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Early Eocene carbon isotope excursions and landscape destabilization at eccentricity minima: Green River Formation of Wyoming

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ABSTRACT

Repeated global reorganizations of carbon cycling and biotic, oceanic and terrestrial processes occurred during the Early Eocene, and appear to have been paced by cyclic variations in the eccentricity of the Earth's orbit. The phase relationship(s) between insolation variation, terrestrial paleoclimate, and atmospheric $p\mathrm{CO}_2$ during these events remains enigmatic however, due to their poorly constrained timing relative to specific orbital configurations. Here we use tiered interpolation between radioisotopic ages and paleomagnetic polarity chrons to compare high-resolution δ^{13}C and lithofacies records from the Wilkins Peak Member of the Green River Formation of western North America to a Fe-intensity XRF record from the western Atlantic Ocean, and to numerical solutions for Earth's orbital configuration. Wilkins Peak Member lithofacies stacking patterns record cyclic geomorphic responses to insolation and climate fluctuations, spanning an interval of 1.8 Ma. Previous macrostratigraphic analyses using ^{40}Ar/^{39}Ar and U–Pb ash bed ages indicate that these cycles reflect long and short eccentricity modulation of precession. Hydrologic variance appears to have occurred inversely with intervals of maximum sediment advection, with carbonate- and evaporite-dominated lacustrine modes during eccentricity maxima, and siliciclastic-dominated alluvial modes during eccentricity minima. Stable carbon isotope analyses of 126 meters of Wilkins Peak Member strata reveal a regular ∼5 per mil oscillation between high-δ^{13}C lacustrine modes and low-δ^{13}C alluvial modes. Tiered interpolation between paleomagnetically characterized terrestrial ash beds facilitates the integration of 11 radioisotopic ages with the geomagnetic polarity timescale, resulting in significant expansion of chron C23 and shortening of chron C22 relative to timescales based on seafloor magnetic anomaly profiles. The new proposed timescale permits direct comparison of terrestrial and marine climate proxy records from the Early Eocene Climatic Optimum at ca. ±250 kyr resolution, and reveals prominent 100 kyr- and 405 kyr-scale oscillations within both records. Wilkins Peak Member δ^{13}C minima, which occurred during low eccentricity alluvial modes, likely coincided with global δ^{13}C minima (Scenario 1), but may alternatively reflect productivity-driven local effects within Lake Gosiute (Scenario 2). If Scenario 1 proves accurate, Early Eocene negative δ^{13}C "hyperthermal" excursions occurred during eccentricity minima rather than maxima as formerly believed.

1. Introduction

Recent discovery of multiple global negative carbon isotope excursions (CIEs; i.e., 'hyperthermals') in Early Eocene marine and terrestrial strata raises important questions about the causal relationships between orbital forcing and Earth's climate and geomorphic systems during warm climate modes (Fig. 1; Galeotti et al., 2010; Zachos et al., 2010). In the ocean, CIEs correspond to influxes of terrigenous clay (Nicolo et al., 2007; Slotnick et al., 2012), faunal changes, and shallowing of the carbonate compensation depth (Leon-Rodriguez and Dickens, 2010). On land, they correspond to lateral expansion and coarsening of alluvial facies and enhanced pedogenesis (Schmitz and Pujalte, 2007; Abels et al., 2012; Foreman et al., 2012). Among multiple proposed mechanisms for CIEs are dissociation of methane hydrates from the continental shelf (Dickens et al., 1997; Zachos et al., 2010), and oxidation of dissolved organic carbon stored in stratified deep ocean waters (Sexton et al., 2011). A full understanding of the forcing mechanism(s) that promoted CIEs is hampered, however, by imprecise constraint of their contemporary orbital configuration(s). Stratigraphic comparisons to numerical orbital solutions (Laskar et al., 2004, 2011) indicate that the Paleocene/Eocene CIE coincided with

