Middle Eocene CO₂ and climate reconstructed from the sediment fill of a subarctic kimberlite maar

Alexander P. Wolfe¹, Alberto V. Reyes²*, Dana L. Royer³, David R. Greenwood⁴, Gabriela Doria⁵, Mary H. Gagen⁶, Peter A. Siver⁷, and John A. Westgate⁸

¹Department of Biological Sciences, University of Alberta, Edmonton, Alberta T6G 2E9, Canada
²Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2E3, Canada
³Department of Earth and Environmental Sciences, Wesleyan University, Middletown, Connecticut 06459, USA
⁴Department of Biology, Brandon University, Brandon, Manitoba R7A 6A9, Canada
⁵Department of Plant Sciences, University of Cambridge, Cambridge CB2 3EA, UK
⁶Department of Geography, Swansea University, Singleton Park, Swansea SA2 8PP, UK
⁷Department of Botany, Connecticut College, New London, Connecticut 06320, USA
⁸Department of Earth Sciences, University of Toronto, Toronto, Ontario M5S 3B1, Canada

ABSTRACT

Eocene paleoclimate reconstructions are rarely accompanied by parallel estimates of CO₂ from the same locality, complicating assessment of the equilibrium climate response to elevated CO₂. We reconstruct temperature, precipitation, and CO₂ from latest middle Eocene (ca. 38 Ma) terrestrial sediments in the post-eruptive sediment fill of the Giraffe kimberlite in subarctic Canada. Mutual climatic range and oxygen isotope analyses of botanical fossils reveal a humid-temperate forest ecosystem with mean annual temperatures (MATs) more than 17 °C warmer than present and mean annual precipitation ~4× present. Metasequoia stomatal indices and gas-exchange modeling produce median CO₂ concentrations of ~630 and ~430 ppm, respectively, with a combined median estimate of ~490 ppm. Reconstructed MATs are more than 6 °C warmer than those produced by Eocene climate models forced at 560 ppm CO₂. Estimates of regional climate sensitivity, expressed as ΔMAT per CO₂ doubling above preindustrial levels, converge on a value of ~13 °C, underscoring the capacity for exceptional polar amplification of warming and hydrological intensification under modest CO₂ concentrations once both fast and slow feedbacks become expressed.

RESULTS

Exploration drill core BHP 99-01 (see Appendix DR1 in the GSA Data Repository¹) captures ≥50 vertical-equivalent meters of lacustrine sediment overlain by 32 m of peat (Fig. 1), together representing the progressive

INTRODUCTION

Efforts to understand climate response to sustained greenhouse gas forcing commonly focus on periods of peak Cenozoic warmth during the Paleocene–Eocene thermal maximum and early Eocene (e.g., Zachos et al., 2008; Lunt et al., 2012a). The subsequent cooling trend of the middle and late Eocene (Pagani et al., 2005) is also relevant because atmospheric CO₂ concentrations dovetail the range projected for the coming century (e.g., Tripati et al., 2008; Jagniecki et al., 2015; Anagnostou et al., 2016; Steinhorsdottir et al., 2016), ultimately crossing the threshold necessary to maintain continental ice sheets (~500 ppm; Royer, 2006). Observations from the Arctic Ocean suggest that ice rafting may have been initiated by the middle Eocene (e.g., Tripati et al., 2008), in apparent conflict with the warmth implied by the terrestrial biota (e.g., Eberle and Greenwood, 2012). Climate models struggle with these critical early Cenozoic intervals because unrealistically high CO₂ forcing is required to produce the temperature responses implied by proxies, particularly for the sparse network of terrestrial high-latitude sites (Lunt et al., 2012a). Furthermore, paleoclimate and CO₂ reconstructions are not commonly derived from the same sedimentary archive; this complicates assessment of proxy-model

GSA Data Repository item 2017202, detailed methods (Appendix DR1), data tables (Tables DR1–DR5) and supplementary figures (Figures DR1–DR5), is available online at http://www.geosociety.org/datarepository/2017 or on request from editing@geosociety.org.

