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Magnitude of the carbon isotope excursion at the Paleocene–Eocene thermal maximum: The role of plant community change

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Abstract

Carbon-isotope measurements ($\delta^{13}C$) of leaf-wax *n*-alkanes from the Paleocene–Eocene Thermal Maximum (PETM) in the Bighorn Basin, Wyoming, reveal a negative carbon isotope excursion (CIE) of 4–5‰, which is 1–2‰ larger than that observed in marine carbonate $\delta^{13}C$ records. Reconciling these records requires either that marine carbonates fail to record the full magnitude of the CIE or that the CIE in plants has been amplified relative to the marine. Amplification of the CIE has been proposed to result from an increase in available moisture that allowed terrestrial plants to increase ^{13}C-discrimination during the PETM. Leaf physiognomy, paleopedology and hydrogen isotope ratios of leaf-wax lipids from the Bighorn Basin, however, all suggest that rather than a simple increase in available moisture, climate alternated between wet and dry during the PETM. Here we consider two other explanations and test them quantitatively with the carbon isotopic record of plant lipids. The "marine modification" hypothesis is that the marine carbonate record was modified by chemical changes at the PETM and that plant lipids record the true magnitude of the CIE. Using atmospheric CO_2 $\delta^{13}C$ values estimated from the lipid record, and equilibrium fractionation between CO_2 and carbonate, we estimate the expected CIE for planktonic foraminifera to be 6‰. Instead, the largest excursion observed is about 4‰. No mechanism for altering marine carbonate by 2‰ has been identified and we thus reject this explanation. The "plant community change" hypothesis is that major changes in floral composition during the PETM amplified the CIE observed in *n*-alkanes by 1–2‰ relative to marine carbonate. This effect could have been caused by a rapid transition from a mixed angiosperm/conifer flora to a purely angiosperm flora. The plant community change hypothesis is consistent with both the magnitude and pattern of CIE amplification among the different *n*-alkanes, and with data from fossil plants. This hypothesis predicts that the magnitude and pattern of amplification of CIEs among different *n*-alkanes will vary regionally and systematically depending on the extent of the replacement of conifers by angiosperms during the PETM.

Keywords: *n*-alkanes; plant lipids; carbon isotopes; hydrogen isotopes; Paleocene–Eocene thermal maximum; global warming

1. Introduction

The Paleocene–Eocene Thermal Maximum (PETM) was a period of abrupt (~10 kyr onset), extreme (4–8 °C) and short-lived (100–200 kyr) warming that occurred about 55.8 million years ago (Kennett and Stott, 1991;

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Koch et al., 1992; Rohl et al., 2000; Farley and Eltgroth, 2003; Zachos et al., 2003; Fricke and Wing, 2004; Sluijs et al., 2006; Zachos et al., 2006) and significantly altered terrestrial and marine ecosystems. During this warming, the composition of plant communities in the Bighorn Basin, Wyoming, changed radically, though largely transiently, partly by the immigration of species formerly found only at lower latitudes (Wing et al., 2005). Vegetation in the Arctic also changed, as demonstrated by a temporary rise in angiosperm pollen and decline in gymnosperm and fern palynomorphs (Sluijs et al., 2006). Vertebrate faunas were strongly affected by immigrations that led to changes in taxonomic and trophic structure of communities and the appearance of modern mammals in North America (Clyde and Gingerich, 1998; Beard and Dawson, 1999; Gingerich, 2003). In the marine realm, the PETM is associated with a mass extinction of benthic foraminifera (Thomas, 1998), change in the composition, distribution and evolutionary rates of marine plankton (Crouch et al., 2001; Kelly, 2002; Gibbs et al., 2006), and profound ocean acidification (Zachos et al., 2005).

