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Notes

Multiple early Eocene hyperthermals: Their sedimentary expression on the New Zealand continental margin and in the deep sea

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ABSTRACT

The Paleocene–Eocene thermal maximum (PETM) ca. 55.5 Ma was a geologically brief interval characterized by massive influx of isotopically light carbon, extreme changes in global climate, and profound variations in Earth system processes. An outstanding issue is whether it was an isolated event, or the most prominent example of a recurring phenomenon. Recent studies of condensed deep-sea sections support the latter, but this finding remains uncertain. Here we present and discuss lithologic and carbon isotope records across two lower Eocene outcrops on South Island, New Zealand. The PETM manifests as a marl-rich horizon with a significant negative carbon isotope excursion (CIE). Above, in sediment deposited between 54 and 53 Ma, are four horizons with similar though less pronounced expressions. Marl beds of all five horizons represent increased terrigenous sedimentation, presumably linked to an accelerated hydrological cycle. Five corresponding clay-rich horizons and CIEs are found in deep-sea records, although the lithologic variations represent carbonate dissolution rather than siliciclastic dilution. The presence of five intervals with similar systemic responses in different environments suggests a mechanism that repeatedly injected large masses of ^{13}C-depleted carbon during the early Eocene.

Keywords: Paleocene–Eocene thermal maximum, PETM, carbon isotope excursion, CIE.

INTRODUCTION

Earth's surface warmed from the late Paleocene, ca. 58 Ma, through the early Eocene, ca. 51 Ma (Zachos et al., 2001). Superimposed on this temperature rise was at least one transient hyperthermal, the Paleocene–Eocene thermal maximum (PETM). During this event, which initiated between 55.3 and 55.7 Ma (Lourens et al., 2005), the carbon isotopic composition (δ^{13}C) of marine and terrestrial carbon decreased by at least 2.5‰ over ~15–30 k.y. in association with warming of both the deep sea by ~4–5 °C and the surface ocean at all latitudes by ~5–9 °C (see Bowen et al., 2006, and references therein). This global negative carbon isotope excursion (CIE) implicates massive addition of ^{13}C-depleted carbon to the ocean and atmosphere from an external carbon reservoir (Dickens et al., 1997). Such carbon input should have shoaled the ocean calcite compensation depth, increased atmospheric pCO$_2$ and temperature, accelerated the global hydrologic and weathering cycles (Dickens et al., 1997; Bowen et al., 2004), and ultimately enhanced continental erosion. Evidence for these expectations has been found in various records (Ravizza et al., 2001; Schmitz et al., 2001; Crouch et al., 2003; Bowen et al., 2004; Hollis et al., 2005; Zachos et al., 2005; Giusberti et al., 2007).

One fundamental issue regarding the PETM is whether it was a unique event requiring an extraordinary cause, or an extreme example of a more common process. Posited sources of massive carbon input include reservoirs external to Earth (e.g., impact of a comet; Kent et al., 2003), from within Earth (e.g., exhalation of thermogenic methane; Svensen et al., 2004), or on Earth's surface (e.g., dissociation of marine clathrates; Dickens et al., 1997; oxidation of terrestrial organic carbon; Kurtz et al., 2003). While each may explain a singular event (to a varying degree of plausibility), the identification of multiple perturbations with similar causes and consequences would necessitate a source capable of repeated carbon injections.

Benthic foraminiferal assemblages display an extinction event (BFEE) at the PETM, likely in response to variations in deep-water temperature, dissolved O$_2$, and/or pH (Thomas, 2003). Similar though less severe turnovers punctuate the long-term warming, suggesting additional PETM-like hyperthermals (Thomas and Zachos, 2000). Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) sediment records may support this inference. At several sites (Fig. 1), a series of significant (>0.5‰) negative CIEs occurred over this interval (Cramer et al., 2003). The most pronounced of the post-PETM CIEs, termed H1 (Cramer et al., 2003), occurred ca. 53.6 Ma (Lourens et al., 2005). On Walvis Ridge, South Atlantic, this CIE coincides with evidence for surface and deep-water warming, and a clay horizon referred to as ELMO, which probably represents lysocline shoaling (Lourens et al., 2005), an oceanic response similar though less severe than that associated with the PETM (Zachos et al., 2005). Above H1-ELMO on Walvis Ridge are several distinct clay-rich horizons, which may represent additional lysocline shoaling events and correspond to other CIEs (specifically H2, I1, and I2, defined by Cramer et al., 2003).

