Contributions to the Eocene climate record of the Antarctic Peninsula

L. C. Ivany

Department of Earth Sciences, Syracuse University, Syracuse NY 13244, USA (lcivany@syr.edu)

Summary Paleotemperatures derived from the $\delta^{18}O$ values of bivalve shell from the La Meseta Formation on Seymour Island, Antarctic Peninsula, indicate ~10°C of cooling during the Eocene, much of which took place in two comparatively short intervals (~52 Ma and ~41 Ma). A short-term excursion to significantly more negative $\delta^{18}O$ values appears to correlate with the middle Eocene climatic optimum of Bohaty and Zachos, and a rapid ensuing shift to much more positive values may reflect cooling associated with a proposed short-lived glacial advance. Late middle-late Eocene temperatures are universally cooler than lower in the section, but average values do not suggest freezing conditions. High-resolution records indicate a decrease in seasonality through the section, with significantly cooler summers in the late Eocene. Pebbly mudstone containing early Oligocene dinoflagellates immediately overlies La Meseta Formation sands, suggesting the potential for glacio-marine deposition at or near the Eocene-Oligocene boundary.

Citation: Ivany, L.C. (2007), Contributions to the Eocene climate record of the Antarctic Peninsula, in Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES X, edited by A. K. Cooper and C. R. Raymond et al., USGS Open-File Report 2007-1047, Extended Abstract 068, 4 p.

Introduction

The Eocene La Meseta Formation of Seymour Island, Antarctic Peninsula, provides one of the only high southern latitude records of climate conditions on the shelf during the Paleogene greenhouse-to-icehouse transition. Here, I summarize the results of collaborative work with a number of individuals (see Acknowledgements) to further refine our understanding of climate change in this region from the early Eocene climatic optimum (EECO) through to the Eocene-Oligocene boundary. Paleoclimate inferences are based on stable oxygen isotope values of marine bivalve shells collected throughout the section and on sedimentological properties of deposits at the top of the section.

Background

Seymour Island is located roughly 100 km east of the Antarctic Peninsula near its northern end. Fossiliferous marine outcrops on the northeast third of the island record much of the Eocene and thus provide an ideal opportunity to study the effects of cooling on high-latitude, marine shelf environments and their associated faunas. The Eocene La Meseta Formation (Elliot and Trautman, 1982) is a shallow marine succession comprised of sandstones, mudstones, and shell banks thought to have accumulated in a variety of inner shelf environments (Sadler, 1988; Porebski, 1995, 2000; Marenssi et al., 1998). The formation has been partitioned into seven distinct, mappable, lithologic units, or Telms ("Tertiary Eocene La Meseta"; Sadler, 1988), subdividing the original three-part lithologic division of Elliot and Trautman (1982). More recently, several authors have defined genetically-related, unconformity-bound, depositional sequences reflecting the interplay of fault-controlled subsidence and eustatic change in sea level (Porebski, 1995, 2000; Marenssi et al., 1998). While the shallow-water facies and confined (fault-bounded) nature of the unit has led to an inferred depositional setting within an estuary (e.g., Marenssi et al., 1998; Porebski, 2000), the diverse invertebrate fauna preserved throughout the unit suggests more normal marine conditions (e.g., Stilwell and Zinsmeister, 1992). Age control within the La Meseta Formation has been based primarily on biostratigraphy and suggests that deposition spanned much of the Eocene (Harwood, 1985; Wrenn and Hart 1988), but uncertainty remains about the age of particular units within.

Paleontological studies of La Meseta floral and faunal assemblages suggest cool to warm-temperate conditions during deposition of the unit (e.g., Case, 1988; Doktor et al., 1996; Francis and Poole, 2002; Stilwell and Zinsmeister, 1992). More recently, Dutton and colleagues (2002) constructed a temperature record based on $\delta^{18}O$ values of shell carbonate from the bivalve genus *Cucullaea*. They infer an average temperature of ~15°C in Telms 2-5, cooling to ~10.5°C in Telms 6 and 7, consistent with an overall pattern of Eocene cooling. Their data, however, have limited temporal resolution because shells were pooled at the level of Telm. The data presented here build on their study, but because stratigraphic resolution is much higher, they exhibit more structure and offer a more detailed record of climate change during this important period of Earth history.

