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An early–middle Eocene Antarctic summer monsoon: Evidence of ‘fossil climates’

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ABSTRACT

A warmer and mostly ice-free South polar region prevailed during the early–middle Eocene, indicative of a low latitudinal temperature gradient. Climatic models mostly fail to reconstruct such a low gradient, demonstrating our poor understanding of the mechanisms involved in heat transfer. Here we describe a new phenomenon that shaped the southern high latitude climate during the early–middle Eocene: the Antarctic summer monsoon. Our palaeoclimatic reconstruction is based on 25 morphotypes of fossil dicotyledonous leaves from the early–middle Eocene fossil leaf assemblage of Fossil Hill from King George Island, the Antarctic Peninsula. We use a novel CLAMP (Climate Leaf Analysis Multivariate Program) calibration which includes new climatic parameters that allow us to characterise better the seasonality in precipitation. Our reconstruction indicates a warm humid temperate climate with strong seasonality in temperature and precipitation. Seasonality in precipitation indicates a rainfall rate of 6.4 ± 1.30 mm/day during summer (summer daily rate of precipitation; SDR) and a summer precipitation representing more than 60.3 ± 8.28% of annual rainfall (ratio of summer precipitation; RSP), which fulfils the definition of a summer monsoon in the modern world. This implies a seasonal alternation of high- and low-pressure systems over Antarctica during the early–middle Eocene. Such a climate regime would have impacted upon global atmospheric circulation and heat transfer. This climatic regime presents a challenge for climatic models and their ability to reconstruct accurately palaeoclimates at high southern latitudes and thereby understand latitudinal heat transfer in a ‘greenhouse Earth’ regime.

1. Introduction

The presence of Cenozoic floras in Antarctica has been known for a long time since the work by Dusén (1908) in the early twentieth century. They are mostly from the Antarctic Peninsula and neighbouring islands, including Seymour Island, Alexander Island and King George Island, which have yielded many fossil sites (Dusén, 1908; Barton, 1964; Orlando, 1964; Thomson and Burn, 1977; Case, 1988; Askin, 1989; Birkenmajer and Zastawniak, 1989; Li, 1994; Doktor et al., 1996; Gandolfo et al., 1998; Poole et al., 2000, 2001, 2003, 2005; Francis and Poole, 2002; Hunt and Poole, 2003; Cantrill and Poole, 2005; Poole and Cantrill, 2006; Francis et al., 2008a). The fossil record of the Antarctic Peninsula is represented mostly by its wood (Poole and Cantrill, 2006); other organs: leaves, palynomorphs, seeds and fruits, flowers, however, have also been discovered and reported.

The Antarctica Peninsula was a continental-margin magmatic arc during the Mesozoic and early Cenozoic (Storey and Garrett, 1985). Palaeogene deposits of King George Island are therefore typically those associated with an active volcanism of a mixed-effusive type (Smellie et al., 1984; Shen, 1994; Xue et al., 1996; Dutra and Batten, 2000). Antarctica was already at a high latitude during the Palaeogene, slightly higher than 60°S (Lawver et al., 1992; Wilford and Brown, 1994; Lawver and Gahagan, 2003).

In this study, we focus on the Eocene climate of this marginal region of Antarctica. The palaeoclimate of the early–middle Eocene Fossil Hill flora from the King George Island is reconstructed quantitatively using physiognomic methods. In the studied flora more than 40 leaf morphotypes have already been described, belonging to pteridophytes, gymnosperms and angiosperms (Li, 1994; Zhou and Li, 1994a, 1994b; Li and Zhou, 2007). Many morphotypes were only attributed to dicots without further resolution of affinities (some of them may represent extinct groups). Nothofagaceous leaves are dominant (Li, 1992). Most of the morphotypes show affinities with the neotropics and the southern part of South America (Li, 1992, 1994).

