The K/X event in Clarence Valley, New Zealand

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**Abstract**

**[1]** The Early Eocene Climatic Optimum (EECO), lasting from ~53 to 50 Ma, is considered to have been the warmest interval throughout the Cenozoic. It comprised of a broad temperature maximum with elevated atmospheric *p*CO2, noticeable shifts in carbon cycling, a variety of faunal and floral changes and several, brief (<200 kyr) intervals of extreme warming. At least for the most prominent of warming events, a long-term drop in δ13C and short-term Carbon Isotope Excursion (CIE) have been coupled to massive fluxes of 13C-depleted carbon into the exogenic system and global climate change. However, much about EECO remains unknown because of a lack of detailed and coupled proxy records. Here, we help rectify this problem by presenting a new lithologic and carbon isotopic record for an ~84-m-thick section of early Eocene upper slope calcareous-rich sediments, now lithified and exposed along Branch Stream, New Zealand. Comparison of new carbon isotopic and lithologic records of this greatly expanded section to nearby Mead Stream identifies multiple negative CIEs in short succession and generally more marl during the lowermost EECO (~53.3-51.7 Ma) <<more than what? Than previously known? Than the upper EECO?>>, with the most prominent of these equating to the K/X warming event, the most prominent of warming events of the EECO. The early Eocene lithologic and δ13C records at Branch and Mead Streams are remarkably similar to each other, with the distinction that sequences at Branch Stream are thicker and generally have a wider range of δ13C across CIEs. Both expanded sections are marked by terrigenous dilution, best explained by enhanced seasonal precipitation, elevated greenhouse-gas concentrations, and likely global warming. These data indicate that the lowermost EECO can be described as a time with a general δ13C-low superimposed by a series of short-term climate perturbations, the most prominent being the K/X event.

Key words: Eocene Hyperthermals, carbon cycling, J-event, X-event, EECO, Early Eocene Climatic Optimum, carbonate platform, stable carbon isotopes, and carbonate sedimentation.**1. Introduction**

[2] Earth’s ocean faces the potential for widespread acidification in the coming millennia as a result of human-induced shifts in marine carbon chemistry (Caldeira and Wickett, 2003). In addition, large fluxes of terrigenous material will likely inundate marginal settings, as suggested by models predicting an intensified hydrological cycle but with a strong seasonal component, particularly at higher latitudes (Meehl et al., 2007a). Properly predicting how the oceans should function in a warmer and more acidic environment is crucial to the continued stability of human civilization. In order to address this concern, it is useful to gain additional insight from past climatic perturbations, particularly during periods characterized by intense warmth.

[3] The Early Eocene Climatic Optimum (EECO) was the warmest interval of the Cenozoic, with a broad temperature maximum, elevated atmospheric *p*CO2, and a variety of faunal and floral changes from ~53 to 50 Ma (Zachos et al., 2008; Hollis et al., 2012; Figure 1). Though the EECO still lacks a formal definition in regards to duration and absolute age, it generally relates to a 2- to 4- Myr interval between 53 and 50 Ma on the Wo-1 age model (Westerhold et al., 2008). By combining information and data from several locations, it is shown the EECO began near a prominent carbon isotope excursion (CIE) coined “K/X”. Similar to the Paleocene Eocene Thermal Maximum (PETM), the CIE of the K/X event is also characterized by ocean warming and carbonate dissolution in deep sea. More recent work has suggested that the EECO is comprised of a series of CIEs with the K/X being the most prominent of many suggested events (Slotnick et al., 2012).

[4] To understand the carbon cycle during the EECO, more detailed records are needed. Carbon cycles fast (< 2 kyr) within the exogenic system and records with appropriate resolution across EECO remain scarce (Figure 1). This reflects a combination of factors, although one appears to be significant shoaling of the carbonate compensation depth (CCD) near the start of EECO (Slotnick et al., *submitted*). Although previous carbon cycle models have already shown how fluxes of carbon between surficial reservoirs can be abrupt (Dickens, 2003; Zeebe et al., 2009), these ideas have not been adequately tested.

[5] The northwest side of Clarence Valley, New Zealand (Figure 2), presents an excellent location to generate detailed early Paleogene stable carbon isotope records. Multiple tributaries of Clarence River (e.g., Mead Stream, Dee Stream, Branch Stream, Muzzle Stream) have exposed thick sediment sequences of limestone and marl originally deposited on the upper to middle slope of a passive continental margin during the Late Cretaceous through Middle Eocene (Crampton et al., 2003). A series of investigations (Strong et al., 1995; Hancock et al., 2003; Hollis et al., 2005a, 2005b; Nicolo et al., 2007; Slotnick et al., 2012), mainly focused on the latest Paleocene and earliest Eocene (i.e., pre-EECO), have demonstrated that 13C records generated along these streams correlate to records generated from samplings of similar sites across the world (Figure 1; Cramer et al., 2003; Zachos et al., 2010; Galeotti et al., 2010; Stap et al., 2010; Chen et al., 2014). This work also has emphasized additional findings (Nicolo et al., 2007; Slotnick et al., 2012): (1) prominent negative CIEs generally occur across horizons with higher amounts of clay (marls); and (2) dissimilar to deep-sea settings, these clay-rich intervals represent enhanced terrigenous accumulation (dilution) rather than reduced carbonate accumulation (dissolution). Presumably, these observations reflect an accelerated hydrological cycle seasonality, whereby during times of elevated warmth at high latitudes, decreased vegetation and intensified chemical weathering debouches greater fluxes of terrigenous material onto the continental slope (Ludwig and Probst 1998; Peterson et al. 2002; Schmitz and Pujalte 2003; Murphy et al. 2004; Held and Soden 2006; Schmitz and Pujalte 2007; Meehl et al. 2007*a*, 2007*b*). Consequently, early Paleogene sections within Clarence Valley became greatly expanded during times of globally warmer climate, which provides an opportunity to generate detailed 13C records over corresponding time intervals.