Methods

Two abundant and consistently present bivalve taxa, the arcid *Cucullaea* and the venerid *Eurhomalea*, were collected in stratigraphic succession from in situ shelly facies throughout the section. Wherever possible, multiple localities were collected within a single stratigraphic horizon in order to assess heterogeneity that may reflect differences in time averaging or spatial variability in environmental conditions. Fossils were collected from 54

localities distributed within 27 stratigraphic horizons through Telms 2-7. Individuals were sectioned along the maximum growth axis and polished to reveal growth banding and internal architecture and evaluated for quality of preservation. Sampling on a Merchantek MicroMill produced powders that were analyzed for their stable oxygen and carbon isotope values. In addition, the $^{87}Sr/^{86}Sr$ ratios of skeletal aragonite from 43 bivalves distributed throughout the section were analyzed in an effort to improve age control within the La Meseta Formation. Paleotemperatures are calculated using the empirically-determined paleotemperature equation of Grossman and Ku (1986) for biogenic aragonite, adjusted by 0.2‰ to correct for the difference between 'average marine water' and SMOW. A value of -2‰ for $\delta^{18}O$ of seawater is used based on estimates from Huber et al. (2003) derived from a coupled ocean-atmosphere climate model specific to the Eocene Antarctic Peninsula region.

Results

$^{87}Sr/^{86}Sr$ ratios of bivalve shells generally fall within the range of Eocene marine seawater (McArthur et al., 2001). Ratios from Telms 2 through 5 represent the early Eocene minimum in marine $^{87}Sr/^{86}Sr$ values, while those from the upper part of the formation consistently establish an age ranging from late middle Eocene (~41 Ma) up through virtually the Eocene-Oligocene boundary (see also Ivany et al., 2006). An unconformity is suggested during the early middle Eocene, between Telms 5 and 6.

Stable oxygen isotope values from *Cucullaea* are, on average, ~.4‰ more positive than those from *Eurhomalea*, and hence yield paleotemperatures cooler by about 2°C. High-resolution microsampling within and across growth bands of each taxon from a single locality reveals that *Cucullaea* grows mainly during the Austral winter (Buick and Ivany, 2004), while *Eurhomalea* appears not to capture the more positive (cooler) portion of the seasonal cycle but records more of the Austral summer. The range of values exhibited by shells at different localities from the same stratigraphic horizon is nearly always statistically indistinguishable, suggesting that conditions across the depositional surface were reasonably consistent from place to place and therefore that any change seen through time in the average $\delta^{18}O$-derived paleotemperature is likely to represent a meaningful shift in Eocene peninsular climate rather than simply the incomplete sampling of a heterogeneous environment.

Within the temporal context provided by strontium isotope stratigraphy, and interpreted solely as temperature, mean $\delta^{18}O$ values of shell aragonite show warm early Eocene temperatures with a maximum of ~15 °C near the base of Telm 3, dropping to 10-11 °C and remaining essentially constant up through the end of Telm 5 (end early Eocene; Figure 1A). Values in the lower part of Telm 6 record a short-lived return to warm temperatures, followed immediately by a drop to ~7°C near 41 Ma. Temperatures continue to cool into Telm 7 and reach a minimum value (~5°C) for the whole Eocene section by ~37 Ma.

Seasonality of temperature approximates 8°C in Telm 3, ~4 °C in Telm 5, and drops to 1-2 °C in Telm 7 (not shown), attributable to drops in both summer and winter temperatures. Summer temperatures drop from 12-15 °C in both Telms 3 and 5 to only about 6 °C in Telm 7, and are more variable in Telms 3-5 than in Telm 7. Winter temperatures decrease consistently from a mean around 10 °C in Telm 3 to around 5 °C in Telm 7. If the $\delta^{18}O$ of seawater were more negative, calculated paleotemperatures would be correspondingly cooler, but it appears that temperatures even in winter did not reach freezing during the intervals sampled.

