A cool temperate climate on the Antarctic Peninsula through the latest Cretaceous to early Paleogene

David B. Kemp[1]*, Stuart A. Robinson[2], J. Alistair Crame[3], Jane E. Francis[3], Jon Ineson[4], Rowan J. Whittle[3], Vanessa Bowman[3], and Charlotte O'Brien[2]

[1]Environment, Earth and Ecosystems, Centre for Earth and Planetary Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK

[2]Department of Earth Sciences, University of Oxford, South Parks Road, Oxford OX1 3AN, UK

[3]British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK

[4]Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen, Denmark

ABSTRACT

Constraining past fluctuations in global temperatures is central to our understanding of the Earth's climatic evolution. Marine proxies dominate records of past temperature reconstructions, whereas our understanding of continental climate is relatively poor, particularly in high-latitude areas such as Antarctica. The recently developed MBT/CBT (methylation index of branched tetraethers/cyclization ratio of branched tetraethers) paleothermometer offers an opportunity to quantify ancient continental climates at temporal resolutions typically not afforded by terrestrial macrofloral proxies. Here, we have extended the application of the MBT/CBT proxy into the Cretaceous by presenting paleotemperatures through an expanded sedimentary succession from Seymour Island, Antarctica, spanning the latest Maastrichtian and Paleocene. Our data indicate the existence of a relatively stable, persistently cool temperate climate on the Antarctic Peninsula across the Cretaceous-Paleogene boundary. These new data help elucidate the climatic evolution of Antarctica across one of the Earth's most pronounced biotic reorganizations at the Cretaceous-Paleogene boundary, prior to major ice-sheet development in the late Paleogene. Our work emphasizes the likely existence of temporal and/or spatial heterogeneities in climate of the southern high latitudes during the early Paleogene.

INTRODUCTION

The latest Cretaceous to early Paleogene (70–41 Ma) was an interval of significant climatic and biotic reorganization. Central to our understanding of climatic evolution through this interval is the quantification of global temperatures. The temperature record of the Late Cretaceous and early Paleogene is now reasonably well constrained for oceanic bottom waters (e.g., Cramer et al., 2009), whereas current knowledge of continental temperatures is substantially poorer. Notably, the true nature of terrestrial climate changes that may have influenced the major biotic reorganizations associated with the end-Cretaceous mass extinction is debated (e.g., Wilf et al., 2003). Moreover, the Cretaceous–Paleogene climate evolution of high-latitude areas such as Antarctica is highly uncertain owing to a paucity of accessible study sites and inadequate dating of existing data. Accurately quantifying past Antarctic temperatures is important, however, for assessing the veracity of paleoclimate models, and because of the key role that the continent played, and continues to play, in modulating global climate.

The Antarctic Peninsula is an area of specific interest to modern and past climatic studies, as it seems particularly sensitive to change (e.g., Bowman et al., 2013). Continental paleotemperature estimates for the Cretaceous–early Paleogene interval are reliant on relatively sparse and isolated paleofloral-derived data (Greenwood and Wing, 1995; Francis and Poole, 2002; Poole et al., 2005). These data suggest that the Antarctic Peninsula experienced cool temperate climates at various times from the Maastrichtian to Eocene, although the stratigraphic resolution of these data is coarse, so the absence of climatic variability could be an artifact. A complementary approach for reconstructing past continental climates is based on the methylation index and cyclization ratio of branched glycerol dialkyl glycerol tetraethers (brGDGTs) in bacterial membrane lipids (Weijers et al., 2007), known as the MBT/CBT paleothermometer. It has the advantage over macrofloral proxies in that the analyses can be carried out on relatively small quantities of bulk sediment sampled at high temporal resolutions, and it is, therefore, not reliant on the presence and discovery of well-preserved flora.

To further our understanding of Late Cretaceous to early Paleogene climate evolution on Antarctica, we present here MBT/CBT–derived continental paleotemperature estimates through the latest Cretaceous to Paleocene of Seymour Island (paleolatitude ~65°S; Fig. 1). We compare these new continental paleotemperature estimates with estimates derived from existing paleofloral proxies and sea-surface temperature (SST) data, and discuss our findings in the context of circum-Antarctic climate evolution through the Late Cretaceous and early Paleogene.