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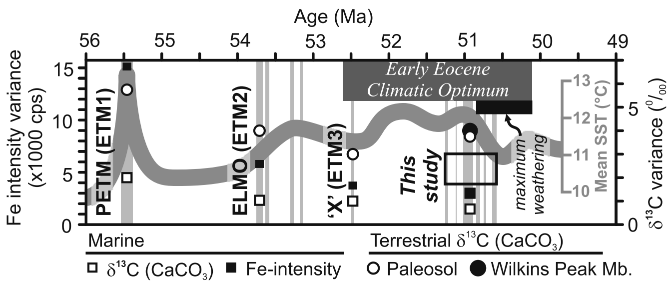

Fig. 1. Early Eocene carbon isotope events and associated marine Fe-intensity fluctuations (Zachos et al., 2010) and their relationship to long-term global temperature variations, the Early Eocene Climatic Optimum (Zachos et al., 2008), and interpreted maximum terrestrial weathering in North America (Hyland and Sheldon, 2013). Paleosol $CaCO_3$ $\delta^{13}C$ variance was measured from carbonate nodules (Koch et al., 1995; Clyde et al., 2001; Abels et al., 2012; Hyland and Sheldon, 2013).

a prolonged eccentricity lull (Galeotti et al., 2010; Zachos et al., 2010). Current geochronology is insufficiently precise to distinguish the eccentricity magnitude-phase of subsequent smaller magnitude CIEs (Fig. 1). Nonetheless, their coincidence with $\delta^{13}C$ and Fe-intensity variance has led paleoceanographers to suggest that CIEs occurred during eccentricity maxima, based on the logic that variance resulted from pronounced precession-driven variation which would have coincided with high eccentricity (Lourens et al., 2005; Lunt et al., 2011).

Terrestrial strata of the Wilkins Peak Member (WPM) of the Green River Formation provide an important constraint of eccentricity phase during CIEs and its effects on terrestrial climate and paleogeography of North America during the Early Eocene Climatic Optimum (EECO, Fig. 1). $^{40}Ar/^{39}Ar$ and ^{238}U–^{206}Pb geochronology indicates that accumulation of the WPM occurred between ~51.7 and ~49.9 Ma (Fig. 2; Smith et al., 2008b, 2010a). Its strata were deposited in an endorheic lake basin at the center of a broad catchment that was isolated from both riverine inputs (Smith et al., 2008b) and from atmospheric moisture (Sewall and Sloan, 2006) by the Cordilleran divide to the west and the basement-cored Laramide uplifts to the east, north, and south (Figs. 3 and 4). Because it was deposited in a hydrologically closed basin, WPM lithofacies record both lake level and changes to intra-basinal clastic and chemical sediment fluxes (Smith et al., 2008a). Its strata consequently contain information about net precipitation, evaporation, and sediment and water mass fluxes that are unavailable in existing exclusively-fluvial terrestrial records of CIE intervals (Abels et al., 2012; Foreman et al., 2012). Several scales of repetitively-stacked lithofacies occur within the WPM in the Bridger subbasin of the Greater Green River Basin (Culbertson, 1961; Eugster and Hardie, 1975), some of which have been suggested to correspond to orbital cyclicity (Fischer and Roberts, 1991; Roehler, 1993; Machlus et al., 2008; Meyers, 2008). Ash-bed geochronology- and macrostratigraphic analysis of basin-wide lithofacies stack-