Our current understanding of post-PETM hyperthermals is unconstrained. This is largely because assessment has been limited to deep-sea records, where dissolution has condensed these events, and where complete recovery of lower Eocene sections has been rare. Here we present lithologic, δ^{13}C, and CaCO$_3$ records across two upper Paleocene–lower Eocene shallow-marine sequences exposed in New Zealand. Our results support a hypothesis that

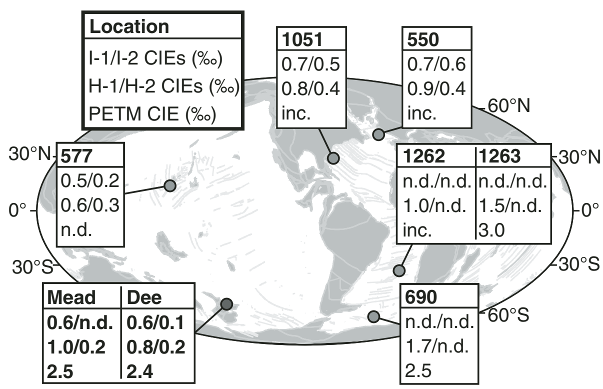

Figure 1. Earth at 53 Ma (http://www.odsn.de/services/paleomap.html) showing locations where early Eocene carbon isotope excursions (CIEs) have been documented in bulk carbonate. These include Deep Sea Drilling Project (DSDP) Sites 550 and 577, Ocean Drilling Program (ODP) Sites 690 and 1051 (Cramer et al., 2003), ODP Sites 1262 and 1263 (Zachos et al., 2005; Lourens et al., 2005), and Mead Stream and Dee Stream (Hancock et al., 2003; Hollis et al., 2005; Table DR1 [see footnote 1]). Numbers—CIE magnitude; inc.—incomplete CIE recovery; n.d.—no data.

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there were at least five significant and similar events between 56 and 53 Ma, of which the PETM is the most pronounced.

LOCATION AND PREVIOUS WORK

Clarence River valley, in northeast South Island, New Zealand, contains streams that cut an uplifted block of Upper Cretaceous–upper Eocene marine sedimentary rocks (Reay, 1993). Sediments were deposited on the outer shelf and upper slope (~100–1000 m water depth) of a passive margin at lat 50°–55°S (Reay, 1993; Hollis et al., 2005). Within the sequence, the Lower Limestone member of the Amuri Limestone formation accumulated during the late Paleocene and early Eocene, and primarily consists of pelagic carbonate, terrigenous aluminosilicates (mostly clay minerals), and biogenic silica (Fig. 2) (Reay, 1993; Strong et al., 1995).

Two excellent Lower Limestone exposures are found along Mead and Dee Streams. Previous work (Strong et al., 1995; Hancock et al., 2003; Hollis et al., 2005) provides a good stratigraphy based on microfossil assemblages and bulk rock $\delta^{13}C$ (Fig. 2). Both sections contain continuous upper slope sediment records from 56 to 53 Ma, although the thicker Mead section represents a deeper environment (Reay, 1993). They also display similar expressions of the PETM. A prominent marl-rich unit (2.4 m thick at Mead; 1.0 m thick at Dee) marks the base of the Eocene (Hancock et al., 2003; Hollis et al., 2005). Consistent with expressions of the PETM at other sites, this unit has a significant (~2.5‰) negative CIE, a BFEE, and brief warm-water plankton occurrences (Hancock et al., 2003; Hollis et al., 2005). Like PETM horizons at other continental margin settings (Schmitz et al., 2001; Giusberti et al., 2007), marl-rich units across the PETM in Clarence Valley represent increased terrigenous accumulation and sedimentation rate (Hancock et al., 2003; Hollis et al., 2005).

