into a broader context. Unfortunately, several problems arose in the isotopic analyses that could not be resolved on the timescale of this project. Test data however, defines a low resolution negative $\delta^{15}N$ excursion of 5.8‰, which may indicate a theoretical shut down of denitrification during the PETM.

BACKGROUND:

Temperature Change: The PETM was a period of global warming approximately 55.8 million years ago. Over a span of about 10 to 20 thousand years, global temperatures increased by 5° to 10°C and then recovered over the next 100 thousand years (Zachos et al., 2003). One of the best records of the Paleocene-Eocene records is in the Bighorn Basin, meaning that several time intervals have already been examined for temperature changes using leaf margin analysis (LMA).

Before PETM (last 2 Myr of the Paleocene) (Wing et al., 2000):
- increased from 12.9(±2.4) to 15.0(±2.4) °C

Beginning of the PETM (Wing et al., 2005):
- increased to 19.8(±3.1) °C

After the PETM (first 1 Myr of the Eocene)(Wing et al., 2000):
- decreased from 18.2(±2.3) to 10.8 (±3.3) °C
- increased again to 15.8(±2.2) then 22.2(±2.0) °C

Isotopic Anomalies: The temperature increase was accompanied by a global negative carbon isotope excursion (CIE) caused by a large (>4500 Gt) release of ^{13}C-depleted carbon (as either CO_2 or CH_4) into the atmosphere and ocean (Zachos et al., 2005). There are many proposed sources for either CO_2 or CH_4 , but seafloor methane may best explain the observations.

Why Methane Fits:

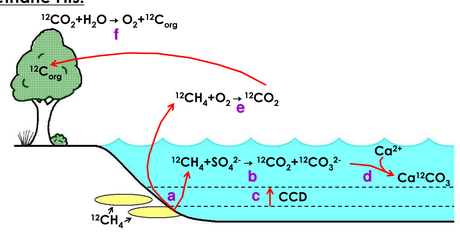

Figure 1. Coupled effects of ^{12}C-enriched Methane Release on Marine and Terrestrial Realms.
a.) $^{12}CH_4$ released into ocean and atmosphere. Methane hydrate has a mean $\delta^{13}C$ of about -60‰, which means it would take much less to produce the CIE compared to any other source (Dickens et al., 1995).
b.) In presence of sulphate reducing bacteria (SRB), methane may form acidity (CO_2) and alkalinity ($HCO_3^- \rightarrow CO_3^{2-}$), shown in a simplified version of the following balanced reaction (Henneke et al., 1997):

$$C_{106}H_{263}O_{110}N_{16}P + 53SO_4^{-2} \rightarrow 39CO_2 + 67HCO_3^- + 16NH_4^+ + HPO_4^{-2} + 53HS^- + 39H_2O$$

c.) Carbonate compensation depth (CCD) rises due to increased acidity.
d.) Calcium carbonate precipitates due to increased CO_3^{2-}(recording PETM CIE).
e.) Methane in atmosphere reacts with O_2 to form CO_2 (in presence of O_2, the half life of methane is only about 7 years, which may account for the very short terrestrial CIE)
f.) CO_2 photosynthesized and incorporated into terrestrial C_{org} record.

HYPOTHESIS:

Fossil flora will show a shift to a hotter climate during the late Paleocene-Eocene Thermal Maximum of Bighorn Basin, Wyoming, meaning there will be more entire-margined leaves.

METHODS/DATA:

Leaf Margin Analysis: Leaf margin analysis is based on the observation made by Wolfe (1979) that in modern forests, mean annual temperature (MAT) is directly correlated to the proportion of dicotyledonous (dicot) species with entire-margined (smooth) leaves. Mean annual temperature is calculated by the following relation (Wolfe, 1979)

$$MAT = 1.14 + 30.6P$$

where *P* is the proportion of entire-margined species in a population. Wilf (1997) noticed that, when working with fossil assemblages consisting of a finite number of species, there is error caused by uncertainty in estimating the true proportion of entire-margined species for a whole flora of a region which is calculated by

$$\sigma = 30.6\sqrt{\frac{P(1-P)}{r}}$$

where *r* is the total number of species in the sample. I examined 110 leaf specimens, and was able to classify 98 of those into 8 dicotyledonous morphospecies, as summarized in figure 2.