The PETM is marked by a large negative carbon isotope excursion (CIE) in terrestrial and marine carbonates and organic matter (Kennett and Stott, 1991; Koch et al., 1992, 1995; Magioncalda et al., 2004; Wing et al., 2005), reflecting a rapid release of ^{13}C-depleted carbon into the ocean–atmosphere system. Several carbon sources have been proposed, including methane clathrates (Dickens et al., 1995), burning of peat and coal (Kurtz et al., 2003), volatile-rich comet (Kent et al., 2003), thermogenic methane (Svensen et al., 2004) and organic matter oxidation due to uplift of epicontinental seas (Higgins and Schrag, 2006). Shoaling of the lysocline in the global ocean, as indicated by dissolution of calcium carbonate in marine sediments, indicates the mass of carbon released was at least 4500 Gt (Zachos et al., 2005). This amount of carbon is comparable to the amount that would be released by burning the entire fossil fuel resource base (Metz et al., 2001).

Carbon in the ocean and atmosphere is well mixed on the time-scale of the onset of the PETM (~10 kyr), and thus one might expect biosphere signatures of this event to reveal an identical and synchronous CIE. However, marine and terrestrial proxies present us with distinct signatures across this interval of time. Specifically, the magnitude of the negative carbon isotope excursion at the Paleocene–Eocene boundary recorded in terrestrial reservoirs is significantly larger than in marine reservoirs: ~6–8‰ in paleosol carbonates (Koch et al., 1995; Bowen et al., 2001; Schmitz and Pujalte, 2003) compared with ~2.5–4‰ in marine carbonates (Kennett and Stott, 1991; Bains et al., 1999; Thomas et al., 2002; Zachos et al., 2003; Tripati and Elderfield, 2004). The cause for the >3‰ difference in terrestrial and marine carbonates has been explored by considering the effects of warming and elevated atmospheric CO_2 on ocean chemistry, soil processes, and carbon isotope discrimination by plants (Bowen et al., 2004). Acidification of the oceans and the associated decrease in $[CO_3^{2-}]$ from the addition of CO_2 could have reduced the amplitude of the marine CIE by ~0.5‰. Increased C-input and soil turnover could have increased the magnitude of the terrestrial CIE by 0.8‰. Bowen et al. (2004) suggested that the remaining 1.7‰ was caused by greater discrimination against ^{13}C by plants during the PETM as the result of a postulated increase in water availability.

Wetter PETM conditions have been inferred from increases in kaolinitic clays in shallow marine sediments of the Tethys, Atlantic and Southern Oceans, possibly reflecting higher rates of chemical weathering (Robert and Kennett, 1994; Cramer et al., 1999; Gibson et al., 2000; Bolle and Adatte, 2001). Increases in terrestrial palynomorphs in nearshore marine deposits in New Zealand also have been interpreted as indicating higher runoff during the PETM (Crouch et al., 2003). In contrast, other evidence favors a drier, or more seasonally dry, climate during the PETM. Schmitz and Pujalte (2003) observed sedimentological changes in northern Spain indicating flashy deposition and highly seasonal precipitation during the PETM. General circulation models (GCMs) suggest latitudinal variability in changes in precipitation, with an increase in total precipitation over continents at higher latitudes and in areas of monsoonal climate (Huber and Sloan, 1999; Shellito et al., 2003). However, GCM results for specific regions disagree, with one showing decreased (Huber and Sloan, 1999) and another showing increased (Shellito et al., 2003) summer precipitation over interior North America during the PETM. Fossil floras from the Bighorn Basin, Wyoming, suggest that precipitation first decreased and then increased during the PETM (Wing et al., 2005). The chemical composition and morphology of paleosols shows even more variability in precipitation, revealing four cycles of wetter and drier conditions during the PETM in the Bighorn Basin (Kraus and Riggins, 2007). Based on these records, the hypothesized increase in ^{13}C-discrimination by plants should not be attributed to a simple increase in water availability in the Bighorn Basin.

Here we consider two hypotheses for reconciling the terrestrial and marine CIEs. The “marine modification” hypothesis is that marine carbonates fail to record the full magnitude of the CIE, and that the excursion seen in terrestrial leaf waxes is the same magnitude as that in the