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 Doria³,⁵, 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 posteruptive 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 ~4x 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.

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., 2001; Anagnostou et al., 2016; Tripati et al., 2008; Lunt et al., 2012a). The subsequent cooling trend of the middle Eocene (e.g., Tripati et al., 2008), in apparent conflict with 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 warm conditions 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 mismatch and frustrated efforts to understand the sensitivity of past equilibrium climate response to greenhouse gas forcing.

Our objective is to assess climate and greenhouse-gas forcing for Northern Hemisphere subarctic latitudes during the latest middle Eocene by exploiting a remarkable terrestrial sedimentary archive. The Giraffe kimberlite locality (latitude ~63°N) comprises the posteruptive sedimentary fill of a maar formed when kimberlite intruded Precambrian tectonic rocks of the Slave Province at 47.8 ± 1.4 Ma (Creaser et al., 2004). Pollen, δ¹⁸O from wood cellulose, and foliar stomata from this locality provide a comprehensive reconstruction of late middle Eocene climate and CO₂ for the northern subarctic latitudes.

RESULTS

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

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 posteruptive sedimentary fill and the position of BHP core 99-01 and key stratigraphic features (arrows). C: Core stratigraphy showing the investigated section directly above tephra horizons dated by isothermal plateau (IPFT) and diameter-corrected (DCFT) glass fission track analyses (1σ uncertainty).

E-mail: areyes@ualberta.ca
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 mean uncertainty of 310 mm. The present-day climate for Yellowknife is likely the dominant source given the presence of well-preserved foliage and wood of this taxon (Fig. DR1). Pollen of *Pinus* preserved foliage and wood of this taxon (Fig. DR1). This wood yields pristine α-cellulose (Fig. DR3) amenable to measurements of stable oxygen isotope ratios (δ¹³O cellulose) by pyrolysis and continuous-flow isotope ratio mass spectrometry, which in turn can provide independent support for paleoclimatic estimates of MAT (Appendix DR1). The values of δ¹³O cellulose range from 23.4‰ to 29.4‰ VSMOW (Vienne standard mean ocean water) (Fig. 2D; Table DR3). Using a Monte Carlo implementation of the Anderson et al. (2002) leaf-water model, we estimated values of δ¹³O for environmental waters (δ¹³Owater) accessed by the trees, and then calculated MAT from these inferred δ¹³Owater values using an empirical relation between Eocene environmental waters and MAT that accounts for Eocene latitudinal temperature gradients (Fricke and Wing, 2004). The δ¹³Owater results yield a MAT estimate of 15.6±2.0 °C at 1σ (Fig. 2E), which overlaps the pollen-based MCR estimate of 14.5±1.3 °C MAT (Fig. DR4).

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 Franks et al. (2014) gas-exchange model, applied to the same foliages (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 unbounded 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 alkenone δ¹³C between 39 and 37 Ma (Zhang et al., 2013) and 650±110 ppm (at 68% confidence) at 40.3 Ma from δ¹³B of pristine foraminiferal 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 (Steinthorsdottir 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).

Figure 3. A: Probability density functions (PDFs) for reconstructed CO₂ concentrations from *Metasequoia* stomatal index (SI), gas-exchange modeling (GE), and random resampling of the combined stomatal index and gas-exchange model reconstructions (CR). B: PDFs for regional climate sensitivity at the Giraffe locality, subarctic Canada (Appendix DR1 [see footnote 1]). In both panels, horizontal lines indicate the 16th to 84th percentile range, with median values marked by squares.
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 most fast and slow feedbacks (Royer, 2016). CS and ESS are typically expressed as globally averaged approximations of the temperature response to incremental CO2 doublings, expressed as ΔMAT relative to preindustrial conditions. However, recent studies have demonstrated the utility of regional approximations for these parameters (Dyez and Ravelo, 2013; Eagle et al., 2013).

The latest middle Eocene MAT and stomatal index CO2 reconstruction from Giraffe, when compared to the present climate of Yellowknife using the approach of Royer et al. (2012), yield a mean regional climate sensitivity of 12.7 °C per CO2 doubling for the North American subarctic latitudes (8.3–21.2 °C at 68% confidence; Fig. 3; Appendix DR1), more than twice the estimated ESS of ~6 °C per CO2 doubling for the Pleistocene climate system (Hansen et al., 2008; Fig. 4). Use of CO2 estimates from the gas-exchange model produces even higher regional climate sensitivity values (14.0–32.8 °C at 68% confidence, median = 20.1 °C; Fig. 3).

These estimates of regional climate sensitivity, based on paleoclimate and CO2 proxies analyzed in parallel from the same sediment archive, highlight the exceptional magnitude of polar amplification under relatively modest CO2 forcing. This contention is supported by temperature reconstructions from Ellesmere Island and Siberia during the Pliocene (Ballantyne et al., 2010; Brigham-Grette et al., 2013), for which independent proxies (e.g., Zhang et al., 2013) indicate CO2 concentrations of ~400 ppm (Fig. 4). Even greater ΔMATs (~32 °C) are estimated from middle Eocene fossil floras of Axel Heiberg Island (Eberle and Greenwood, 2012), also dominated by Metasequoia, when CO2 was possibly as low as ~420 ppm (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 fold 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 ΔMAT 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 (Poulsen 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 (Paganli 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. McCarron, 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 Pagani (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.