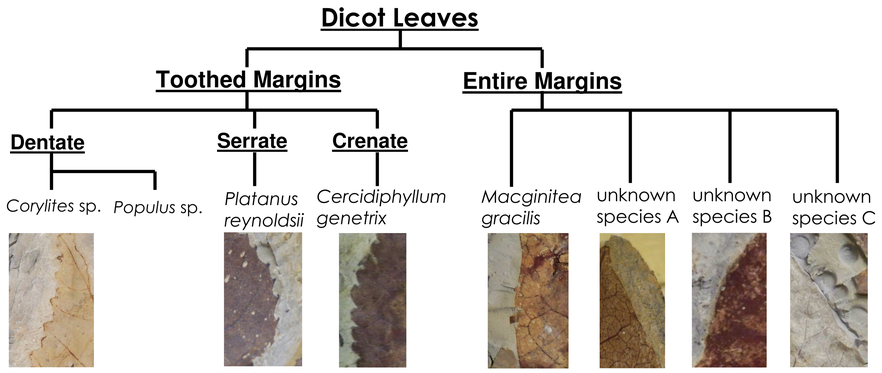

Figure 2. Morphotyping of Dicot Leaves

With equal numbers of toothed and smooth leaves, P=0.5 resulting in a mean annual temperature of 16.4(±5.4) °C. The large error is due to the small number of species (r) in the fossil assemblage.

C/N Isotope Fractionation: Isotopes were measured using the IsoPrime© continuous flow mass spectrometer and Elemental Analyzer. The results of the runs of the standards yields the error for the measurements presented in figure 3B and 3C. Ten shales were to be analyzed for both carbon and nitrogen, but the nitrogen proved to be immeasurable, possibly due to error in preparing the samples for the mass spectrometer. The portion of the mass spectrometer set-up used in analyzing carbon was also recently broken, so carbon was unable to be analyzed. In lieu of this, the data from 10 test samples (6 shales, 4 leaf fragments) analyzed last November are presented in figure 3.

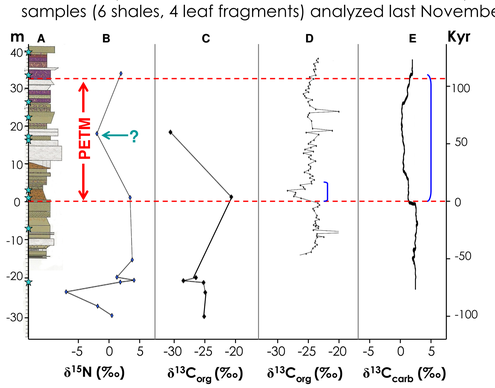

Figure 3. Comparison of PETM isotope records. Red dotted lines representing approximate beginning and end of PETM. (A) Stratigraphic section with meter levels and lithology, blue stars representing the 10 shales we analyzed. (B) $\delta^{15}N$ of the test samples (σ=0.118) with blue arrow indicating a possible negative trend. (C) $\delta^{13}C$ (organic) of the test samples (σ=0.0756). (D) $\delta^{13}C$ (organic) of a nearby Bighorn Basin section (CAB10), blue bracket showing short CIE. (E) $\delta^{13}C$ (carbonate) of Oceanic Drilling Program (ODP) site 690B, with timescale, blue bracket showing long CIE (Röhl et al., 2000; Farley and Eltgroth, 2003).

DISCUSSION/CONCLUSIONS:

Paleoclimate: Upon studying the assemblage, cataloging the morphospecies, and calculating the proportion of entire-margined species and the mean annual temperature, there appears to be a decrease in temperature from 19.8(±3.1) °C at the onset of the PETM (Wing et al., 2005) to 16.4(±5.4) °C that I calculated at the end of the PETM. The proportion of entire-margined leaves (P) decreased from 0.61 to 0.5, meaning that my hypothesis was falsified.

A $\delta^{15}N$ Trend: Nitrogen isotope variations have previously not been studied during the PETM, but could potentially provide important insights into this enigmatic biogeochemical anomaly. Although the test data is of poor resolution, there is one data point that could suggest an interesting trend defined by a 5.8 ‰ decrease in $\delta^{15}N$, as shown by the blue arrow in figure 3. Whereas such a trend can not truly be shown by only three points spanning 33 meters of sediment, a higher resolution study showing a negative nitrogen isotope excursion might be used to support the hypothesized release of methane into the ocean and atmosphere.

While speculative, a negative shift in $\delta^{15}N$ in terrestrial plant material could indicate a shut down of denitrification ($NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$) due to anoxic soil conditions (Gavin et al., 2009), the decrease in oxygen having been caused by the oxidation of methane to form CO_2 in the atmosphere (Figure 1e). In the normal denitrification process, NO_3^- becomes enriched in ^{15}N and the resulting N_2 gas is enriched in ^{14}N. When this process shuts down, the ^{14}N builds up in the NO_3^- pool causing a negative shift in $\delta^{15}N$ which can then be recorded in plant material.

FUTURE WORK:

In order to better understand how climate responds to large amounts of carbon entering the atmosphere, more time intervals through the PETM need to be examined. There are still large gaps in the record that need to be filled, both in Bighorn Basin, and throughout the world. Also, the large error on my estimate is due to a small number of species collected. This could be reduced by returning to the locality and collecting more specimens.

Nitrogen isotopes had never been examined for the PETM before this study. I used bulk rock organics, but with the proper sampling, one could look at leaf material of a single species through the PETM. I propose a higher resolution study of nitrogen using the species *Cercidiphyllum genetrix*, which is abundant during the PETM, in order to uncover the trend that has been suggested.

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