[6] The 13C record at Mead Stream across the start of EECO (~53.3 to 51.7 Ma) shows at least ten negative CIEs (Slotnick et al., 2012). The most prominent of these equates to the K/X CIE identified in several deep-sea records (Cramer et al., 2003; Westerhold and Röhl, 2009; Dickens and Backman, 2013), as well as in at least one other continental margin sequence (Galeotti et al., 2010). In other words, EECO is characterized by multiple CIEs in short succession. Initially, this seems to contrast with records at condensed deep-sea locations. However, this is not the case with many of the more prominent horizons correlating to negative CIEs. The objectives of this study are twofold: to characterize the chemostratigraphy and related lithostratigraphy of the K/X CIE, as well as that of the greater EECO. Presented within is an integrated chronostratigraphic framework and local lithologic characterization from separate locations along a proto-New Zealand shelf (Branch and Mead Streams). The project is based on stable isotope and carbonate content analyses across magnetochrons C24n to C23n. Both the Branch Stream and Mead Stream sedimentary successions have promise to reconstruct the carbon cycle and chemical evolution of early Eocene oceans during the warm EECO.

**2. Setting and Previous Work**

*2.1. Location and Section*

**[7]** Clarence Valley trends NE-SW for ~80 km between the Seaward and Inland Kaikoura Ranges in Marlborough, on the north end of South Island, New Zealand (**Figure 2**). A series of late Cretaceous, Paleocene and early to middle Eocene marine lithostratigraphic units dipping 45 to 55° northwest, now called Muzzle Group, bound the northwest side of the river. These units are spectacularly exposed in sections along gorges that have been incised roughly perpendicular to strike by several streams. In general, the sequences transition from a shelf environment in the southwest (e.g., Seymour Stream) <<Is Seymour Stream in the area covered by figure 2? If so, label Seymour Stream in the figure>> to an upper-middle slope environment in the northeast (e.g., Mead Stream), with a paleo-shelf break centred near Muzzle Stream in the middle (Reay, 1993). Stratigraphic continuity and thickness also generally increase to the northeast towards Mead Stream (Crampton et al., 2003).

**[8]** During the early Eocene, the overall depositional setting occurred along a north-facing embayment of a passive continental margin at ~55 to 50°S paleolatitude (Reay 1993; Strong et al. 1995; Hollis et al. 2005a). In this environment, variable amounts of biogenic carbonate and terrigenous clay, as well as minor amounts of biogenic silica, accumulated on the seafloor. With the advent of major tectonism in New Zealand, beds were subsequently uplifted, folded, and faulted apart, so that the ancient marine strata presently exist along the Clarence River with high dip angles (Strong et al., 1995; Crampton et al., 2003; Hollis et al., 2005a).

**[9]** The principle stratigraphic units of interest to this study are uppermost Lower Limestone and Lower Marl, which comprise the lower portion of Amuri Limestone (**Figure 2**). The latter is a rock formation within Muzzle Group, which originally accumulated during the late Paleocene through the early Eocene (Reay 1993; Hollis et al. 2005*a*). These lithologic units outcrop along Branch Stream and comprise an 84 m thick near-continuous calcareous-rich package of uppermost Lower Limestone and Lower Marl, a sequence that corresponds to a 65 m thick sequence at Mead Stream.

Lower Limestone, outcropping from 0 to 21 m, typically contains centimetre- to decimetre-scale (cm- to dm-) beds dominated by hard limestone. Some marl-rich horizons outcrop just below the top of Lower Limestone. Some marl partings or thin (<10 cm) marl horizons separate Lower Limestone beds with two distinct horizons consisting of more individual marl beds; these include the J CIE and BS-CIE-4 (**Table 2**). Lower Marl, outcropping from 21 to 84 m, primarily consists of thicker and more frequent beds of marl from 21 to 64 m followed by a subsequent interval of even more common marl beds. At first, marl beds seem sporadic but do generally follow the occurrence of CIEs such as the K/X CIE, the L CIEs, BS-CIE-10, and BS-CIE-11, such that Lower Marl generally corresponds to EECO. No previous detailed assessments have been carried out at Branch Stream. Discussed here is only a portion of the much thicker Upper Cretaceous to Middle Eocene Amuri Limestone stratigraphic succession.

**[10]** At Mead Stream, a series of works previously resolved the chronostratigraphic framework, including most of Lower Marl (Reay, 1993; Strong et al. 1995; Hancock et al., 2003; Hollis et al. 2005*a*; Hollis et al., 2005b; Nicolo et al. 2007; Slotnick et al., 2012). At Mead Stream, a “zero” datum was set at the Cretaceous-Paleogene Boundary. Lower Limestone and Lower Marl at Mead Stream were previously logged at a centimetre-scale (Hollis et al., 2005a; Nicolo et al., 2007; Slotnick et al., 2012). Lower Marl conformably overlies Lower Limestone and includes the J, X, and L CIEs, plus many more at Mead Stream (Slotnick et al., 2012).

**[11]** Muzzle Group rocks at Branch Stream are far more difficult to log and to sample than at Mead Stream because a significant (~ 120 m tall) waterfall and a set of cascades break the overall section into segments (**Figures 3, 4A, 4B**). Except for an initial stratigraphic log from Branch Stream (Reay, 1993), unlike at Mead Stream, minimal work has been carried out subsequently. As such, the chronostratigraphic framework remains poorly resolved. Two freshly exposed sequences, separated by a substantial bend in the tributary, outcrop along the true right side of the gorge. The lower of the two sections, coined middle section, includes 37 m of primarily limestone and some marl. The base is located ~50 m above the top of the waterfall. Cascades occur along the entire extent with most relating to the presence of large boulders with a diameter of 2 to 5 m residing within the stream. Most boulders originate from a large rock fall located along the true left side of the gorge, adjacent to the middle section. Separately, one prominent cascade at 32 m and the substantial stream bend may instead reflect a lithologic shift from limestone to marl, with a prominent marl sequence outcropping along the bend. The upper section resides above the bend in the stream and is characterized by 53 m of ~50% limestone and 50% marl. Lower flow velocities and stream slope make access and sampling easier than the middle section. As in the middle section, the proportion of marl to limestone generally increases up the upper section. The base is located ~20 m above the top of the middle section. Although cascades do characterize the stream along the upper section, they are much smaller in size and extent. Boulders along this portion of the stream are derived from meta-sediments upstream.