MATERIALS AND METHODS

Seymour Island contains one of the most expanded Cretaceous–Paleogene (K-Pg) successions known. Our studied interval comprises ~700 m of predominantly shallow-marine deltaic to estuarine sediments deposited in a large backarc basin fed from the Antarctic Peninsula magmatic arc (Crame et al., 1991). The K-Pg boundary occurs in the uppermost part of the López de Bertodano Formation, where it is marked by a minor iridium anomaly (Elliot et al., 1994; Fig. 2). An unconformity separates the López de Bertodano Formation from the overlying Sobral Formation, which is early Paleocene in age (Bowman et al., 2012,

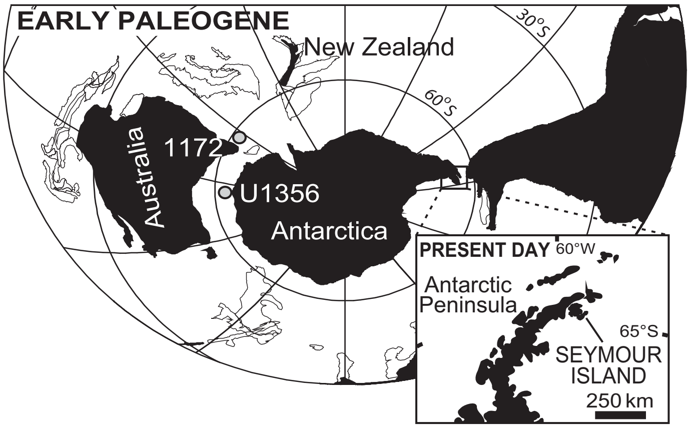

Figure 1. Paleogeographic and present-day maps showing location of Seymour Island, Antarctic Peninsula, and other localities discussed in text. Paleogeographic map is redrawn after Bijl et al. (2009). 1172 and U1356 are ocean drilling sites discussed in the text.

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*E-mail: david.kemp@open.ac.uk.

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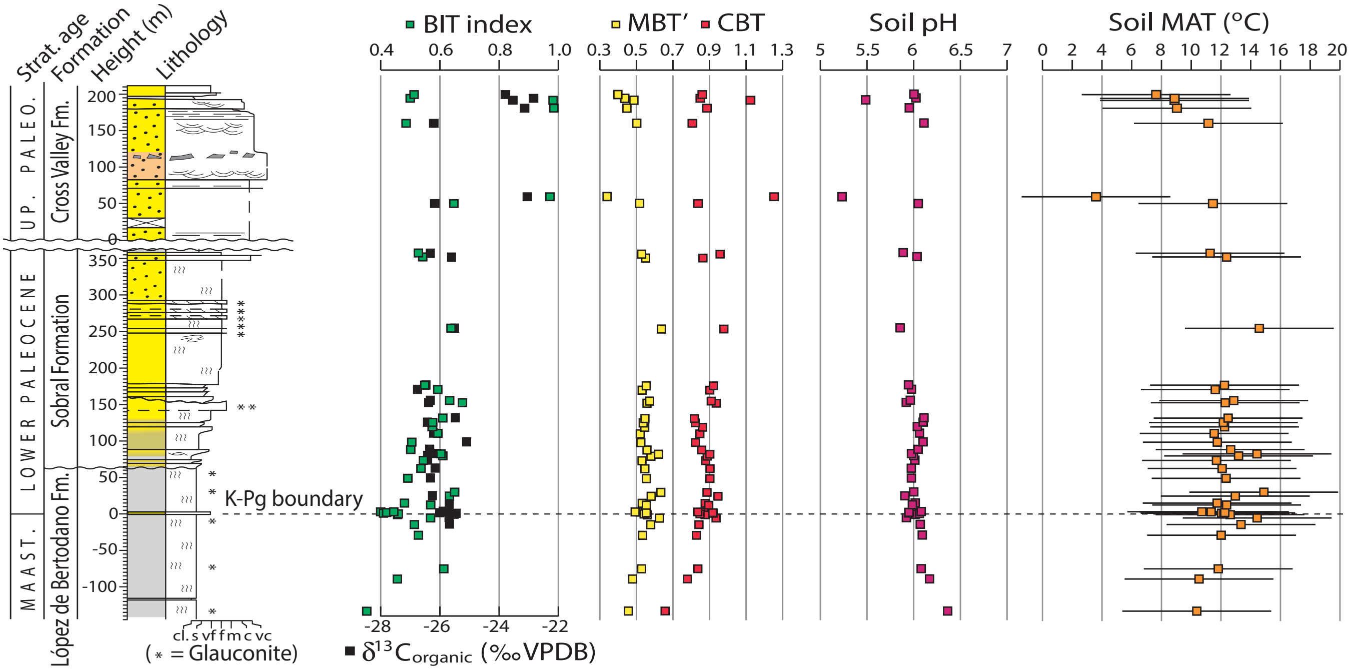