Paleoclimatic Implications

Because most $^{87}Sr/^{86}Sr$ ratios fall within the range for typical Eocene seawater and $\delta^{18}O$ data show no pronounced negative values, salinity variation within the unit is apparently minimal. At the base of Telm 6, where concern is greatest for the influence of isotopically negative meteoric runoff, $\delta^{18}O$ values are consistent at 10 different localities, suggesting a real temperature signal rather than reduced and variable salinity.

The overall trend in mean oxygen isotope values is broadly consistent with the pattern of increasing $\delta^{18}O$ and cooling temperature reported by Dutton et al. (2002), but these data reveal a greater level of complexity in $\delta^{18}O$ and temperature through the Eocene section than anticipated from the earlier, lower-resolution work. Several features of the global (Zachos et al., 2001) and Southern Ocean (Stott et al., 1990; Bohaty and Zachos, 2003) marine records of $\delta^{18}O$-based paleotemperatures are evident in this shelf section. First, given the uncertainty in strontium isotope age estimates, it is likely that maximum temperatures near the base of Telm 3 reflect the early Eocene climatic optimum (EECO). Strontium isotope ratios from Telm 2 consistently yield age estimates of ~54 Ma, indicating that the EECO (roughly 51-53 Ma) should be encompassed within the La Meseta Formation section. Inferred EECO temperatures in Telm 3 are at least 4 °C warmer than earlier or later samples. Inferred paleotemperatures at Seymour Island during the EECO are comparable to those inferred in the Arctic Ocean at the time based on TEX_{86} (~18°C, Sluijs et al., 2006), but less than those suggested at the Paleocene-Eocene thermal maximum (PETM).

The extreme but short-lived excursion toward negative $\delta^{18}O$ values at the base of Telm 6 may also have a parallel in the open ocean, making the alternative explanation of a facies change to brackish water less likely. Taken at face value, the $\delta^{18}O$ shift indicates warming of shelf waters to temperatures comparable to those reached during the EECO,

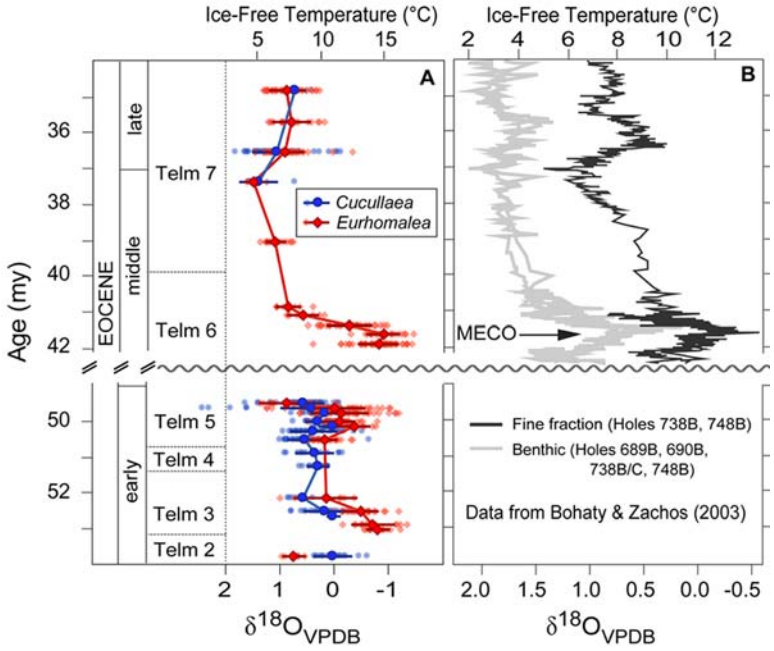

Figure 1. Stable oxygen isotope data from two La Meseta Formation bivalve genera, plotted by genus and compared to data from the Southern Ocean from Bohaty and Zachos (2003). A) $\delta^{18}O$ values and ice-free temperature, with means and standard deviations superimposed. Ages based on $^{87}Sr/^{86}Sr$ ratios. Temperatures are calculated using $\delta^{18}O_{SW}$=-2‰; B) $\delta^{18}O$ values from surface and deep waters in the Southern Ocean, showing MECO; temperatures were calculated using a $\delta^{18}O_{SW}$=-1‰.