**3. Methods**

3.1. *Stratigraphic log and samples*

**[12]** Following work at Mead Steam, we photographed and logged the middle and upper segments at Branch Stream (**Figures 3 - 6**). A “zero” datum was set as low in the middle segment as possible, just above the waterfall and within uppermost Lower Limestone. From this datum, the strata appear continuous for at least 150 m of stream length; thus, much of Lower Marl can be examined (**Figures 4A, 4B**). Individual decimetre-scale beds were measured perpendicular to dip, identified as one of three lithologies (limestone, marly limestone, or marl), and catalogued numerically (**Figure 6**). The total length of exposed logged section was 84 m after correcting for dip and changes in stream direction.

**[13]** Three-hundred and sixty-seven fresh rock samples were chiseled from the sides of Branch Stream over the logged section. Samples varied in size and shape but generally exceeded 300 g. Sampling was carried out to minimize bias towards marl-rich horizons, which exists in the current totality of Lower Limestone and Lower Marl samples collected at Mead Stream (Hollis et al., 2005; Nicolo et al., 2007, 2010; Slotnick et al., 2012). Sampling was also done to ensure stratigraphic overlap between the middle and upper segments. In the end, the average sampling resolution is approximately 22 cm. This is similar to the current sampling resolution over the corresponding interval at Mead Stream, although less skewed to CIEs (Slotnick et al., 2012; Slotnick et al., *in prep*).

3.2 *Sample preparation and analyses*

**[14]** Samples were tallied as marl, marly limestone, or limestone and bagged in the field, carried out on foot, and transported to a rock preparation lab. Weathering rinds were detached with a rock saw. Remaining samples were freeze-dried to remove potential water, and powdered in a tungsten carbide rock mill. Powdered sample material was then analysed for carbonate content and stable isotope composition.

**[15]** The carbonate bomb method (Dunn, 1980) was used for determining carbonate contents A ±1.3% analytical precision (1σ) was determined from calibration curves and from multiple analyses of an in-house standard. Bulk stable isotopes were measured at the Stable Isotope Lab, GNS Science, Wellington, New Zealand. Analyses were completed on a GVI IsoPrime Carbonate Preparation System at a reaction temperature of 25°C for 24 hours and run via dual inlet on the IsoPrime mass spectrometer. All results are reported with respect to Vienna PeeDee belemnite (VPDB) via integration to the NBS-18 and NBS-19 standards and then normalization to Carrera Marble, an internal standard, with reported values of 2.04‰ for δ13C and -6.40‰ for δ18O. The external precision for these measurements is < 0.1‰ for δ13C and < 0.2‰ for δ18O. Similar to Mead Stream, stable oxygen isotope values are reported but only in passing, because they are significantly depleted in 18O, suggesting oxygen isotope exchange with meteoric water (Banner and Hanson, 1990; Bishop et al., *in press*).

**4. Results**

4.1 *Lithology and Bedding*

**[16]** Uppermost Lower Limestone, particularly from 0.0 to 5.3 m, contains cm- to dm-thick beds dominated by hard, grey limestone (**Figure 6A)**. Two relatively marl-rich horizons outcrop from 2.5 to 2.7 m and from 3.5 to 3.7 m, collectively comprising 8% of this basal interval.

**[17]** Unlike at Mead Stream, the transition from Lower Limestone to Lower Marl is not clearly defined at Branch Stream (**Figure 5A; Figure 6**). Instead, a gradual transition occurs between 5.3 and 21.8 m, where abundance of marl-rich horizons increases. Marl layers comprise ~15% of the succession from 5.3 to 21.8 m, but ~48% of the succession from 21.8 to 83.4 m. Although the beds are tilted, there is no obvious internal deformation within this interval, suggesting the gradual transition relates to primary sedimentation.

**[18]** Lower Marl (*sensu stricto*) begins at 21.8 m and continues for the remainder of the logged section. The unit includes frequent and thick marl and some marly limestone beds as well as limestone beds. Marl layers account for ~50% of the succession from 21.8 to 30.2 m, ~25% of exposed outcrop from 30.2 to 63.8 m, and ~88% of the succession from 63.8 to 83.4 m. The only noticeable internal deformation within Lower Marl at Branch Stream is an interval of boundinage from 48.5 to 49.0 m. Scree also covers ~3 m of section near the base of the upper segment, although this can be documented in the middle segment.

*4.2 Carbonate content*

**[19]** Carbonate contents, although variable, show distinct trends (**Figure 6, Table 1)**. Across all samples, carbonate contents average 72±8% (1σ) and range from 45 to 85%. Partitioned by lithology, the means and deviations of carbonate contents at 1σ are 61%±5% (n=102), 71%±4% (n=58), and 77%±4% (n=226) for marl, marly limestone, and limestone, respectively. Carbonate content is generally lower across specific intervals: (65%±7% for intervals 10.6 to 17.4 m, 27.5 to 31.8 m, 45.8 to 48.0 m, and 64.0 to 83.4 m) in comparison to the rest of the section (74%±7%). Above 60 m, carbonate contents generally drop from 80 to 60%.

*4.3* *Carbon isotopes*

**[20]** Bulk carbonate δ13C yield an explicit curve with noticeable trends and distinct CIEs, ranging between 1.52 and 0.24‰ with an average of 0.93±0.23‰ at 1σ (**Figure 6, Table 1**). The most enriched values (1.23 to 1.52‰) span two intervals: from 0 to 7.2 m, and from 58.0 to 61.4 m. The most depleted values (<1.00‰) span most of 8.1 to 51.0 m interval, as well as from 63.7 to 66.6 m, and from 73.6 to 80.0 m. Values typically become more depleted from 0 to 30 m. Numerous CIEs, defined as marked drops in δ13C across short intervals (<5 m), span most of the studied interval. The lowest δ13C values of ~0.30‰ describe the most extreme CIE peak.