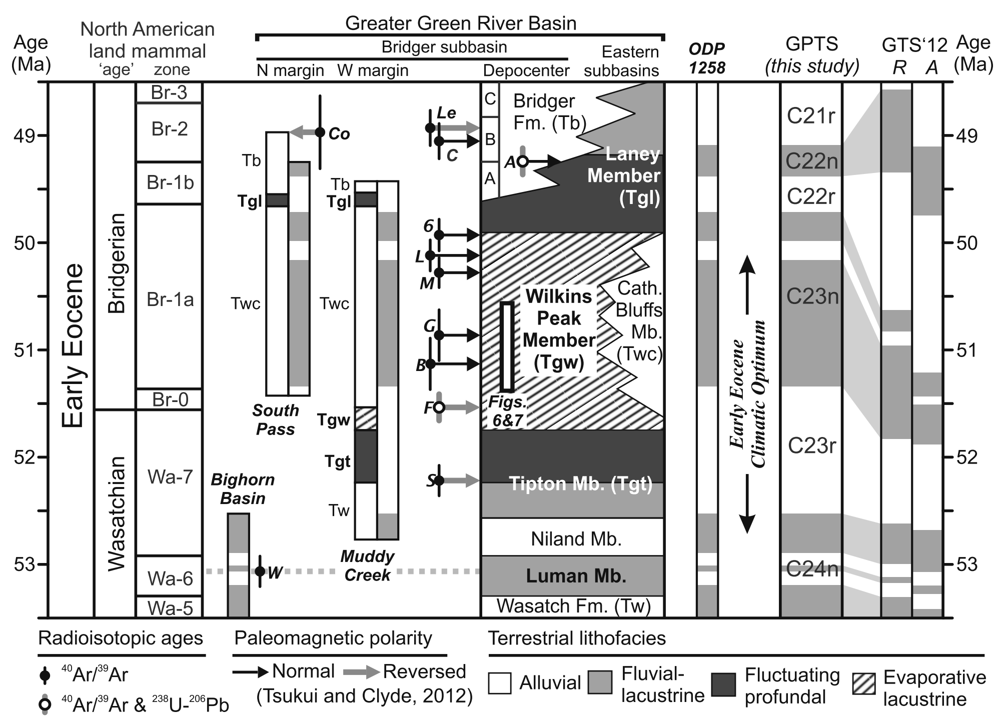

Fig. 2. Early Eocene lacustrine and alluvial strata (Clyde et al., 1997, 2001; Zonneveld et al., 2003; Smith et al., 2008b), radioisotopic geochronology (Smith et al., 2008b, 2010a), ash bed paleomagnetic polarity (Tsukui and Clyde, 2012), terrestrial biostratigraphy (Zonneveld et al., 2000; Woodburne et al., 2009), and magnetostratigraphy in the Greater Green River Basin (Clyde et al., 1997, 2001); magnetostratigraphy and radioisotopic geochronology from the Bighorn Basin (Clyde et al., 1994; Tauxe et al., 1994; Smith et al., 2004, 2010a); and magnetostratigraphy in core from ODP site 1258 (Westerhold and Röhl, 2009). Green River Formation subdivisions are shown in bold type. Cf. Table 2 for details concerning the tiered interpolation used to calculate inter-ash bed ages. Radioisotopic ages for the Willwood ash (W), Scheggs tuff (S), Firehole tuff (F), Boar tuff (B), Grey tuff (G), Main tuff (M), Layered tuff (L), Sixth tuff (6), and Analcite tuff (A), Church Butte tuff (C), Continental tuff (Co), and Leavitt Creek tuff (Le) are depicted with fully propagated 2σ uncertainties, and are calculated relative to the 28.201 Ma age for Fish Canyon rhyolite sanidine (Kuiper et al., 2008) using λ (^{40}K) values and uncertainties of Min et al. (2000). $^{40}Ar/^{39}Ar$ and U–Pb ages are error-weighted means of $^{40}Ar/^{39}Ar$ and U–Pb ages (Smith et al., 2010a). Geomagnetic polarity timescale (GPTS) used for this study shown relative to both the "Radioisotopic" (R) and "Astro-Age" (A) age models of the GTS 2012 (Vandenberghe et al., 2012). The "Radioisotopic" age model is based on a tiered interpolation between ages for the Willwood ash and Continental tuff that was spline-scaled using the location of seafloor magnetic anomalies in the south Atlantic Ocean (Cande and Kent, 1992). Note that the Continental tuff was mistakenly used as a calibration point for chron C22n in "Radioisotopic" age model of the GTS 2012 based on extrapolation of the normal polarity interval in the lower Bridger Formation to the paleomagnetically uncharacterized upper Bridger Formation at the top of Continental Peak in which the Continental tuff occurs. New paleomagnetic analyses by Tsukui and Clyde (2012) indicate the Continental tuff and similarly aged Leavitt Creek tuff record reversed remnant magnetic polarity, and thus occurs at the base of chron C1r instead. The "Astro-Age" (A) age model of the GTS 2012 is based on chron and subchron durations originally calculated by Westerhold and Röhl (2009) using a sixth order polynomial fit to Fe-intensity at ODP site 1258, which have been stacked atop the astrochronologically-determined 57.101 Ma age of Hilgen et al. (2010) for the base of chron 24r.