followed rapidly by ~7°C of cooling. $^{87}Sr/^{86}Sr$ ratios from bivalves immediately above the negative excursion yield ages of 40.4 – 41.3 Ma, indicating that this warming may coincide with the middle Eocene climatic optimum (MECO, 41-42 Ma) observed in sediments deposited in the Southern Ocean on the Maud Rise and the Kerguelen Plateau (Bohaty and Zachos, 2003) (Figure 1B). The amount of warming during this event on the Seymour Island shelf is ~5°C, slightly more than that noted in Southern Ocean surface waters (Bohaty and Zachos, 2003), and the entire excursion appears to have taken place within only ~1my, a duration comparable to that seen in the Southern Ocean. If this is in fact the MECO, the subsequent rapid cooling would be coeval with the short-lived middle Eocene glaciation proposed to immediately follow the MECO by Tripati and others (2005) from deep-sea $\delta^{18}O$ data. In this case, a portion of the observed positive $\delta^{18}O$ shift may be due to ice growth rather than cooling temperatures.

Late middle and late Eocene $\delta^{18}O$ values/temperatures are universally more positive/cooler than in the earlier part of the record. As in the Southern Ocean record from Bohaty and Zachos (2003), minimum surface-water temperatures are attained ~37 Ma. This is roughly coincident with the earliest evidence for glaciation in Greenland based on the presence of ice-rafted debris (Eldrett et al., 2007). The slight trend back to more negative $\delta^{18}O$ values in bivalves preserved in the upper part of Telm 7 may record the interval of late Eocene warmth, or at least the interruption of cooling, recognized in both the Southern Ocean (Bohaty and Zachos, 2003) and the global benthic record (Zachos et al., 2001) just prior to the onset of glaciation in the early Oligocene. While late Eocene $\delta^{18}O$ values remain just shy of freezing paleotemperatures, the presence of pebbly mudstone containing earliest Oligocene dinoflagellates associated with a thin diamict and immediately overlying latest Eocene shelf deposits suggests the potential for ice advance at or near the Eocene-Oligocene boundary in the Peninsula (Ivany et al., 2006).

These data provide high-latitude shelf paleotemperatures through the Eocene that can be compared to those from tropical settings to quantify the evolution of the pole-to-equator thermal gradient during the course of global cooling. Pearson et al. (2007) report tropical Eocene shelf temperatures that hover around 30-33 °C for the duration of the epoch, warmer and surprisingly stable in comparison to those based on deep-sea cores (e.g., Zachos et al., 1994). Paleotemperatures derived from La Meseta Formation bivalves suggest that the meridional temperature gradient at the EECO approximates 15 °C, and increases to near 25 °C at the coolest part of the late Eocene. As the steepening of this gradient has consequences for the biogeographic distribution of marine shelf organisms, these data predict that thermally-induced biogeographic differentiation on shelves peaked in the early Eocene shortly after the EECO, and again immediately following the MECO. The most significant taxonomic and ecologic turnover in the Eocene section corresponds to changes in temperature inferred from the middle Eocene shift in stable isotope values. Below the MECO, shelf faunas were mollusc-dominated and show evidence for the typical suite of skeleton-crushing predators that characterize most Cenozoic shelf assemblages. Above the MECO and ensuing glaciation, molluscan diversity drops and faunas are characterized by an abundance of low metabolic rate, epifaunal suspension feeders and slow-moving predators (Aronson et al., 1997; Aronson and Blake, 2001; Werner et al., 2004). The MECO and subsequent rapid cooling led to faunal turnover that initiated development of today's archaic shallow-water benthic communities.

These data offer the first taxonomically consistent record of paleotemperature variation with this level of stratigraphic resolution throughout the Eocene in an Antarctic marine shelf section. The agreement of our $\delta^{18}O$ data

from near shore peninsular Antarctic habitats with those from the Southern Ocean, in both general pattern as well as detail, affirms the use of shallow shelf carbonates as useful archives for paleoclimate reconstruction. In addition, the La Meseta Formation record demonstrates that climate perturbations recorded as far away as the Kerguelan Plateau (Bohaty and Zachos, 2003) were ubiquitous, high southern latitude phenomena, experienced on the shelf as well as in the open ocean.