APPROACH AND METHODS

Marine carbon isotope records show five negative CIEs between 56 and 53 Ma. The oldest and most pronounced is the PETM; the other four occurred between 54 and 53 Ma (Fig. 3; Fig. DR1 in the GSA Data Repository[1]). Walvis Ridge sediment sections have five seemingly contemporaneous magnetic susceptibility (MS) spikes (Fig. 3; Fig. DR1) that mark clay-rich horizons.

[1]GSA Data Repository item 2007180, Figure DR1 (H1, H2, I1, and I2 event correlations), Table DR1 (lithologic and isotopic results), and Table DR2 (CIE ages and depths), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

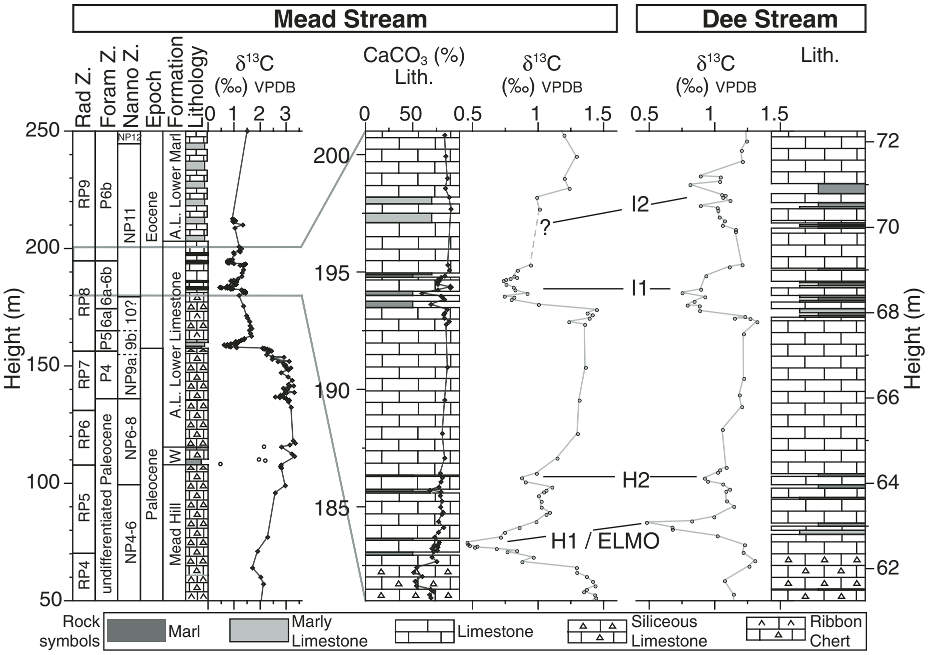

Figure 2. Early Paleogene sequence at Mead Stream and detailed interval of interest (54–53 Ma) at Mead Stream and Dee Stream. Formation names, lithology, biostratigraphy, and bulk carbonate $\delta^{13}C$ for Mead Stream (excepting those across the interval of interest) are from Hollis et al. (2005) with minor biostratigraphic refinements. Mead Stream $\delta^{13}C$ open circles denote values depleted by organic carbon enrichment (Hollis et al., 2005). W—Waipawa Limestone; A.L.—Amuri Limestone. Mead Stream "Lower Marl" lithologic symbols, while emblematic of the section, do not represent actual heights. Four negative carbon isotope excursions (CIEs) in highlighted interval have been correlated to H1, H2, I1, and I2 CIEs documented by Cramer et al. (2003).