**[21]** Eleven distinct marl-rich intervals span Lower Marl from 8 to 81 m. Each is coupled to a distinct CIE, with δ13C magnitudes ranging from -0.2 to -0.6‰ (**Table 2**). Marls relate to lower carbonate contents and usually shifts to lower δ13C, although the later is not always the case for lower magnitude events. Magnitude and thickness of each excursion does not relate to carbonate content or recessed patterns across each marl-rich interval, suggesting that δ13C is disassociated from rock type and reflects primary signals in carbonate accumulation, regardless of carbonate contents.

**5. Discussion**

5.1 *Age and Stratigraphic Correlation*

**[22]** Incorporation of datums derived from foraminifera assemblages provide some age constraints. However, poor preservation and tough disaggregation methods as well as likely diachronous occurrences in lower latitude sites limit the reliability of first and last occurrences (FO and LO). As such, this makes the use of standard early Paleogene bio-zones for age control at Clarence Valley sequences unreliable. Thus, integration of non-faunal age datums was necessary. Carbon isotope stratigraphy at Branch and Mead Streams provided useful correlation tie points (**Figure 7**), becoming key constituents of the Branch Stream age model.

**[23]** The Waipawan/Mangaorapan boundary, in upper E4, was identified along a nearby farm track in the marl underlying the last c. 1m-thick limestone bed before the section becomes marl-dominated. When correlated lithologically to the Branch Stream section, this boundary can be placed at 62 m. The top of Lower Marl is probably Heretaungan, but the Heretaungan/Mangaorapan contact has yet to be identified. Two samples, at 126.25 and at 126.80 m, in the transition from Upper Limestone to Upper Marl are Bortonian.

**[24]** Stratigraphic correlation using carbon isotope stratigraphy between Branch and Mead Streams span uppermost Lower Limestone and Lower Marl, providing twelve tie points (three first order and eight second order) from 8 to 73 m (**Table 3**). Lower Marl is well exposed at Branch Stream whereas upper Lower Marl at Mead Stream is deformed (i.e.; boundinage, shear, isoclinal folds, and faults) and scree span covers much of the uppermost ~63 m.

*5.2 Carbon Isotope Trends and Excursions*

**[25]** Bulk carbonate δ13C trends are similar between Mead and Branch streams. Carbon isotopes at both locations drops from 53.3 to 52.9 Ma. This is followed by a rise from 52.9 to 52.2 Ma and then largely a drop from 52.2 to 51.7 Ma. Geologically brief (<200 kyr) negative CIEs mark much of the background δ13C shifts. The most prominent example is the K/X CIE, but there are at least eight and probably more short excursions, each characterized by a CIE with a magnitude of up to -0.8‰ (**Figures 6, 7, 8**).

**[26]** Six prominent CIEs, occurring elsewhere, were identified in outcrop in Lower Limestone and Lower Marl at Branch Stream. Near the base of the sampled sequence, at ~7.3 to 10.3 m, or ~53.3 to 53.2 Ma, is a horizon with marl-rich inter-beds with particularly low carbonate contents and a -0.5‰ CIE. This interval probably corresponds to the J CIE (Cramer et al., 2003). The prominent marl-rich interval from 27.7 to 31.8 m or at ~52.9 Ma, characterized by consistently lower carbonate contents (~60 to 65% wt. %) and a -0.5‰ CIE, almost assuredly correlates with the K CIE (Cramer et al., 2003; Agnini et al., 2009) and X horizon at Site 1262 (Röhl et al. 2005). It marks the extreme low in δ13C at Branch Stream, and if correlated to Mead Stream, represents the low in Paleogene δ13C records, observations that are consistent with other localities (Cramer et al., 2003; Agnini et al., 2009; Röhl et al. 2005). An additional CIE with -0.4‰ magnitude closely following K/X at 33.8 to 36.6 m or ~52.8 Ma is a probable event present at both Mead and Branch Streams, but has not been identified elsewhere. The -0.5‰ magnitude CIE at 45.8 to 51.6 or ~52.5 to 52.4 Ma likely correlates to the L CIE (Cramer et al., 2003). Two additional CIEs outcrop at 63.3 to 67.0 m (~52.1 Ma) and at 73.4 to 80.3 m (~51.9 to 51.8 Ma), both of which also occur at Mead Stream (Slotnick et al., *in prep*). Embedded between these prominent events are a series of lower magnitude (0.1 to 0.3‰) CIEs, particularly between the J and K/X CIEs from ~10.6 to 27.7 m or 53.2-53.0 Ma, that also occur at Mead Stream.

**[27]** The J CIE marks the beginning of a general long-term δ13C low, as identified at nearby Mead Stream (Slotnick et al., 2012). Consistent with global compilations of carbon and oxygen isotopes (e.g.; Zachos et al., 2008), this realization further identifies the J CIE as a good chronostratigraphic marker for the onset of EECO. But, we resist defining the start of EECO using chemostratigraphic profiles alone from Mead and Branch Streams since doing so would invoke circular reasoning for links between siliciclastic inputs (below) and Earth surface temperature.

**[28]** The K/X CIE is the most prominent early Paleogene event within the 1.7 Myr sampled portion of Branch Stream, as marked by the lowest δ13C values (<0.4‰). The event may represent a cross-over in long-term (> 1 Myr) δ13C trends, as identified by a distinct drop before and gradual rise afterward. But, an extended record such as at Mead Stream (e.g.; Slotnick et al., *in prep*) is necessary for proper documentation. The broader stratigraphic interval is characterized by a series of marl-rich horizons in short succession, each corresponding to a ≤ -0.6‰ magnitude CIE. This is consistent with previously published records at nearby Mead Stream (e.g., Slotnick et al., 2012) and with variations in the magnetic susceptibility record at Site 1262 (Zachos et al., 2004). As such, we confirm there were at least four, if not, up to six CIEs between J and K/X CIEs­­ (53.3 to 53.0 Ma) and an additional four CIEs younger than the K/X CIE (52.8 to 51.8 Ma) with the second one corresponding to the L CIE (Cramer et al., 2003). Altogether, these CIEs largely correspond to the lowermost 1.5 Myr of the “loosely” defined EECO but were likely overlooked in recovered deep-sea sediments due to low sampling resolution and the condensed nature of much of the recovered early Paleogene deep-sea section. Our new record indicates that the EECO can be best described as a time when multiple CIEs occurred in short succession, although their exact number between 53.3 to 51.7 Ma remain elusive due to lack of well-resolved stratigraphic sections and lack of high-resolution δ13C records at multiple locations.

