Organic Geochemistry 118 (2018) 4–14

Contents lists available at ScienceDirect

Organic Geochemistry

journal homepage: www.elsevier.com/locate/orggeochem

The last forests on Antarctica: Reconstructing flora and temperature from the Neogene Sirius Group, Transantarctic Mountains

Rhian L. Rees-Owen[a,b,*], Fiona L. Gill[a], Robert J. Newton[a], Ruza F. Ivanović[a], Jane E. Francis[c], James B. Riding[d], Christopher H. Vane[d], Raquel A. Lopes dos Santos[d]

[a] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK
[b] School of Earth and Environmental Sciences, University of St Andrews, St Andrews KY16 9AL, UK
[c] British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK
[d] British Geological Survey, Environmental Science Centre, Keyworth, Nottingham NG12 5GG, UK

ARTICLE INFO

Article history:
Received 4 April 2017
Received in revised form 2 November 2017
Accepted 5 January 2018
Available online 12 January 2018

Keywords:
Antarctica
Neogene
Sirius Group
Terpenoids GDGT
Palaeovegetation
Palaeotemperature
Palaeoenvironment

ABSTRACT

Fossil-bearing deposits in the Transantarctic Mountains, Antarctica indicate that, despite the cold nature of the continent's climate, a tundra ecosystem grew during periods of ice sheet retreat in the mid to late Neogene (17–2.5 Ma), 480 km from the South Pole. To date, palaeotemperature reconstruction has been based only on biological ranges, thereby calling for a geochemical approach to understanding continental climate and environment. There is contradictory evidence in the fossil record as to whether this flora was mixed angiosperm-conifer vegetation, or whether by this point conifers had disappeared from the continent. In order to address these questions, we have analysed, for the first time in sediments of this age, plant and bacterial biomarkers in terrestrial sediments from the Transantarctic Mountains to reconstruct past temperature and vegetation during a period of East Antarctic Ice Sheet retreat. From tetraether lipids (MBT′/CBT palaeothermometer), we conclude that the mean continental summer temperature was ca. 5 °C, in agreement with previous reconstructions. This was warm enough to have allowed woody vegetation to survive and reproduce even during the austral winter. Biomarkers from vascular plants indicate a low diversity and spatially variable flora consisting of higher plants, moss and algal mats growing in microenvironments in a glacial outwash system. Abietane-type compounds were abundant in some samples, indicating that conifers, most likely Podocarpaceae, grew on the Antarctic continent well into the Neogene. This is supported by the palynological record, but not the macrofossil record for the continent, and has implications for the evolution of vegetation on Antarctica.

1. Introduction

Since the first appearance of angiosperms on Antarctica in the Cretaceous more than 100 million years ago (Ma), Antarctic vegetation has undergone a significant secular change from a diverse fern-conifer dominated ecosystem, to a podocarp-southern beech temperate rainforest during the Late Cretaceous, to a low diversity tundra flora dominated by angiosperms in the Neogene (Dettmann and Thomson, 1987; Francis et al., 2008; Bowman et al., 2014). The trend correlates broadly with long term cooling seen from the mid-Eocene and the expansion of the Antarctic Ice Sheet (Zachos et al., 2008).

Generally, the mid- to late-Neogene Period (17–2.5 Ma) was characterised by an atmospheric CO_2 level similar to or lower than present, and warmer and fluctuating temperature values relative to today (Beerling and Royer, 2011). The interval is of particular interest in Antarctic science because of the complexity of both cryosphere and biosphere dynamics in the region (e.g. Lewis et al., 2008; Cook et al., 2013; Pollard et al., 2015). The scarcity of Neogene terrestrial deposits on Antarctica makes reconstructing vegetation difficult. However, it appears that an extensive, low diversity mosaic tundra vegetation existed over a wide geographical range throughout the Oligocene to the mid Miocene (24–14 Ma; Hill, 1989; Raine, 1998; Askin and Raine, 2000; Prebble et al., 2006) and survived multiple episodes of glacial advance and retreat (Ashworth et al., 2007). Questions remain over both the timing of the disappearance of this tundra vegetation and its composition. In the McMurdo Dry Valleys at least, woody vegetation appears to have been rendered extinct by the expansion of