Figure 1. A: Location of the Giraffe kimberlite in the Slave Province, Northwest Territories, Canada. Gray star indicates Yellowknife, the location of the nearest climate station. B: Schematic cross section of post-eruptive sedimentary fill and the position of BHP core 99-01. C: Core stratigraphy showing the investigated section directly above tephra horizons dated by isotopic analyses (1σ uncertainty).
infilling of the maar basin. Both facies have remarkable preservation of aquatic and terrestrial plant fossils (Wolfe et al., 2006; Doria et al., 2011). We analyzed a 21 m section (vertical equivalent depth) of peat in core BHP 99-01, representing ~20 k.y. assuming reasonable accumulation rates and only moderate compaction. The common sampling interval over which we estimate the mean climate state and CO2 concentration includes multiple samples from 7 m of vertical equivalent thickness (Fig. 2), or ~7 k.y. of continuous deposition. Two rhyolitic tephra beds are present in the core directly below the lacustrine-to-peat transition (Fig. 1C). Glass fission track dating (Westgate et al., 2013) of both tephra beds gives a weighted mean age (±1σ) of 37.84 ± 1.99 Ma (Table DR1 and Appendix DR1).

Paleoclimate of the Latest Middle Eocene Subarctic

Pollen assemblages from Giraffe sediments are well preserved, diverse, and include numerous extant North American taxa (Fig. DR1). The relative abundance of angiosperm pollen (53%–74%) is higher than that of gymnosperms throughout the section (Fig. DR2). The former is strongly dominated by fagalean types (Quercoidites, Castanea, and Corylus), with lesser contributions from Ulmipollenites, Ericalceae taxa, and the Eocene indicators Platycarya swasticoides and Pistillipollenites meggiorii. Conifer pollen is strongly dominated by Cupressaceae, for which Ericalean taxa, and the Pistillariellaceae are strongly represented (Fig. DR2). Conifer pollen is strongly dominated by Cupressaceae, for which Ericalean taxa, and the Pistillariellaceae are strongly represented (Fig. DR2).

The Milankovitch-driven ~6-kyr cyclicity of the LME climate is evident from the pollen assemblages (Fig. DR2). The former is strongly dominated by Cupressaceae, for which Ericalean taxa, and the Pistillariellaceae are strongly represented (Fig. DR2). Conifer pollen is strongly dominated by Cupressaceae, for which Ericalean taxa, and the Pistillariellaceae are strongly represented (Fig. DR2). Conifer pollen is strongly dominated by Cupressaceae, for which Ericalean taxa, and the Pistillariellaceae are strongly represented (Fig. DR2).

Atmospheric CO2 Reconstruction

Stomatal indices derived from Giraffe Metasequoia leaves (Doria et al., 2011) yield a combined median reconstructed atmospheric CO2 concentration for all stratigraphic levels of ~630 ppm (433–1124 ppm at 68% confidence) (Figs. 2F and 3; Table DR4). Combined CO2 estimates from the Frank et al. (2014) gas-exchange model, applied to the same sedge (Appendix DR1), are somewhat lower, ranging from 353 to 561 ppm at 68% confidence with a median of ~430 ppm (Fig. 3A). Given overlap between the two methods of CO2 reconstruction, and because the stomatal index proxy is unbiased at high CO2 concentrations (Doria et al., 2011), we resampled randomly from the combined stomatal index and gas-exchange model reconstructions to yield a consensus median CO2 concentration of ~490 ppm (378–778 ppm at 68% confidence). This approach reduces biases inherent to either technique.

This CO2 reconstruction is lower than inferences of ~800–1000 ppm from alkane δ13C between 39 and 37 Ma (Zhang et al., 2013) and 650 ± 110 ppm (at 68% confidence) at 40.3 Ma from δ13C of pristine foraminifer calcite (Anagnostou et al., 2016), but in agreement with estimates of 385–467 ppm (at 68% confidence) from the stomatal distributions of Canadian High Arctic Metasequoia foliage dating broadly to between 47.9 and 37.8 Ma (Maxbauer et al., 2014) and ~350–650 ppm from the stomatal density of extinct fagalean foliage (Steinhorsdottir et al., 2016). The results from the Giraffe locality thus support lower CO2 concentrations than previously envisaged for greenhouse climate intervals (Franks et al., 2014).
DISCUSSION