Acknowledgements. This contribution summarizes work involving a number of people on several different aspects of the Paleogene Seymour Island record. Kacey Lohman and Franek Hasiuk are collaborators on the geochemical records, Rich Aronson, Dan Blake, Alexander Glass, John Werner, and Ryan Moody on the paleoecological record, Stefaan Van Simaeys, Eugene Domack, and Scott Samson on the inferred glacial record, and Devin Buick and Nicole Miklus on paleoseasonality records. Lora Wingate ran the stable isotope analyses, and Cristina Story, Allison Cattani, and John Schue assisted with preparation and sampling. Vanessa Thorn helped with editing. John Evans is gratefully acknowledged for inspiration and help in the field. This research was supported by grants from NSF's Office of Polar Programs to Ivany and Lohmann (OPP-0125409, OPP-0125589), and an REU supplement to Ivany. Field work was supported by NSF grants to Aronson and Blake (OPP-9908828, OPP-9908856, and ANT-0245563).

References

Aronson, R. B., D. B. Blake, and T. Oji (1997), Retrograde community structure in the late Eocene of Antarctica, Geology, 25, 903-906.

Aronson, R. B., and D. B. Blake (2001), Global climate change and the origin of modern benthic communities in Antarctica, Am. Zool., 41, 27-39.

Bohaty, S. M., and J. C. Zachos (2003), Significant Southern Ocean warming event in the late middle Eocene, Geology, 31, 1017-1020.

Buick, D. P., and L. C. Ivany (2004), 100 years in the dark: extreme longevity of Eocene bivalves from Antarctica, Geology, 32, 921-924.

Case, J. A. (1988), Paleogene floras from Seymour Island, Antarctic Peninsula, in Geology and Paleontology of Seymour Island, Antarctic Peninsula, edited by R. M. Feldmann, and M. O. Woodburne, pp. 523-530, Geol. Soc. Am. Mem., 169, Boulder, Colorado.

Doktor, M., A. Gazdzicki, A. Jerzmanska, and S. J. Porebski (1996), A plant-and-fish assemblage from the Eocene La Meseta Formation of Seymour Island (Antarctic Peninsula) and its environmental implications, Palaeontologica Polonica, 55, 127-146.

Dutton, A. L., K. C. Lohmann, and W. J. Zinsmeister (2002), Stable isotope and minor element proxies for Eocene climate of Seymour Island, Antarctica, Paleoceanography, 17, doi:10.1029/2000PA000593.

Eldrett, J. S., I. C. Harding, P. A. Wilson, E. Butler, and A. P. Robert (2007), Continental ice in Greenland during the Eocene and Oligocene, Nature, 446, 176-179.

Elliot, D. H., and T. A. Trautman (1982), Lower Tertiary strata on Seymour Island, Antarctic Peninsula, in Antarctic Geosciences, edited by C. Craddock, pp. 287-297, University of Wisconsin Press.

Francis, J. E., and I. Poole (2002), Cretaceous and early Tertiary climates of Antarctica: evidence from fossil wood, Palaeogeogr., Palaeoclimatol., Palaeoecol., 182, 47-64.

Grossman, E. L., and T.-L. Ku (1986), Oxygen and carbon isotope fractionation in biogenic aragonite: temperature effects, Chem. Geol., 59, 59-74.

Harwood, D. M. (1985), Cretaceous to Eocene Seymour Island siliceous microfossil biostratigraphy, in Workshop on Cenozoic Geology of the Southern High Latitudes - Sixth Gondwanan Symposium, Ohio State University, Columbus, Ohio, pp. 17-18.

Huber, M., L. Sloan, and C. Shellito (2003), Early Paleogene oceans and climate: A fully coupled modeling approach using the NCAR CCSM, in Causes and Consequences of Globally Warm Climates in the Early Paleogene, edited by S. L. Wing, P. D. Gingerich, B. Schmitz, and E. Thomas, pp. 25-47, Geol. Soc. Am. Spec. Pap., 369, Boulder, Colorado.