* Corresponding author at: School of Earth and Environment Sciences, University of St Andrews, St Andrews, KY16 9AL, UK.
E-mail address: rlro@st-andrews.ac.uk (R.L. Rees-Owen).

https://doi.org/10.1016/j.orggeochem.2018.01.001
0146-6380/© 2018 The Authors. Published by Elsevier Ltd.

the East Antarctic Ice Sheet around 13.8 Ma (Lewis et al., 2007, 2008). However, palynological data from Deep Sea Drilling Project (DSDP) Site 274 in the Ross Sea suggests that southern beech trees (*Nothofagus*) were present into the Pliocene (5–2.5 Ma; Fleming and Barron, 1996). The macrofossil record indicates that Antarctic flora was dominated by *Nothofagus* at that time. Nevertheless, some pollen records suggest that conifers existed on Antarctica until at least until ca. 15 Ma (Warny et al., 2009).

The Sirius Group in the Transantarctic Mountains has played a key role in the reconstruction of the Neogene flora of Antarctica. Fossil discoveries from Oliver Bluffs (Fig. 1; 85°S, 166°E; Francis and Hill, 1996; Hill et al., 1996) are some of the most important palaeobotanical discoveries on the continent in recent years. The age of these deposits has been the subject of a contentious debate (Barrett, 2013). The plant fossils have been biostratigraphically dated by close association with late Pliocene marine diatoms (Harwood, 1986; Webb et al., 1984), thought to indicate the incursion of seaways deep into the Antarctic interior. This relatively young age has been challenged by multiple studies that suggest the diatoms represent wind-blown contamination from the open ocean much further away (Burckle and Potter, 1996; Stroeven et al., 1996). Additionally, cosmogenic exposure dating suggests these sediments are much older (at least 5 Ma, but possibly as old as 17 Ma; Ackert and Kurz, 2004); further details of this ongoing debate are given by Barrett (2013). Nevertheless, it is clear that the deposits represent a period of late Neogene Antarctic deglaciation, where the East Antarctic Ice Sheet had retreated far enough to allow tundra shrubs to grow 480 km from the South Pole. Not only do these sediments provide rare data on the evolution of vegetation on the Antarctic continent during the Neogene, but also insight into the Antarctic terrestrial climate during a warmer world.

The macrofossil and palynomorph record at Oliver Bluffs represent a low diversity angiosperm flora, including exceptionally preserved leaves and wood of *Nothofagus* (Carlquist, 1987; Webb and Harwood, 1987; Hill and Trustwell, 1993; Francis and Hill, 1996; Hill et al., 1996) as well as flowers, fruit, seeds and the remains of vascular plants with a cushion habit (Ashworth and Cantrill, 2004). Furthermore, at least five species of moss have been identified (Hill et al., 1996; Ashworth and Cantrill, 2004). There is no macrofossil record of coniferous plants at Oliver Bluffs, but rare bisaccate pollen grains suggest their presence, perhaps as *Podocarpidites* (Askin and Markgraf, 1986; Askin and Raine, 2000). The question of whether there were conifers in the interior of Antarctica has not been unequivocally answered. Resolving the issue would greatly enhance our understanding of Antarctic floral evolution.

Biomarkers from plants provide valuable information on terrestrial environments and climate. Those from vascular higher plants can reconstruct past floras and depositional environments. Some, such as aliphatic lipids (e.g. *n*-alkanes, *n*-alkanols) are non-specific, whereas others, particularly of the terpenoid family, provide valuable chemotaxonomic information (e.g. Otto and Wilde, 2001). For example, tricyclic diterpenoids (e.g. abietanes) are characteristically produced by conifers, whilst non-steroidal pentacyclic triterpenoids (e.g. oleanane-type compounds) are specific to angiosperms (Otto and Simoneit, 2001; Otto et al., 2005). Using a biomarker approach to understand vegetation gives additional insight into past floral change, because preservation biases in the macro- and microfossil record differ from those in the biomarker record (Diefendorf et al., 2014).