Figure 2. Organic geochemistry and paleotemperature data from Seymour Island, Antarctica. Methylation index of branched tetraethers (MBT′), cyclization ratio of branched tetraethers (CBT), soil pH, and mean annual air temperature (MAT) are calculated using equations of Peterse et al. (2012). Error bars equate to the ±5 °C uncertainty inherent in MBT′/CBT calibration data set (Peterse et al., 2012). BIT—branched and isoprenoid tetraether; MAAST.—Maastrichtian; UP.—Upper; PALEO.—Paleogene; cl.—clay; s—silt; vf—very fine sand; f—fine sand; m—medium sand; c—coarse sand; vc—very coarse sand.

and references therein; Fig. 2; see also the GSA Data Repository[1]). The Cross Valley Formation unconformably overlies the Sobral Formation, infilling a deeply incised valley. Marine palynological data indicate that the Cross Valley Formation is late Paleocene in age (Wrenn and Hart, 1988; Fig. 2; see the Data Repository).

MBT/CBT paleotemperatures were determined on 41 samples. For glycerol dialkyl glycerol tetraethers (GDGT) analysis, 8–20 g of sediment was solvent extracted ultrasonically following the methods outlined by Schouten et al. (2007). Extracts were analyzed for GDGT abundance using an Agilent 1200 HP-LC-MS online to a G6130A single quadrupole mass spectrometer. Soil pH and mean annual air temperature (MAT) were calculated from analysis of MBT and CBT abundances using the calibration equations of Peterse et al. (2012) (see the Data Repository). This latest calibration uses an MBT quantification distinct from that originally presented in Weijers et al. (2007), hereafter referred to as MBT′ (see Peterse et al., 2012, for details). Repeat analysis of standards and samples yielded MBT′ and CBT uncertainties that equated to absolute temperature errors of <0.5 °C. This analytical uncertainty is well within the calibration error of ±5 °C (Peterse et al., 2012). The organic matter within our samples was also characterized through organic carbon isotope analysis ($\delta^{13}C_{org}$) and calculation of the branched and isoprenoid tetraether (BIT) index, which is a measure of the terrestrial (branched) versus marine-derived GDGT content (Fig. 2; Hopmans et al., 2004).

RESULTS

The relatively high BIT indices, coupled with abundant fossil wood observed in the field, indicate a predominantly terrestrial origin for the organic matter within the analyzed samples (Fig. 2). The calculated BIT index values (mean of 0.56) preclude the use of the TEX_{86} proxy for marine paleotemperature determination owing to the risk of terrestrially derived isoprenoid GDGTs biasing calculated TEX_{86} values (Weijers et al., 2006). BIT index, $\delta^{13}C_{org}$, MBT′, CBT, soil pH, and calculated temperature are plotted in Figure 2 against a composite log of the studied interval.

Our data demonstrate that MATs from the López de Bertodano and Sobral Formations average 12.4 ± 5 °C (Fig. 2). Within the Cross Valley Formation this average decreases to 8.7 ± 5 °C, which includes one markedly lower value of 3.6 °C (Fig. 2). This value and four other relatively low temperatures (7–10 °C) calculated from the Cross Valley Formation are associated with organic matter with markedly higher $\delta^{13}C_{org}$ values than determined from samples elsewhere in the succession (>2‰ difference; Fig. 2). It is thus possible that the organic matter in these samples was at least partly derived from soils formed in a region distinct from that of the rest of the succession. However, $\delta^{13}C_{org}$ does not correlate with temperature or any other measured index in the succession, and samples associated with these relatively low temperatures are not associated with consistently different BIT indices or pH, MBT′, or CBT values.

DISCUSSION

Our results indicate the existence of a predominantly cool temperate climate during the latest Cretaceous and Paleocene of Seymour Island, with possible subantarctic and warm temperate interludes (Figs. 2 and 3). Although high-latitude MBT′/CBT paleotemperature estimates may be biased toward summer-month temperatures (e.g., Pross et al., 2012), the veracity of our record is supported by sparse paleofloral temperature proxies from Seymour Island and the Antarctic Peninsula region (e.g., Francis and Poole, 2002; Poole et al., 2005; Fig. 3). Our findings are also in broad agreement with recent SST estimates of surrounding shelf seas from $\delta^{18}O$ analysis of fossil shells from the López de Bertodano Formation by Tobin et al. (2012) (Fig. 3). These authors concluded that SSTs were close to ~8 °C through the latest Maastrichtian, with pronounced warming episodes occurring just prior to and across the K-Pg boundary that they dated

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[1] GSA Data Repository item 2014205, Table DR1 (all data), and Figure DR1 (available age control for the studied succession), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