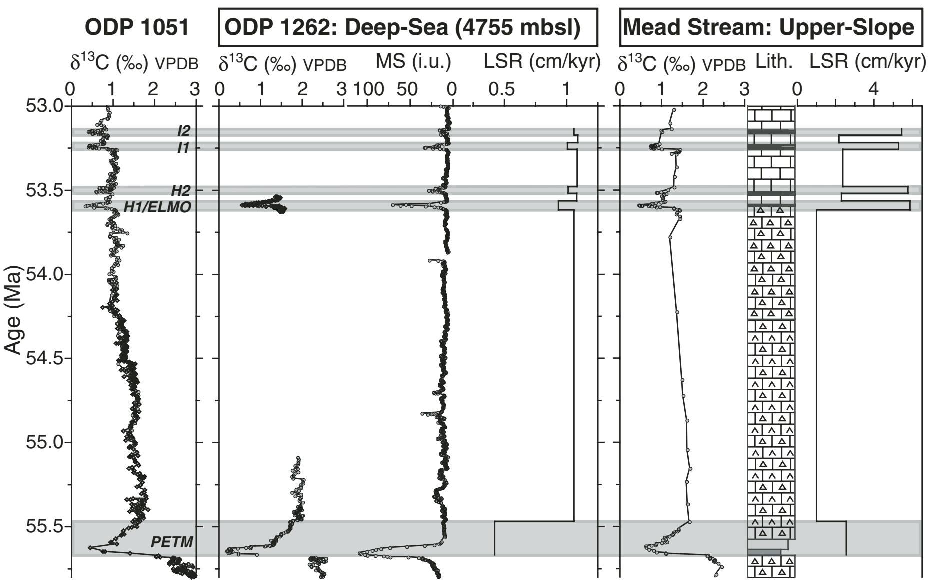

Figure 3. Ocean Drilling Program (ODP) Site 1051 early Eocene sequence contains representative marine carbonate $\delta^{13}C$ record that highlights Paleocene–Eocene thermal maximum (PETM), H1, H2, I1, and I2 carbon isotope excursions (CIEs) (Cramer et al., 2003). ODP Site 1262 bulk $\delta^{13}C$ records across PETM (Zachos et al., 2005) and H1 (Lourens et al., 2005) CIEs, Site 1262 magnetic susceptibility (MS) (Zachos et al., 2004), and Mead Stream bulk carbonate $\delta^{13}C$ allow for correlation of these CIEs between locations. Increases in MS between PETM and H1 correlate to a core break and an anomalous diagenetic bleb (Zachos et al., 2004). An age model generated for Site 1262 allows for calculation of linear sedimentation rate (LSR).

Upper Paleocene–lower Eocene rocks at Mead and Dee Streams have been logged perpendicular to dip above markers set at 0.0 m. The PETM onset is 157.6 m upsection of the Cretaceous-Tertiary boundary at Mead (Hollis et al., 2005), and 26.0 m upsection of a green bed at Dee (Hancock et al., 2003). Given available stratigraphy, sediment deposited from 54 to 53 Ma should be from ~175 to 200 m at Mead, and from ~60 to 70 m at Dee. We relogged these intervals, and exhumed fresh rock samples for laboratory analyses. Beds were delineated as limestone, siliceous limestone, marl, or marly limestone.

Mead Stream sample splits were analyzed for $CaCO_3$ content using the "carbonate bomb" technique (Table DR1), which has an analytical precision of ~0.5%. Crushed and dried splits of all samples from both sections were analyzed for carbon isotope composition in the Stable Isotope Laboratory at University of California, Santa Cruz. Powdered samples (~100 µg) were analyzed using an Autocarb device coupled to either a Prism or Optima Mass Spectrometer. Carbon isotope values were calibrated to the Vienna Peedee belemnite standard using NBS-19 and an in-house standard Carrara Marble (Table DR1). Analytical precision for individual analyses is better than ±0.05‰. Oxygen isotope values were measured with a precision of ±0.1‰ (Table DR1), but are not discussed because fluids have altered original $\delta^{18}O$.

RESULTS AND DISCUSSION

Studied intervals are principally limestone (Fig. 2). However, both have two shorter intervals (181.6–188.1 m and 193.4–198.6 m at Mead; 62.2–64.8 m and 67.8–71.2 m at Dee) with two horizons of intermittent marl-rich beds. Marl-rich beds are 1–27 cm thick, and have lower $CaCO_3$ contents but higher amounts of fine silt to clay-sized siliciclastic material (~30%–45%) than background limestone beds (~15%) (Table DR1; Fig. 2). The only other Lower Limestone marl-rich horizon marks the PETM. Significant amounts of biogenic chert complicate some intervals (e.g., 160.0–182.5 m at Mead), which predictably record relatively low $CaCO_3$ content (Fig. 2).