The fossil discoveries at Oliver Bluffs are thought to represent warm interglacials that allowed the flora to be briefly re-established from coastal refugia (Askin and Markgraf, 1986). Temperature values for these warm periods have been reconstructed from analysis of the biological limits of fossil plants, weevils and freshwater molluscs found at Oliver Bluffs, suggesting values significantly higher than the modern ones, i.e. 5 °C during the summer vs. ca. −26 °C for the present day (Francis and Hill, 1996; Ashworth and Kuschel, 2003; Ashworth and Preece, 2003). The distribution of branched glycerol dialkyl glycerol tetraethers (brGDGTs), a suite of bacterial membrane lipids, can be used to empirically reconstruct soil pH and continental temperature (using the so-called MBT′/CBT palaeothermometer; Weijers et al., 2007; Peterse et al., 2012). No geochemical thermometers have been applied to terrestrial Antarctic deposits during this interval.

This study describes the first biogeochemical study of the Sirius Group at Oliver Bluffs. The use of a geochemical thermometer adds an additional and robust dimension to our understanding of continental temperature during Southern Hemisphere deglaciations.

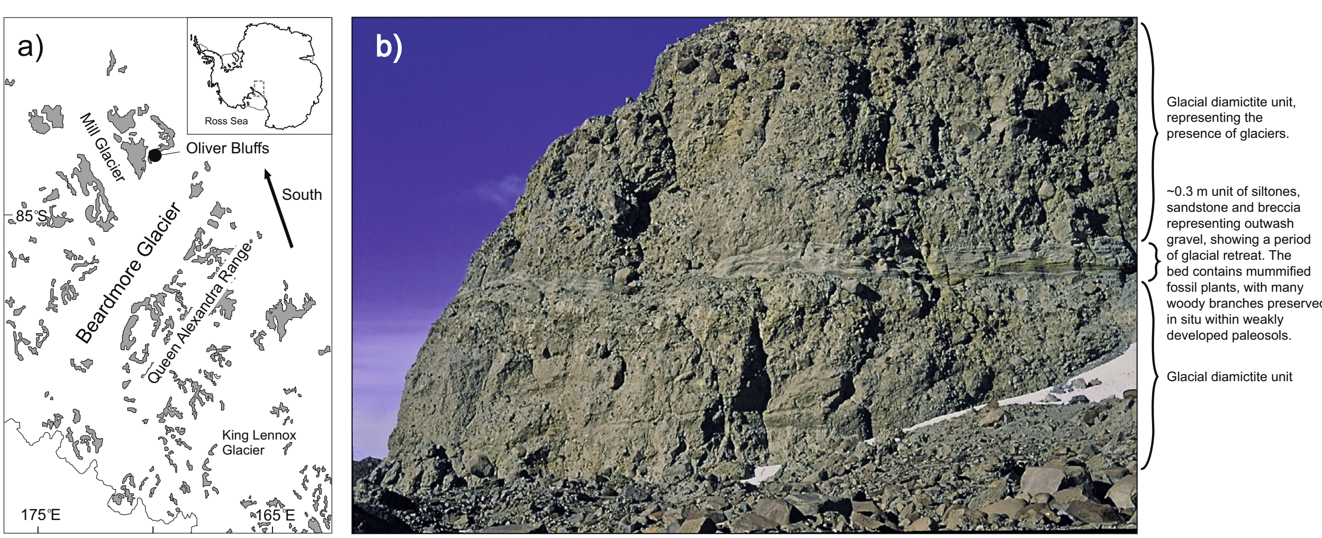

Fig. 1. (A) Map of Beardmore glacier region with Oliver Bluffs marked. Grey areas denote outcrops and white areas ice-covered land and the Ross Ice Shelf. (B) Geological section at Oliver Bluffs, Dominion Range. The bluff in the picture consists of thick units of glacial diamictite, representing times when glaciers were present in the region. Interbedded between the diamictites is a layer up to 0.3 m thick of siltstones, sandstones and breccias, representing an interval of glacial retreat during which immature soils developed on the land surface, intermittently covered by outwash gravels. Small dwarf shrubs of southern beech and other plants grew in the soils, now preserved as mummified fossil plants within weakly developed palaeosols.