5.3 Generic Cause of Marl-Rich Units

**[29]**  Broad lithological shifts coincide with peak warmth from 53.4 to 51.7 Ma. An initial change from “pure” limestone in Lower Limestone to marl-limestone beds of varying proportion in Lower Marl characterizes the lower interval of the measured Branch Stream section. This was followed by an eventual shift to primarily marl ~25 m below the base of Upper Limestone. Marl became a major lithological component in Lower Marl during the EECO (Slotnick et al., 2012). Limestone, originally accumulated as individual foraminifera and calcareous nannofossils, transitioned into marl, a “mixed” lithology, with elevated clay contents. Increased fluxes of terrigenous material likely resulted from enhanced seasonal precipitation and related chemical weathering (Robert, 2004).

**[30]**  Clay-rich intervals in Amuri Limestone indicate particularly warm conditions (Hollis et al., 2005a). Consistent with observations at Mead Stream (Hollis et al., 2005a; Nicolo et al., 2007; Slotnick et al., 2012), clay-rich intervals are rare in Lower Limestone but are common lithological components in Lower Marl when background conditions were warmer. Throughout the marine realm, clay-rich facies likely accumulated in two ways, consistent to the “accordian effect” (Nicolo et al., 2007; Slotnick et al., 2012), a two-component system primarily consisting of clay and carbonate. 1) Along continental margins, fluxes of terrigenous material can dilute calcareous-rich marine sediments and cause higher sedimentation rates (Schmitz et al., 2001; Hollis et al. 2005*a*, 2005*b*; Giusberti et al., 2007; Nicolo et al., 2007; John et al. 2008; Slotnick et al., 2012) and at high latitudes (Sluijs et al., 2008), lowering carbonate contents. 2) In deep ocean environments, loss of carbonate from dissolution can cause lower sedimentation rates without affecting the accumulation of clay particles (Lourens et al., 2005; Zachos et al. 2005; Leon- Rodriguez and Dickens 2010; Stap et al., 2010; Zachos et al. 2010), also lowering carbonate contents.

**[31]**  Correlation of the early Eocene Branch Stream section to that at Mead Stream (Slotnick et al., 2012) and at other locations (e.g., Zachos et al., 2010) by carbon isotope stratigraphy allow for sedimentation rates to be constrained so that multiple sites can be compared. Common CIEs or distinct δ13C shifts are well known at Mead Stream (Slotnick et al., 2012; Slotnick et al., *in prep*) allowing for tie points with known ages from Mead Stream to be extended to a remarkably similar Branch Stream δ13C record. Stratigraphic thicknesses were then placed in the time domain so that differences in sedimentation rate could be compared between both locations.

**[32]** Fairly high compacted sedimentation rates (i.e., >3.5 cm/kyr) characterize the EECO interval at both Branch and Mead Streams, but are consistently higher at the more proximal Branch Stream. In addition, sedimentation rates, although relatively higher during the EECO (Slotnick et al., 2012), are consistently higher in marl-rich units [from 53.3 to 52.9 Ma when marls first appear (5.5 to 10.3 cm/kyr) and from 51.9 to 51.5 Ma (5 cm/kyr)] relative to limestone beds [from 52.9 to 52.2 Ma (4.2 cm/kyr)]. This consistent offset can be explained by dilution of carbonate sedimentation in marginal settings. This phenomenon clearly occurring at multiple high-latitude Clarence Valley locations is particularly compelling, since long-term periods (EECO) were warm at high latitudes (Zachos et al., 2008) throughout New Zealand (Hollis et al., 2012). Additional age datums would better refine this assessment.

**[33]** Similar to Mead Stream, δ13C values are slightly different for each lithology (limestone: 0.99±0.22‰ at 1σ; marly limestone: 0.87±0.21‰ at 1σ; marl: 0.85±0.25‰ at 1σ). This suggests δ13C is slightly lower for marl beds, implying negative CIEs relate lower δ13C values to more marl. Unlike at Mead Stream (Slotnick et al., in prep), it is not as clear if negative CIEs consistently occur near the base of marl bed sets, although this appears to be the case across the K/X CIE. The idea is that a skewed relationship between long-term carbon cycling and temperature exists in the time domain such that long-term δ13C lows are more likely to occur near the base of bed sets diluted by terrigenous material or marls. This suggests expanded stratigraphic sequences spanning the “warm” EECO at both Branch and Mead Streams relate to the clay component of the “accordian effect” in continental margin settings, confirming terrigenous dilution was prevalent during EECO. In open-ocean depositional settings, clay-rich condensed sequences instead reflect only the accumulation of background clays due to carbonate dissolution.

**[34]** As suggested by previous studies from other Clarence Valley sequences (Hollis et al., 2005a; Nicolo et al., 2007; Slotnick et al., 2012), the amount of terrigenous dilution is related to the intensity of the hydrological cycle and absolute temperature. In turn, this alters the composition and accumulation rates of certain lithologies, particularly during the warm EECO interval (Hollis et al., 2012). This implies thicker and more frequent marls accumulate during warmer conditions. But, is accumulation similar throughout the same margin or do depositional trends exist? Consistently higher sedimentation rates and lower δ13C across the K/X CIE at the more proximal Branch Stream section relative to that at Mead Stream indicates more dilution in proximal settings. This suggests the degree of terrigenous dilution also may relate to location along the same margin.