This vegetation, coupled with volcanic activity, is typical of a Valdivian environment now found in southern Chile (Poole et al., 2001, 2003). The vegetation mostly consists of Myrtaceae, Araliaceae, Podocarpaceae, and Cupressaceae, along with the Nothofagaceae. The Valdivian vegetation is characterised by catastrophic events which allow it to be maintained (Veblen and Ashton, 1978; Veblen et al., 1980). On King George Island during the Eocene, volcanism induced

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this disturbance (Poole et al., 2001, 2003). Because the diversity of the Fossil Hill Flora assemblage is quite high, it is unlikely to represent early pioneering stages but was probably derived from mature vegetation typical of later serial stages (Poole et al., 2001).

The presence of plant fossils in this now snow world is enough to demonstrate that the climate was warmer in the Eocene and widely distributed data show that globally this was a time of marked warmth (Zachos et al., 2001). Faunal (Reguero et al., 2002) and sedimentary (Dingle and Lavelle, 2000) proxy data also indicate a temperate climate for the Antarctic Peninsula during the early–middle Eocene. The middle Eocene palaeoclimate of King George Island has been reconstructed at several locations based either on wood or leaf fossils indicating a warm temperate climate with high precipitation (Birkenmajer and Zastawniak, 1989; Hunt and Poole, 2003; Poole et al., 2005; Francis et al., 2008b; Reguero and Marenssi, 2010; Table 1). In this 'greenhouse world', climatic conditions at high latitudes were markedly warmer than they are today and point to distinctive climatic heat transfer mechanisms compared to today and is suggestive of a weak meridional gradient (Korty et al., 2008). Climatic models mostly fail to reconstruct such a low gradient, demonstrating our poor understanding of the mechanisms involved in heat transfer (Korty et al., 2008). The general discrepancy between models and proxies for this geological time, and generally for periods with greenhouse climates (Korty et al., 2008), requires new mechanisms to explain heat transfer between low and high latitudes. Detailed reconstructions are needed to discuss the climatic mechanisms.

In this study, we have three aims: to develop a new method to reconstruct the seasonality in precipitation; to reconstruct the palaeoclimate of the Fossil Hill flora; and to describe possible climatic mechanisms at high latitudes during a 'greenhouse Earth' regime.

2. Material and methods

2.1. Fossil locality

The plant fossils studied here were collected from the Fossil Hill Formation of Fossil Hill (62°12′S, 58°57′W), the Fildes Peninsula, southernmost part of King George Island (Fig. 1; Li, 1994), during two Chinese expeditions to Antarctica. The Fossil Hill Formation was dated to early–middle Eocene (52 ± 1–43 ± 2 Ma) based on K/Ar and Rb/Sr isotopic dating (Li et al., 1989). Some radiometric dates from King George Island are controversial (Hunt and Poole, 2003). However, the composition of the flora is indicative of a Palaeogene age (Torres, 2003) and thus consistent with the radiometric age.

2.2. Fossil assemblage

The Fossil Hill flora consists of 25 morphotypes of dicotyledonous leaves (Fig. 2) that are complete enough for CLAMP study. Twenty species are already published (Li, 1994; Li and Zhou, 2007); five morphotypes are still unpublished. Nothofagaceae are dominant in the vegetation with six species represented: *Nothofagus oligophlebia* Li, 1994, *Nothofagofolia zastawniakiae* (Dutra) Li and Zhou, 2007, *N. carpinoides* Li and Zhou, 2007, *N. betulifolia* (Dutra) Li and Zhou, 2007, *N. multinervis* Li and Zhou, 2007, and *N.* sp. Other species are: *Lomatia mirabilis* (Dusén) Li, 1994, *Pentaneurum dusenii* (Zastawniak) Li, 1994, *Oreopanax guinazui* Berry 1938, *Rhoophyllum nordenskjoeldi* Dusén 1899, and *Myrtiphyllum bagnalense* Dusén 1899. Several morphotypes have less clear affinities, *Dicotylophyllum latitrilobatum* Zastawniak 1989, *D. elegans* Li, 1994, *D.* sp. 1, *D.* sp. 2, *D.* sp. 3, *D.* sp. 4, *D.* sp. 5, *D.* sp. 6, *D.* sp. 9, and *D.* sp. 10 (Li, 1994). All fossil species are kept in Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences.