Bulk carbonate $\delta^{13}C$ records at Mead and Dee streams exhibit similar trends (Table DR1; Fig. 2). Across the studied interval, both records display background $\delta^{13}C$ values of 1.2‰–1.5‰ and four short, distinct decreases in $\delta^{13}C$ (lack of accessible outcrop precluded complete sampling at Mead). The lowest and upper middle anomalies are the largest (~0.9‰ and 0.6‰, respectively), whereas the lower middle and highest are the smallest (~0.2‰). Although the four $\delta^{13}C$ anomalies span the four marl-rich horizons, adjacent limestone and marl beds have similar $\delta^{13}C$ values, suggesting these are primary signals in carbonate rather than manifestations of different lithology.

Rocks deposited in the Clarence River valley between 56 and 53 Ma contain five horizons characterized by marl-rich beds and significant decreases in $\delta^{13}C$. The lowermost horizon, with an ~2.5‰ drop in bulk carbonate $\delta^{13}C$, represents the PETM (Hancock et al., 2003; Hollis et al., 2005). Based on shape, amplitude, and approximate timing of the other $\delta^{13}C$ anomalies, we correlate the overlying four horizons to the H1-ELMO, H2, I1, and I2 CIEs (Fig. DR1). The second horizon is found near the boundary of planktonic foraminiferal zones P6a and P6b, and just above the base of nannofossil zone NP11 (Fig. 2). This is, with available data, the expected onset age (ca. 53.6 Ma) of the H1 CIE and ELMO (Lourens et al., 2005). It has a CIE about one-third to one-half the amplitude of that across the PETM, similar to observations at other locations (Fig. 1). The third horizon, positioned immediately above the H1 CIE and having a small $\delta^{13}C$ anomaly (Fig. 2), is most likely the H2 CIE. The fourth horizon is found near the top of radiolarian zone RP8, within planktonic foraminiferal zone P6b and nannofossil zone NP11 (Fig. 2). This correlates with the I1 CIE, and we note that the drop in $\delta^{13}C$ is less than that of H1, as found elsewhere (Fig. 1). The fifth horizon, which is just above I1, has a stratigraphic position and small $\delta^{13}C$ anomaly (Fig. 2) similar to the I2 CIE. In summary, the same succession of CIEs—PETM followed by two pairs, H1-H2 and I1-I2—is recorded in lower Eocene sediments from widely separated deep-sea locations (Cramer et al., 2003) and a high southern latitude upper slope environment. Clearly, all five CIEs represent global carbon cycle perturbations.

A remarkably complete lower Eocene section was recovered at ODP Site 1262 beneath 4755 m of water on Walvis Ridge. The lower two of five clay-rich horizons in this section correlate with the PETM and H1 CIEs, and mark $CaCO_3$ dissolution (Zachos et al., 2005; Lourens et al., 2005). We propose, on the basis of their character (MS intensity) and stratigraphic position (Fig. DR1), that the upper three clay-rich horizons correlate with the H2, I1, and I2 CIEs, and that they also represent periods of deep-sea $CaCO_3$ dissolution. Because absolute ages for all five events remain uncertain, we have derived an age model that is consistent with available age datums, but that accounts for decreasing sedimentation across the dissolution horizons. In this model, the average sedimentation rate between the end of the PETM, set at 55.47 Ma, and the onset of the H1 CIE, set at 53.62 Ma, is related to the average $CaCO_3$ content (extrapolated from MS; Lourens et al., 2005) over the same depth range (Table DR2). Based on this relationship, variations in $CaCO_3$ content were linearly related to sedimentation rate between the onset of the H1 CIE and the conclusion of the I2 CIE. This gives onset ages for the H2, I1, and I2 CIEs of ca. 53.52, 53.26, and 53.18 Ma, respectively. While these ages differ from those presented by Cramer et al. (2003) (Table DR2), their ages also imply differential sedimentation rates at Site 1262, consistent with $CaCO_3$ dissolution and diminished deposition during the events.