Ivany, L. C., S. Van Simaeys, E. W. Domack, and S. D. Samson (2006), Evidence for an earliest Oligocene ice sheet on the Antarctic Peninsula, Geology, 34, 377-380.

Marenssi, S. A., S. N. Santillana, and C. A. Rinaldi (1998), Stratigraphy of the La Meseta Formation (Eocene), Marambio (Seymour) Island, Antarctica, Asociación Paleontológica Argentina, Publicación Especial, 5, 137-146.

McArthur, J. M., R. J. Howarth, and T. R. Bailey (2001), Strontium isotope stratigraphy: LOWESS Version 3: Best fit to the marine Sr-isotope curve for 0-509 Ma and accompanying look-up table for deriving numerical age, J. Geol., 109, 155-170.

Pearson, P. N., B. E. van Dongen, C. J. Nicholas, R. D. Pancost, S. Schouten, J. M. Singano, and B. S. Wade (2007), Stable warm tropical climate through the Eocene Epoch, Geology, 34(3), 211-214.

Porebski, S. J. (1995), Facies architecture in a tectonically-controlled incised-valley estuary: La Meseta Formation (Eocene) of Seymour Island, Antarctic Peninsula, Studia Geologica Polonica, 107, 7-97.

Porebski, S. J. (2000), Shelf-valley compound fill produced by fault subsidence and eustatic sea-level changes, Eocene La Meseta Formation, Seymour Island, Antarctica, Geology, 28, 147-150.

Sadler, P. M. (1988), Geometry and stratification of uppermost Cretaceous and Paleogene units on Seymour Island, northern Antarctic Peninsula, in Geology and Paleontology of Seymour Island, Antarctic Peninsula, edited by R. M. Feldmann, and M. O. Woodburne, pp. 303-320, Geol. Soc. Am. Mem., 169, Boulder, Colorado.

Sluijs, A., S. Schouten, M. Pagani, et al. (2006), Subtropical Arctic Ocean temperatures during the Paleocene/Eocene thermal maximum, Nature, 441, 610-613.

Stilwell, J. D., and W. J. Zinsmeister (1992), Molluscan Systematics and Biostratigraphy, Lower Tertiary La Meseta Formation, Seymour Island, Antarctic Peninsula, Washington D.C., American Geophysical Union, 192 pp.

Stott, L. D., J. P. Kennett, N. J. Shackleton, and R. M. Corfield (1990), The evolution of Antarctic surface waters during the Paleogene: Inferences from the stable isotopic composition of planktonic foraminifers, ODP Leg 113., in Proc. Oc. Drill. Proj., Sci. Res., 113, edited by P. F. Barker, J. P. Kennett, et al., pp. 849-863.

Tripati, A., J. Backman, H. Elderfield, and P. Ferretti (2005), Eocene bipolar glaciation associated with global carbon cycle changes, Nature, 436, 341-346.

Werner, J. E., D. B. Blake, and R. B. Aronson (2004), Effects of late Eocene cooling on Antarctic marine communities, GeoSur 2004 – International Symposium on the Geology and Geophysics of the Southernmost Andes, the Scotia Arc and the Antarctic Peninsula. Bollettino di Geofisica, 45, supplement 2, 239-242.

Wrenn, J. H., and G. F. Hart (1988), Paleogene dinoflagellate cyst biostratigraphy of Seymour Island, Antarctica, in Geology and Paleontology of Seymour Island, Antarctic Peninsula, edited by R. M. Feldmann, and M. O. Woodburne, pp. 321-447, Geol. Soc. Am. Mem., 169, Boulder, Colorado.

Zachos, J. C., M. Pagani, L. Sloan, E. Thomas, and K. Billups (2001), Trends, rhythms, and aberrations in global climate 65 Ma to present, Science, 292, 686-693.

Zachos, J. C., L. D. Stott, and K. C. Lohmann (1994), Evolution of early Cenozoic marine temperatures, Paleoceanography, 9(2), 353-387.