**[35]** Almost assuredly, land-derived sediments cannot accumulate at the same rate at numerous marine settings. Multiple factors including climate, tectonic activity, soil types, slope of rivers, extent of drainage basins, coastal geology and geomorphology impact sediment delivery to the marine realm. Along the same continental margin, most factors impacting terrigenous sediment supply minimally change, such as extent of river drainage and degree of tectonic activity, particularly along the <1 Myr timeframe. This implies short-term (<1 Myr) factors related to climate largely overwhelm delivery of terrigenous material to a continental margin. By comparing nearby localities, identification of depositional patterns of terrigenous material is possible. In the case of Mead versus Branch Stream localities, consistently higher sedimentation rates at Branch Stream generally correspond to lower carbonate contents and lower δ13C than Mead Stream. This correlation is particularly strong when marls first appear between the J and K/X CIEs and when marl becomes the prominent lithology at ~52.2 Ma at Branch Stream. This indicates the amount of terrigenous dilution is greater at more proximal localities.

**[36]** Lower δ13C across the K/X CIE at Branch Stream indicates another earth system dynamic also affects the composition of the marginal sediments in this area. One this to consider is that rivers discharge terrigenous material with particularly low δ13C in the form of dissolved organic carbon (DOC) to the marine realm. The amount of DOC to terrigenous discharge is likely proportional such that more DOC enters marine waters when delivery of terrigenous material is highest, as long as vegetation cover does not decrease with warmth. If correct, greater amounts of depleted δ13C material would be transported to marginal settings when terrigenous discharge is high, in turn, mixing with sediments causing an apparent carbon fractionation towards lower δ13C in the most proximal marginal sequences. This assumes two important concepts: 1) Low DOC delivery to the marine realm leads to an insignificant volume reaching even proximal settings such as the paleo-shelf-break. 2) Regardless of DOC delivery to the marine realm, most is likely destroyed before it reaches more distal settings (i.e.; Mead Stream), implying distal δ13C values are more representative of marine sediments. Alternatively, lower δ13C during the K/X CIE at Branch Stream may instead reflect weakened oceanic circulation with a layered, stagnant water column overlying a margin. In this scenario, proximal settings would be overlain by surface water masses whereas distal settings would be overlain by mixed-layer water masses. Although carbon cycles relatively fast throughout the world’s oceans (<2 kyr), surface water masses may have higher dissolved CO2 concentrations comprised of lower δ13C relative to mixed layer water masses.

**[37]** The lack of a formal definition for EECO, a ~1-2 Myr period of warmth during the early Eocene, causes ambiguous interpretations, particularly between different locations. To minimize error and uncertainty, use of the same data-type is necessary as a basis for stratigraphic correlation. Confounding matters further is the skewed coupling between temperature and carbon cycling in the time domain, as identified by minimum δ13C values occurring near the base of EECO (i.e. K/X CIE).

**[38]** The lowermost EECO interval between the J CIE and a δ13C high of 1.48‰ at Branch Stream or 1.39‰ at 252 m at Mead Stream span 53 and 46 m, respectively. Averaged compacted sedimentation rate through this interval is 4.8 cm/kyr at Branch Stream or 4.2 cm/kyr at Mead Stream, a contrast to much lower linear sedimentation rates for the EECO at open ocean Sites 1262 and 577 of 0.9 and 0.4 cm/kyr, respectively. In addition, these rates are more than double that of the interval leading up to EECO, which include the also expanded PETM, the H, and I lithologies at Mead Stream (1.8 cm/kyr). This comparison could not be properly ascertained at Branch Stream since the measured section did not include the interval leading up to the EECO. Overall, Clarence Valley lithological sequences appear to be greatly expanded for lowermost EECO, particularly at the more proximal Branch Stream.

**[39]** Similar to Mead Stream, the magnitude of CIEs during lowermost EECO does not co-vary to thicknesses and frequencies of marl beds through the measured section. Magnitudes, however, are generally lower than during the PETM (-2.5‰) or H-1/ETM-2 (-1.0‰) events, ranging between -0.2 and -0.8‰. The lithologic expressions of CIEs vary, particularly with respect to the marl lithotype. Since the EECO is warm, following a long-lived warming and associated δ13C drop from 58 to 53 Ma (Zachos et al. 2008; Zachos et al., 2010; Slotnick et al., 2012), more marl should comprise the sequence relative to limestone but likely with more irregularity compared to the interval leading up to the EECO. This assumes the flux of terrigenous sediment should increase along with absolute temperature. Thus, the lack of variance between δ13C and marl during lowermost EECO is not too surprising. The lower magnitude CIEs during the EECO reflect a net transfer of 13C-depleted CO2 from an organic “capacitor” to the exogenic carbon cycle (Dickens, 2011), damping the excursion for every short-term input of 13C-depleted CO2 and associated environmental perturbation. If the record could be extended through older strata, then a comparison to the local expression of pre-EECO sedimentation could be done.

**[40]** The surrounding setting is important to integrate. Extensive carbonate deposition along the New Zealand margin spanned the Eocene and Oligocene, a time characterized by subsidence and deepening (King et al., 1999). Amuri Limestone thickness generally increases with paleo-depth in Clarence Valley sequences (Reay, 1993) with the distal Mead Stream section hosting the thickest units. Although not sampled at Branch Stream, this trend is embodied by Dee Marl, a clay-rich unit spanning the PETM in Lower Limestone, which thickens towards the basin, with a thickness of 0.8 m at Muzzle Stream (Hollis et al. 2005*b*), 1.0 m at Dee Stream (Hancock et al. 2003), and 2.4 m at Mead Stream (Hollis et al. 2005*a*). Interestingly, an opposite relationship occurs in shallower sequences at Muzzle and Dee Streams where Dee Marl represents a larger proportion of Lower Limestone (Hancock et al., 2003; Hollis et al., 2005b). Dee Marl represents only one short-lived event over <200 kyr. For a longer duration of time (i.e., > 1 Myr), this observation would imply that the proportion of marl to limestone should increase as sequences thickens towards the paleo-coast with increased fluxes of terrigenous material. This is exemplified by lowermost Lower Marl with generally more marl and being ~15% thicker at Branch Stream than at Mead Stream. Dee Marl and the base of Lower Marl is separated by ~2.6 Myr, enough time for a gradual shift to warmer climate and subsequently more terrigenous material reaching marginal settings. If true, climate likely overwhelmed long-term delivery of sediment to the paleo-New Zealand margin by increasing the flux of terrigenous material.