Table 1
Comparison of Fossil Hill with other floras. MAT, mean annual temperature; MAP, mean annual precipitation; GSP, growing season precipitation; LMA, leaf margin analysis; CLAMP, climate leaf analysis multivariate program; WP, wood physiognomy. Data from Poole et al. (2005), except * from this study.

Parameter	Method	Dragon Glacier	Fossil Hill	James Ross Basin
MAT (°C)	LMA	10.5	8.8	
	CLAMP	10.6	11.5*	
	WP		11.7	10.9
MAP (mm)	LMA	1039	1059	
	WP		3707	3889
GSP (mm)	CLAMP	885	1259.3*	

2.3. Palaeoclimate reconstruction

Two methods based on fossil leaves can be applied to reconstruct comprehensive palaeoclimate: Nearest Living Relative (NLR)-based techniques and physiognomic techniques. Antarctic Palaeogene floras belong to the 'palaeoflora mixta' that group plants with NLR growing under different climate of Southern hemisphere, temperate and tropical conditions (Romero, 1978). Therefore, the NLR-based techniques, like the coexistence approach (CoA) (Mosbrugger and Utescher, 1997), cannot be applied. Among the physiognomic techniques, CLAMP (Climate Leaf Analysis Multivariate Program; Wolfe, 1993) gives the most comprehensive climate reconstructions (Kennedy et al., 2002). In its most widely used form CLAMP links 31 physiognomic characters from leaves of woody dicots with 11 climatic parameters and is calibrated on modern floras (Wolfe, 1993; Spicer, 2000).

Although the standard CLAMP analysis indicates seasonality of precipitation, it does not reveal whether the wet season occurs in winter or in summer. The Eocene climate of Antarctica exhibited high seasonality as indicated by sedimentology (Dingle and Lavelle, 2000) and by palaeobotany (Poole et al., 2005). To characterise better seasonality of precipitation we established a new CLAMP calibration by including new climatic parameters: the summer daily rate of precipitation and the summer ratio of precipitation to that of the whole year. The summer is defined as including 5 months: MJJAS for the northern hemisphere and NDJFM for the southern hemisphere (Zhang and Wang, 2008). In our calibration we include 10 climatic parameters: MAT (mean annual temperature), WMMT (warm month mean temperature), CMMT (cold month mean temperature), LGS (length of the growing season), GSP (growing season precipitation), MMGSP (mean monthly growing season precipitation), 3-WET (precipitation during the three wettest months), 3-DRY (precipitation during the three driest months), SDR (summer daily rate of precipitation), and RSP (ratio of summer precipitation). We used a calibration primarily based on the PhysgAsia1 dataset (Jacques et al., 2011). However, we used a different source for meteorological data: primary monthly precipitation data and monthly temperatures for all modern sites were extracted from a global gridded dataset (Hijmans et al., 2005). This was done using the geographical information system software ArcGis 9.3. The gridded meteorological maps have a resolution of 30-arc-seconds and are freely available online (www.worldclim.org). Temperatures were corrected using a global average altitudinal cooling rate (0.5 °C/100 m). The different climatic parameters used in this calibration were then calculated from these primary parameters. Specific humidity, relative humidity and enthalpy are other parameters often used in CLAMP calibrations. However, as they are not included in the global dataset we used, we did not include them in this calibration. This meteorological calibration file is called GRIDMetMonsoon1.

Analyses were carried out using Canonical Correspondence Analysis (CANOCO v.4.0). Regression equations for the CLAMP vector scores against the observed climate parameters were calculated in Axes 1–4 space using SPSS 17.0.

One analysis was carried out using PhysgAsia1 and GRIDMetAsia1, the original gridded meteorological dataset for PhysgAsia1 (Jacques et al., 2011), for comparison with the new calibration.

All modern sites were used as active for the calibration and the analysis; the Fossil Hill flora was included as passive in the analysis.