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Was the Arctic Eocene 'rainforest' monsoonal? Estimates of seasonal precipitation from early Eocene megafloras from Ellesmere Island, Nunavut

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ABSTRACT

The early Eocene was the warmest interval of the Cenozoic, and included within it were several hyperthermal events, with the Paleocene–Eocene Thermal Maximum (PETM) the most pronounced of these. These globally warm climates extended into the Arctic and substantive paleobotanical evidence for high Arctic precipitation (MAP > 150 cm/yr) is indicative of an Arctic rainforest, which contradicts some climate models that show low Arctic precipitation. Prior studies of Arctic early Eocene wood stable-isotope chemistry, however, have shown a summer peak in precipitation, which suggests modern analogs are best sought on the summer-wet east coast of the Asia (e.g., China, Japan, South Korea), not the winter-wet west coasts of the Pacific Northwest of North America). Furthermore, some prior modeling data suggest that highly seasonal 'monsoon-type' summer-wet precipitation regimes (i.e., summer:MAP > 55%) characterized certain mid and lower latitude regions in the early to mid-Eocene. Presented here is a new analysis using leaf physiognomy of 3 leaf megafloras (Split Lake, Stenkul Fiord and Strathcona Fiord) and palynofloral Bioclimatic Analysis from the Margaret Formation from Ellesmere Island, placed stratigraphically as early Eocene, possibly occurring during or following one of the early Eocene hyperthermals. These new data indicate high summer precipitation in the Arctic during the early Eocene, which in part corroborates the results from Eocene wood chemistry. Nevertheless, in contradiction to the wood analysis, monsoonal conditions are not indicated by our analysis, consistent with current modeling studies. High summer (light season) and winter (dark season) precipitation in the Eocene Arctic during hyperthermals would have contributed to regional warmth.

1. Introduction

Global warming is currently causing Arctic temperatures to rise at two times the rate of lower latitudes, a trend that is predicted to continue affecting polar latitudes well into the future (ACIA, 2005; Serreze and Barry, 2011; Stroeve et al., 2012). The mild ice-free Arctic environments of the late Paleocene and early Eocene represent one of the best deep time analogs for evaluating a rapidly changing global climate on a high latitude system (Eberle and Greenwood, 2012). Some of the best examples of these ancient paleoenvironments can be found in the Canadian Arctic on Ellesmere Island (Fig. 1). This island and the surrounding region were once inhabited by lush swamp forests, and thermophilic fauna such as alligators and giant tortoises (Estes and Hutchison, 1980; McIver and Basinger, 1999; Eberle and Greenwood, 2012; Eberle et al., 2014).

The hyperthermals of the early Eocene are considered to be some of the most abrupt and dramatic climatic warming events of the entire Cenozoic (Zachos et al., 2008; McInerney and Wing, 2011). The rising warmth that began in the late Paleocene continued into the Eocene epoch (Zachos et al., 2008). The warming of the early Eocene led to two hyperthermal events, the PETM/ETM1 (Paleocene–Eocene Thermal Maximum, or Eocene Thermal Maximum 1) and the ETM2 (Eocene Thermal Maximum 2), as well as the prolonged warming of the EECO (Early Eocene Climatic Optimum) (Zachos et al., 2008). These hyperthermal events not only increased mean global temperatures, but also had an effect on hydrologic cycles (Pagani et al., 2006; Zachos et al., 2008; Leng et al., 2010; Hyland and Sheldon, 2013; Krishnan et al., 2014). The EECO resulted in a temperature acme not only for the Eocene, but for the entire Cenozoic (Zachos et al., 2008). The PETM, however, represents the most abrupt and dramatic of these events, char-

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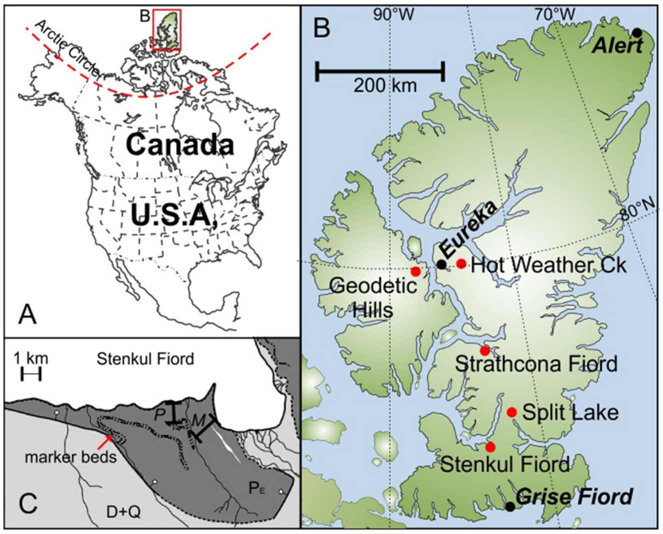

Fig. 1. Location maps. A, North America showing position of Ellesmere Island; B, Ellesmere Island showing location of the 3 fossil localities and other sites mentioned in the text; C, detail of Stenkul Fiord showing main outcrop. PE, Paleogene Eureka Sound Group sediments; D + Q, Devonian rocks and undifferentiated drift. P and M, measured sections. Red dotted line represents the Arctic Circle. Adapted from Kalkreuth et al. (1998), Eberle and Greenwood (2012), and Harrington et al. (2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

acterized by a negative carbon isotope excursion (between 2300 and 6800 Gt ^{13}C depleted carbon; Ma et al., 2014) with temperatures rising 5–8 °C in ≤20 ky with a global increase not exceeding 5 °C, for 100–250 ky, making the PETM a useful analog for modern warming (e.g., Sluijs et al., 2006, 2007, 2009; Zachos et al., 2008; Dunkley-Jones et al., 2013; Wing and Currano, 2013; Eldrett et al., 2014).