*5.4* *An Earth systems perspective*

**[41]**  In order for lithologic and carbon isotopic records at Branch and Mead Streams to be representative of global climate during early Eocene, they must reflect regional accumulation trends of Amuri Limestone along the paleo-margin of New Zealand. Previous work indicated this to be the case at a number of sites in northeastern South Island (Reay 1993; Hancock et al. 2003; Hollis et al. 2005*a*, 2005*b*), although these previous studies spanned a greater portion of Amuri Limestone. Since the measured section at Branch Stream only includes uppermost Lower Limestone and Upper Marl, and since data resolution in previous work was lower, it is less certain if this argument holds for the ~2 Myr EECO interval. In lieu of this limitation, the sedimentological profile at Branch Stream still seems likely to accurately reflect regional responses to changing environmental conditions during early Eocene.

**[42]** Specific short-term (<200 kyr) and long-term (>1 Myr) processes in the exogenic carbon cycle likely impact sedimentation predictably along marginal and in open-ocean settings. Rapid and massive injections of 13C-depleted CO2 can cause negative CIEs, warmth, and carbonate dissolution over short time frames in the open ocean, regardless of the source (Dickens et al. 1997; Zachos et al. 2005; Leon-Rodriguez and Dickens 2010; Stap et al. 2010). In response to CO2 injections, intensified hydrological cycles are consistently predicted by climate model simulations (Murphy et al. 2004; Held and Soden 2006; Meehl et al. 2007*a*, 2007*b*) and by river discharge data (e.g., Peterson et al. 2002), even when a range of climate sensitivities to CO2 doubling is incorporated. These models predict that in response to the higher CO2 present in the environment, more water is carried from low to high latitudes in the atmosphere and suggest that precipitation becomes more seasonal and variable. Mid-latitude locations, such as in New Zealand, may experience even greater precipitation with greater variability over a shorter time of year (Meehl et al. 2007*a*, 2007*b*). Thus, in marginal settings more clay deposition should result due to intensified chemical weathering, decreased vegetation, increased erosion, and the overall greater discharge of terrigenous material from rivers to continental margins (Ludwig and Probst 1998; Schmitz and Pujalte 2003; Meehl et al. 2007*a*, 2007*b*; Schmitz and Pujalte, 2007).

**[43]** The detailed correlation of early Eocene CIEs in expanded sequences at Branch and Mead Streams indicate a series of short-term climatic perturbations during EECO occurred for ~2 Myr. Each was characterized by slightly different systemic responses given different locations but in close proximity. Although accumulated EECO strata at both Branch and Mead Streams were marked by intervals of terrigenous dilution, lower δ13C and thicker strata at Branch Stream generally characterize them. Both reflect links in Earth systems involving enhanced seasonal precipitation, sluggish oceanic circulation, and carbon input to the exogenic system. Simulations from climate models identify similar precipitation changes and sluggish conditions of oceanic circulation during times of massive carbon input over instantaneous periods of warming, such as what might happen in the coming millennia (Meehl et al. 2007*a*, 2007*b*; Allan and Soden 2008; Schmittner et al., 2008).

**[44]** Changing boundary conditions during the LPEE characterize the interval leading into the EECO, when δ13C of benthic foraminifera dropped by ∼2‰. In addition, deep-sea sediment records indicate that the CCD generally deepened from 58 to 51 Ma (Hancock et al., 2007; Zachos et al., 2008; Leon-Rodriguez and Dickens, 2010; Komar et al., 2013). This suggests there were long-term increases in the net flux of 13C-depleted carbon at a slow enough rate for alkalinity supply to keep up with carbon inputs, thereby keeping oceans buffered. When EECO began, it was already an abnormally warm interval following long-term temperature rises and increased mass of carbon in the exogenic system. This precursor shift in δ13C and rise in warmth minimized the magnitude each CIE could reach while maximizing the flux of terrigenous material during EECO, such as how the lithologic expression of lowermost EECO is interpreted to reflect at Branch Stream.

**[45]** Following low δ13C during EECO was a ∼1‰ rise in benthic foraminifera δ13C and δ18O (Zachos et al., 2008), marking a climatic reversal and substantial rise in the CCD as identified in multipe deep-sea sediment sequences (Hancock et al. 2007; Leon-Rodriguez and Dickens 2010). This may correspond to the rise in bulk carbonate δ13C at Branch Stream from the peak of the K/X CIE through the uppermost ~1.2 Myr of measured section. These isotope data suggest a shift towards lower net long-term fluxes of 13C-depleted carbon to the ocean and atmosphere, indicating possible initiation of cooler conditions, although timing of when cooling began may not correspond temporally (at 1 Myr scale) to changes in net carbon fluxes. A CCD rise suggests more carbonate dissolution may have occurred when larger fluxes of terrigenous material entered oceans during the EECO, diluting marginal sequences further. If true, this bolsters why the early Eocene record at Branch Stream is particularly expanded in comparison to the record at Mead Stream and why both records are in contrast to condensed deep-sea sections.

**[46]** Upper Limestone subsequently follows Lower Marl, a lithological shift that may correspond to the end of EECO and a dropoff in fluxes of terrigenous material when cooling of the Cenozoic likely began. Following Upper Limestone is Upper Marl, the uppermost lithological unit of Amuri Limestone (Reay 1993). This second clay-rich unit, which likely includes the lithological expression of the Middle Eocene Climatic Optimum (MECO) from ~41.5 to 40.9 Ma (Bohaty and Zachos, 2003), may represent another interval of increased terrigenous discharge to the northern margin of past New Zealand. Additional data would enable a more robust evaluation of this concept.