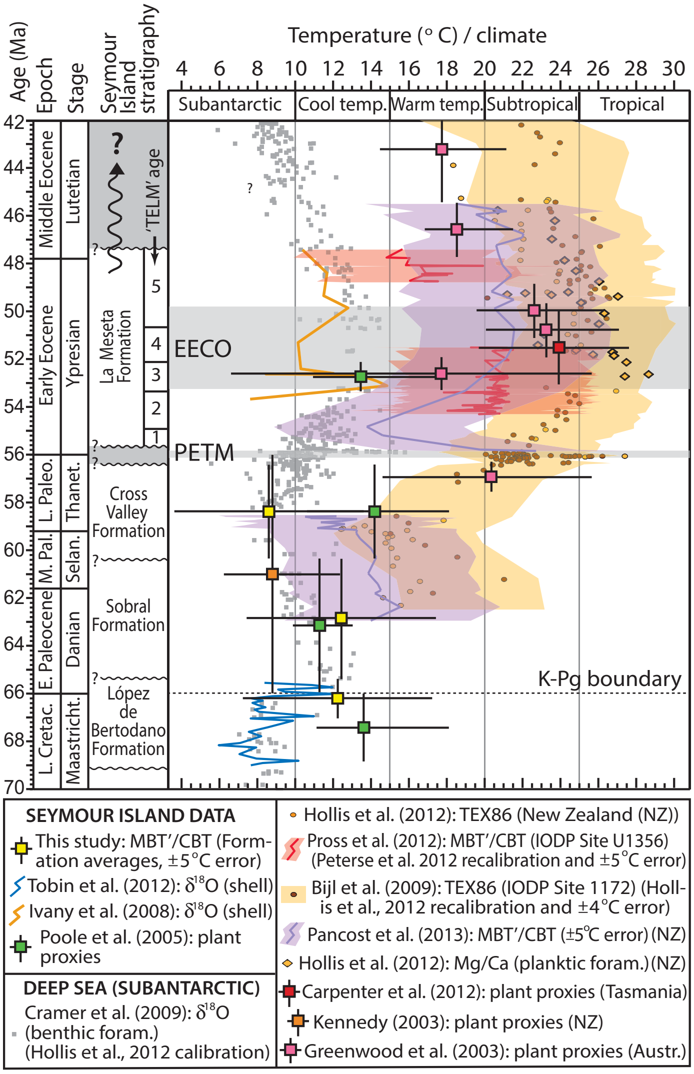

Figure 3. Compilation of multi-proxy paleotemperature data through Late Cretaceous to middle Eocene in circum-Antarctic region. Our methylation of branched tetraethers/cyclization of branched tetraethers (MBT′/CBT) paleotemperatures are plotted as formation averages from 41 samples analyzed in this study. Note that precise ages and durations of Seymour Island formations are uncertain (see main text and Data Repository [see footnote 1] for details of available age control). Age model displayed and age errors for our data thus show maximum likely age span for each formation. Error bars shown for plant proxy paleotemperature data are taken directly from original references and equate to maximum range of uncertainty in age and temperature (including calibration errors if provided). Shaded regions of MBT′/CBT and TEX$_{86}$ data correspond to calibration error of these estimates. All MBT′/CBT paleotemperatures are calculated using calibration equations of Peterse et al. (2012). All data have been compiled based on stratigraphic ages provided in original references, tied here to time scale of Gradstein et al. (2012). La Meseta Formation "TELM" ages are from Ivany et al. (2008). Precise age of La Meseta Formation is debated (see main text for discussion). Paleotemperature data of Kennedy (2003) from three separate study sites have been averaged to a single point owing to high uncertainties in age. EECO—Early Eocene Climatic Optimum; PETM—Paleocene–Eocene Thermal Maximum; K-Pg—Cretaceous-Paleogene; temp.—temperate; foram.—foraminifera; Austr. —Australia; L.—Late; E.—Early; M.—Middle; Cretac.—Cretaceous; Pal./Paleo.—Paleogene; Maastricht.—Maastrichtian; Selan.—Selandian; Thanet.—Thanetian; IODP—Integrated Ocean Drilling Program. Climate subdivisions from Hollis et al. (2012).