Marked shifts in the character of precipitation characterized the PETM and the other Eocene hyperthermals, and the response on a regional scale was complex with shifts to wetter or drier climates recorded in different areas (Zachos et al., 2008). Mid-latitude environments that were warm and wet were marked by a decrease in precipitation that preceded or occurred during the PETM (Wing et al., 2005; Collinson et al., 2009; Garel et al., 2013; Kraus et al., 2013). High latitude environments that were temperate and wet, such as the Canadian High Arctic, Spitzbergen and North Sea, instead experienced an increase in both temperature and precipitation (Uhl et al., 2007; Greenwood et al., 2010; Eldrett et al., 2014). The north polar region of the early Paleogene represents an environment that has no satisfactory modern analogue, relegating it to fossil environment status, as defined in Jacques et al. (2014), although the winter-wet west coast forests of North America and the coastal forests of east Asia have been suggested as possible analogues (Greenwood et al., 2010; Schubert et al., 2012). Extensive studies in the literature document the presence of flora and fauna in the early Cenozoic that exist nowhere near these latitudes today (e.g., Hickey et al., 1983; Dawson et al., 1993; LePage and Basinger, 1991, 1995; McIver and Basinger, 1999; LePage, 2001, 2007; Lepage, 2003; Eberle, 2005; Eberle et al., 2014; Harrington et al., 2012). In addition, multiple studies have analyzed the climate of this fossil environment using paleontological and other available proxies from Arctic sediments (e.g., Greenwood and Wing, 1995; Jahren and Sternberg, 2003, 2008; Greenwood et al., 2010; Eldrett et al., 2009, 2014).

Although some climate models have shown low to moderate Arctic paleoprecipitation during the early to middle Paleogene (Shellito et al., 2003), the majority of studies have shown high precipitation (annual precipitation >150 cm/yr), mesothermal conditions (i.e., mean annual temperature ∼12–15 °C), and moderate winter temperatures (cold month mean temperature >0 °C) characterized climates of high latitude Arctic rain forests during the late Paleocene through the PETM and into the middle Eocene (Greenwood et al., 2010; Eberle and Greenwood, 2012; Huber and Goldner, 2012). Notably, Huber and Goldner (2012) reconstructed global precipitation patterns of Eocene, identifying the existence of a robust global monsoonal precipitation pattern. In a summary of their model, much of the middle and lower latitudes of the Eocene were shown as monsoonal, while high latitudes such as the Arctic remained ever-wet or equable. However, Schubert et al. (2012) used a high-resolution carbon isotope analysis of fossil wood from the Arctic, showing a summer peak in precipitation that they defined as monsoonal.

Zhang and Wang (2008) noted that there are many different ways to define a monsoon and each definition can affect the interpretation of a monsoonal circulation. For the purpose of this study the definition and character of a summer monsoon follows the Zhang and Wang (2008) index for a region where the summer daily rate of precipitation is equal to 3 mm/day or more (i.e. 3 warmest months precipitation >28 cm), and the ratio of summer to annual precipitation exceeds 55% (Zhang and Wang, 2008). This index also accounts for the extended boreal winter and summer seasons, whereby summer is defined as May, June, July, August, September and winter is defined as November, December, January, February, March (Zhang and Wang, 2008).

Based on both paleoclimate proxy evidence and climate model sensitivity experiments, highly seasonal 'monsoon-type' summer-wet precipitation regimes seem to have characterized the early Eocene hyperthermal conditions in several regions of the earth (e.g., Greenwood, 1996; Hubert and Goldner, 2012), as well as the Arctic and Antarctic (e.g., Huber and Goldner, 2012; Schubert et al., 2012; Jacques et al., 2014; Krishnan et al., 2014). However, other proxy and modeling data for Arctic regions implies Eocene polar rain forests consistent with no or low precipitation seasonality (Eldrett et al., 2009; Greenwood et al., 2010; Eberle and Greenwood, 2012; Huber and Goldner, 2012). The hydrological cycle of a post-PETM high latitude environment, as evidenced by climate models and paleo-precipitation reconstructions from paleobotanical proxy data, was likely a significant component in maintaining high-latitude warm and equable climates (Abbot et al., 2009; Heinemann et al., 2009; Greenwood et al., 2010; Speelman et al., 2010: Tindall et al., 2010; Huber and Caballero, 2011; Huber and Goldner, 2012; Pross et al., 2012; Schubert et al., 2012; Kiehl and Shields, 2013).

Presented here is a new analysis applying Leaf Area Analysis (LAA), Leaf Margin Analysis (LMA) and Climate Leaf Analysis Multivariate Program (CLAMP) to 3 leaf megafloras from 3 separate localities within the Margaret and Mount Moore Formations (Split Lake, Stenkul Fiord, and Strathcona Fiord), as well as a palynoflora from Stenkul Fiord, all from Ellesmere Island (Fig. 1). These floras can be stratigraphically placed as latest Paleocene or early Eocene in age (Kalkreuth et al., 1996; Harrison et al., 1999; Eberle and Greenwood, 2012; Harrington et al., 2012; Schubert et al., 2012; Reinhardt et al., 2013), and therefore present an opportunity to evaluate regional precipitation at high northern polar latitudes during the globally warm early Paleogene.

2. Geological context

The early Paleogene fossil localities on Ellesmere Island and Axel Heiberg islands are part of a series of units that constitute the Eureka Sound Group. The formations which encompass the Eureka Sound Group span the late Cretaceous to the Middle Eocene in age (Miall, 1986; Ricketts, 1986, 1994; Harrison et al., 1999; Thorsteinsson et al., 2009; Eberle and Greenwood, 2012; Reinhardt et al., 2013). Miall (1986) divided the Eureka Sound