*5.5* *Comparison to Modern climate*

**[47]** Future climatic simulations predict intense warming and intensification of the hydrological cycle (Held and Soden 2006; Friedlingstein et al., 2006; Meehl et al. 2007*a*, 2007*b*), similar to observations from prominent Eocene hyperthermals. Humans are predicted to release ~5,000 gigatonnes of carbon into the exogenic system if fossil-fuel emissions continue and carbon-sequestration does not increase from current levels (Caldeira and Wickett, 2003). Carbon, primarily released as CO2, will warm the planet and acidify the oceans exacerbating the rise in the CCD. Perturbations will not wane until carbon is buried and removed from the carbon cycle, or probably ~100 kyr post-release. For more robust climate predictions, identifying and comparing similarities between past abrupt climatic perturbations (i.e., K/X CIE) and modern climate (i.e., today) changes related to warmth will provide us with a better understanding of what we should expect with respect to the tempo and mode of climatic changes in the future. One reasonable analogue for usage is terrigenous dilution, as identified at Branch and Mead Streams (Nicolo et al. 2007; Slotnick et al., 2012). This suggests that in a warmer climate, no matter if in the past or future, intensified chemical weathering, more siliciclastic erosion, and an intensified hydrological cycle, are likely.

**6. Conclusion**

**[48]** Branch Stream exposes an expanded and continuous section of sedimentary rocks. Recent studies at nearby sections (i.e., Mead Stream) indicate sediments originally accumulated during the early Paleogene on a continental slope along the northern margin of New Zealand (Strong et al., 1995; Hollis et al., 2005a). Stratigraphic correlation to other locations in Marlborough indicates this section is representative of regional sediment accumulation profiles of the South Pacific and is consistent with the broad viewpoint that major changes in carbon cycling and climate spanned the early Paleogene (Zachos et al., 2008; Slotnick et al., *in prep*). This study provides new lithologic, carbonate content, and bulk carbonate δ13C records at Branch Stream, so that dynamic earth system processes can be compared and better understood between different depositional settings along the same margin during the lowermost EECO.

**[49]** Similar to the well-documented stratigraphic section at neighbouring Mead Stream, Lower Limestone is bounded above by Lower Marl, but is generally thicker at Branch Stream. The transition from Lower Limestone to Lower Marl can be described as occurring over a wide 17 to 20 m interval as carbonate contents generally decrease. The later stratigraphic unit, consisting of varying proportions of marl and limestone, represents the lowermost EECO from ~53.3 to 51.7 Ma. In particular, marl is more frequent and carbonate contents are lower during ten specific intervals in the Lower Marl, but is even more prevalent with consistently lower carbonate contents in eight of these intervals (**Figure 6**). Bulk carbonate δ13C analyses of these marl-rich intervals indicate they correspond to CIEs. The most prominent marl sequences and CIE marks the K/X and L events. Altogether, these records indicate that the lowermost EECO was characterized by a series of short-term negative CIEs.

**[50]** Each negative CIE almost assuredly represents abrupt releases of 13C-depleted CO2 into the exogenic system (Dickens et al. 1995, 1997; Thomas and Shackleton 1996; Lourens et al. 2005; Zachos et al. 2005; Zeebe et al. 2009; Leon-Rodriguez and Dickens 2010; Dickens 2011). Marls at Branch and Mead Streams resulted from increased fluxes of terrigenous material and associated carbonate dilution. Marls most likely reflect accelerated hydrological cycles with heightened seasonality (Giusberti et al. 2007; Nicolo et al. 2007; John et al. 2008), particularly since several CIEs have already been linked to warmer Earth surface temperatures (Sluijs et al. 2007; Zachos et al. 2010; McInerney and Wing 2011; Westerhold et al. 2011). If correct, greater chemical weathering and physical erosion would occur in continental settings, transporting more siliciclastic material to marginal settings, particularly at higher latitudes. The EECO, as generally articulated by Lower Marl, is greatly expanded at Branch Stream, more so than the also greatly expanded but more distal Mead Stream record. These records indicate warmer climates overwhelmed the delivery of fine terrigenous material to this margin during lowermost EECO. In conclusion, a series of warm events with pulses of increased terrigenous discharges to high latitude margins best describe this time interval.

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Figure Captions:

**Figure 1**: Published Mg/Ca, δ18O, δ13C …etc. climate records from the late Paleocene to early Eocene (49 to 62.5 Ma). Pertinent climatic intervals and CIEs are highlighted, as well as the time interval covered by data latter presented by this study. Timing of CIEs are indicated by corresponding letters across the middle x-axis.

**Figure 2**: Map of Clarence Valley with the locations of the Mead and Branch Streams highlighted.

**Figure 3**: Map of logged section at Branch Stream. Left: Part of Topo50 sheet Bs27, Tapuae-O-Uenuku. Right: Detailed Lower Marl section at Branch Stream. Note GPS coordinates do not exactly match position of stream as depicted on topographic map.

**Figure 4**: Photos of Branch Stream showing event outcrops and locations of paleomag and geochemistry samples. A) Lower section with “0” datum and outcrops of J and K/X events. B) Upper section with outcrop containing L CIE.

**Figure 5**: Photos of specific features at Branch Stream with locations of geochemistry samples for reference. A) When marl becomes more prevalent in lower section between J and K/X CIEs . B) Tie point between lower and upper logged sequences . C) K/X CIE at base of upper section. D) Predominantly limestone with inter-bedded marl just above L CIE. E) Base of logged Branch Stream section with “0” horizon marked. F) Close-up of K/X CIE . G) View of Mount Tapuae-O-Ueneku through narrow gorge of Upper Limestone.

**Figure 6**: Branch Stream-Mead Stream stratigraphic correlation using lithostratigraphy and geochemical data.

**Figure 7**: Branch and Mead Stream data plotted in age domain.

**Figure 8**: Lower Marl data comparison between Branch Stream and Mead Stream. Branch section equates to 195.61 to 324.36 m above K/Pg at Mead. Data from different lithologies is subdivided.

**Figure 9:** Plot of δ13C versus CaCO3 wt. % for Branch and Mead Streams.

**Figure 10**: Plot of δ18O for Branch versus Mead Streams in time domain. See if shows something. Does this depend on: (i) fluid flow, (ii) degree of meteoric diagenesis, and/or (iii) amount of carbonate than other?