as contemporaneous with episodes of enhanced Deccan Trap volcanism (Tobin et al., 2012; Fig. 3). Coeval terrestrial palynomorph data from Seymour Island similarly support a short interval of warming immediately prior to the K-Pg boundary (Bowman et al., 2013). This warming was likely a global phenomenon based on evidence from other widely distributed terrestrial and marine records (Wilf et al., 2003, and references therein). Within our Seymour Island MBT′/CBT data we note an increase in paleotemperatures leading up to the Cretaceous-Paleogene boundary broadly coeval with the warming recognized by Tobin et al. (2012) and Bowman et al. (2013) (Fig. 2). However, the resolution afforded by the data, limited primarily by the calibration uncertainty of the MBT′/CBT–derived estimates, does not allow us to unambiguously reconcile our data with these other records. Indeed, the precise magnitude of the temperature change noted by Wilf et al. (2003) and Tobin et al. (2012) is likely to be between 3 °C and 7 °C; i.e., potentially within the calibration uncertainty of the MBT′/CBT method (Peterse et al., 2012). Regardless of the precise pattern of continental climate change through the K-Pg of Seymour Island, our data support the suggestion that climate was relatively stable, and, in line with the findings of Wilf et al. (2003), refutes previous assertions that the earliest Paleocene was marked by major warming of ~10 °C (Wolf, 1990).

Our new data add important detail to an emerging picture of climatic evolution through the Late Cretaceous and early Paleogene of the circum-Antarctic region, summarized in Figure 3. Within this broader context, we note that the cool temperate paleotemperatures we deduce for the Antarctic Peninsula region in the Paleocene are consistent with paleofloral and MBT′/CBT–derived estimates from New Zealand (Kennedy, 2003; Pancost et al., 2013; Fig. 3). These continental paleotemperatures are also largely within error of coeval SST estimates from the surrounding southwest Pacific (Bijl et al., 2009; Hollis et al., 2012; Fig. 3). A pronounced warming in the southwest Pacific occurs through the latest Paleocene and early Eocene, culminating in the Early Eocene Climatic Optimum (EECO) (Bijl et al., 2009; Hollis et al., 2012; Fig. 3). This climatic optimum is also ostensibly apparent in continental paleotemperature proxies from the surrounding region, specifically southern Australia (Greenwood et al., 2003; Carpenter et al., 2012), New Zealand (Pancost et al., 2013), and East Antarctica (Integrated Ocean Drilling Program Site U1356; Pross et al., 2012; Fig. 1) (Fig. 3). The large uncertainties in paleotemperature estimates derived from these continental proxies undoubtedly temper the clarity of this observation, but the pattern of a relatively cool Maastrichtian–Paleocene followed by a warmer early Eocene would be reasonably predicted for Antarctica based on a benthic δ^{18}O compilation (Cramer et al., 2009; Hollis et al., 2012; Fig. 3). It is conspicuous that paleotemperatures determined from the Eocene La Meseta Formation of Seymour Island do not appear to show the same trend and are indistinguishable from the paleotemperatures proposed for the Maastrichtian–Paleocene (Greenwood and Wing, 1995; Poole et al., 2005; Ivany et al., 2008; Fig. 3). In part, this observation may stem from uncertainties in the choice of the correct δ^{18}O$_{seawater}$ value in the calibration of molluscan δ^{18}O SST data (Ivany et al., 2008). Equally, there is debate regarding the exact Eocene age of the La Meseta Formation (Ivany et al., 2008; Pross et al., 2012). Nevertheless, in line with the observations of Carpenter et al. (2012), the reconstructed SSTs for the La Meseta Formation are ~10 °C cooler than coeval SSTs from any portion of the early or middle Eocene at Ocean Drilling Program (ODP) Site 1172—positioned at the same paleolatitude as Seymour Island in the southwest Pacific (~65°S; Bijl et al., 2009; Fig. 3). The Maastrichtian–Eocene paleotemperature record from Seymour Island thus emphasizes that long-term climate variability in the Antarctic Peninsula region was muted relative to other parts of the circum-Antarctic, which has been ascribed to the effects of the proto-Leeuwin and proto–east Australian currents delivering relatively warmer surface flow to the southern Australian–East Antarctic and southwest Pacific regions respectively (see for example Huber et al., 2004; Carpenter et al., 2012; Hollis et al., 2012; Pross et al., 2012; Fig. 1).

CONCLUSIONS

Our data provide the first geochemically quantified, high-resolution estimates of Antarctic continental temperatures during the Maastrichtian and Paleocene. As such, they help elucidate the climatic history of the continent and place into context the regional and temporal changes in climate that occurred through this key interval of Earth history. Our brGDGT-based paleotemperature estimates indicate that a predominantly cool temperate climate prevailed during the late Maastrichtian and Paleocene on the Antarctic Peninsula. This finding is in close agreement with sparse paleofloral constraints on Antarctic climate for this interval. Our work also exemplifies the potentially dynamic nature of early Paleogene climate evolution in the southern high latitudes.

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