Clay-rich horizons also mark the PETM in continental margin sections (e.g., Schmitz et al., 2001; Giusberti et al., 2007). In these cases, the PETM horizon is expanded, presumably because greater warmth and an accelerated hydrological cycle enhanced continental erosion and terrigenous siliciclastic flux to continental margins (Ravizza et al., 2001; Bowen et al., 2004). Any simple sedimentation rate model for the Mead and Dee sections shows that clay-rich horizons representing the PETM, H1, H2, I1, and I2 are similarly expanded due to siliciclastic dilution. For example, our ages for the five events (Table DR2) necessitate major increases in sedimentation rates across the PETM, H1, H2, I1, and I2 (Fig. 3). Although evidence for warming has only been documented across the PETM and H1 CIEs, all five events are associated with enhanced terrestrial discharge to continental margins, and therefore probably a rise in temperature. With our age model, sedimentation rate variations across the five horizons at Mead Stream do not scale to the magnitude of their associated CIEs. This may reflect differences in sea level or background temperature. In particular, the PETM occurred when background temperatures were relatively cool, whereas the younger Eocene events occurred when temperatures were significantly warmer (Zachos et al., 2001).

CONCLUSIONS AND IMPLICATIONS

We document the lithology and bulk carbonate $\delta^{13}C$ of two outcrop sections originally emplaced on the upper continental slope of New Zealand during the early Paleogene. Five marl-rich horizons with low $\delta^{13}C$ and elevated sedimentation rates characterize both sections over the interval between 56 and 53 Ma. The lowest horizon marks the PETM (Hancock et al., 2003; Hollis et al., 2005). Based on stratigraphic relationships and $\delta^{13}C$ signatures, the other four correlate to the H1, H2, I1, and I2 CIEs documented in deep-sea sections (Cramer et al., 2003; Lourens et al., 2005). However, in the deep sea these events are marked by lowered sedimentation rates due to $CaCO_3$ dissolution. This suggests that there were five globally significant events between 56 and 53 Ma with similar characteristics at the same location but different responses between environments. Magnitude appears to be the primary distinguishing feature characterizing these events; the PETM was the most pronounced.

Because the five events have similar systemic responses in different environments, they probably have a similar generic cause. All five CIEs appear to represent massive inputs of isotopically light carbon during a long-term warming trend. As evidenced by condensed clay layers at Walvis Ridge, the carbon inputs involved CO_2 increases that led to dissolution of carbonate on the seafloor. As evidenced by expanded marl-rich horizons in Clarence Valley, these carbon injections were associated with warming and an accelerated hydrologic cycle that increased continental erosion. If these inferences can be further substantiated, they constrain explanations for the PETM as well as early Paleogene climate and carbon cycling as a whole: a dynamic source must have repeatedly injected large quantities of ^{13}C-depleted carbon into the ocean or atmosphere. Further, the nominal 100 k.y. between carbon injection events (according to our age model) may indicate orbital pacing, as has been suggested for the PETM and HI CIEs (Lourens et al., 2005).

Marine gas hydrates have been the most widely cited source of the carbon injected during the PETM. This hypothesis argues that a precursor deep-sea warming dissociated gas hydrates in marine sediment to free gas bubbles, which escaped via seeps or sediment failure and subsequently oxidized to CO_2 (Dickens et al., 1997; Dickens, 2003). Our results may constrain this idea significantly. Modeling efforts suggest that marine gas hydrates, serving as a dynamic CH_4 capacitor, could release a series of carbon injections across the early Eocene, but that due to estimates of the reservoir size and input flux to the capacitor, these injections would have to become successively smaller in mass (Dickens, 2003). The merits and demerits of other potential carbon sources have yet to be assessed within the context of multiple carbon injections.

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