High Polar Amplification under Modest CO₂ Forcing

These data provide an integrated estimate of the mean climate state for the continental subarctic Giraffe locality over the multimillennial interval common to all proxies. The MCR-inferred paleotemperature and reconstructed CO₂ concentrations can be plotted along a range of estimates for the sensitivity of MAT with respect to atmospheric CO₂ (Fig. 4). Present-day estimates of global Charney climate sensitivity (CS) include a subset of fast feedbacks only, while Earth-system sensitivity (ESS) includes most fast and slow feedbacks (Royer, 2016). CS and ESS are typically expressed as a range of estimated values for the degree of poleward heat transfer by water vapor (Pagani et al., 2014; Carmichael et al., 2016) estimated from middle Eocene proxies (Maxbauer et al., 2014). Pronounced middle Eocene polar amplification is likewise expressed in the Southern Hemisphere high latitudes, where temperate rainforests dominated by Nothofagus and araucarian conifers existed along the Wilkes Land margin of East Antarctica, implying MATs >10 °C and MAPs several times higher than present (Pross et al., 2012).

Early Eocene climate model simulations for the latitudes of subarctic North America (Lunt et al., 2012a; Carmichael et al., 2016) underestimate the multiple proxy constraints presented here. For example, at 560 ppm CO₂, the ensemble mean of three models (Lunt et al., 2012a) for the Giraffe region underestimates reconstructed MAT by 15.5 °C, with a minimum underestimate of 6.4 °C (Fig. 4). At 1120 ppm CO₂, more than twice the inferred CO₂ from Metasequoia foliage, the ensemble mean MAT is 11.3 °C lower than proxy MATs, with a minimum underestimate of 4.5 °C (Fig. 4). The model results compiled by Lunt et al. (2012a) consistently estimated colder-than-present preindustrial Yellowknife MATs in 280 ppm CO₂ control runs. However, even when this model-dependent artifact is taken into account by expressing MAT relative to instrumental Yellowknife MAT (Fig. DR5), model MATs remain substantially lower than the proxy-based ΔMATs presented here for the Giraffe region (Table DR5).

Many mechanisms have been explored to explain the amplified warmth of high latitudes during the Cretaceous and Paleogene, including state-dependent CS (Caballero and Huber, 2013), decreased atmospheric pressure (Poulson et al., 2015), altered cloud physics (Kiehl and Shields, 2013), biogenic aerosols (Beerling et al., 2011), and teleconnection dynamics with tropical oceans (Korty et al., 2008). Changes in atmospheric circulation such that low pressure centers and associated cyclogenesis became quasi-permanent features over the polar regions in the absence of perennial sea ice cover were also probable. Such configurations appear necessary to increase MAP by the amounts mandated by the proxy record at Giraffe and elsewhere, whereas intensification of the hydrologic cycle also increases poleward heat transfer by water vapor (Pagan et al., 2014; Carmichael et al., 2016). Despite obvious differences in boundary conditions with respect to the state of the cryosphere and biosphere, these configurations provide some degree of analogy with contemporary warming of the Arctic, where dramatic losses of Northern Hemisphere sea ice over the last decade have contributed to deepening lows over the Arctic Ocean, coupled to enhanced cyclogenesis that in turn exerts a strong positive feedback on remaining sea ice (Screen et al., 2011; Simmonds and Rudeva, 2012).

Because future temperatures are unlikely to decline appreciably over the time scales required for most fast and slow feedbacks to become fully expressed (centuries to millennia; Royer, 2016), even if all anthropogenic greenhouse gas emissions are eliminated (Archer and Brovkin, 2008), the latest middle Eocene forest ecosystem preserved in the Giraffe kimberlite offers considerable insight toward understanding high-latitude climate states under elevated, but not extreme, atmospheric CO₂ concentrations.

ACKNOWLEDGMENTS

We thank BHP Billiton Inc. and the Geological Survey of Canada for access to cores; the Natural Sciences and Engineering Research Council (Canada) (Greenwood, Reyes, Westgate, and Wolfe); the U.S. National Science Foundation (Siver); J. Basinger for discussions on Metasequoia; G. Braybrook for scanning electron microscopy; the Climate Change Consortium of Wales, D. McCarroll, and N. Loader for assistance with stable isotopes; R. Zetter for advice on pollen morphology; and G. Ludvigson, M. Steinthorsdottir, B. Jacobs, and several other anonymous reviewers. We dedicate this paper to our departed colleagues Leo Hickey (1940–2013) and Mark Pagan (1960–2016), who trailblazed much of our thought concerning greenhouse worlds of the past, and Art Sweet (1942–2017), pillar of Canadian palynology and the first to analyze Giraffe pipe pollen.