EARLY TERTIARY PALAEOCLIMATE OF KING GEORGE ISLAND, ANTARCTICA—EVIDENCE FROM THE FOSSIL HILL FLORA

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Abstract: The Fossil Hill flora from Fildes Peninsula on King George Island, Antarctica, consists of more than 40 forms of ferns, gymnosperms and angiosperms. It contains a mixture of neotropical and subantarctic elements, mostly resembling the Early Tertiary palaeoflora of southern South America. According to “the nearest living relative method” and “leaf physiognomical analysis”, the plants of the Fossil Hill flora probably grew under a kind of temperate to warm temperate climatic conditions. The mean annual temperature was probably a little more than 10°C; the mean annual range of temperature could be low; and the precipitation was abundant. The area where the plants of the Fossil Hill flora were growing was at rather low altitude. In order to determine the cause of the warm and humid climate at the time the author proposes the following hypothesis. During the Cretaceous and early-middle Palaeogene, Antarctica, Australia and South America as parts of Gondwana formed a nearly continuous landmass along the southern margin of the ancient Pacific Ocean, its southern part being effectively separated from other oceans and continents at that time. Thus it is reasonable to assume that a warm oceanic current flowing polewards from the equator transported huge quantities of heat to Gondwana and provided the above-mentioned climatic conditions for plant growth at least in those areas at rather low altitudes along the southern margin of the ancient Pacific Ocean.

Key words: palaeoclimate, Early Tertiary, King George Island, plant fossils, oceanic circulation

Introduction

At present Antarctica is a vast continent—a world of ice and snow, surrounded on all sides by seas and oceans, 98% of its land is covered by ice with an average thickness of 2450 m, but up to 4750 m in places. Air temperatures range from a little higher than freezing to ca. –30°C in summer and from –20°C to –65°C in winter, the lowest temperature recorded so far being –89.6°C. Under these extreme conditions, there are only two species of flowering plants to be found in the Antarctic Peninsula: Deschampsia antarctica (Poaceae) and Colobanthus quitensis (Caryophyllaceae), the remaining plants being cryptogams, including mosses and lichens. However, according to available palaeobotanical evidence, both vegetation and climate in this continent during the period of the Cretaceous and the Early Tertiary were widely different from what they are today.

The present author made a detailed study of the fossil plants (called the Fossil Hill flora) collected from Fossil Hill, 1.5 km northwest of Great Wall Station on Fildes Peninsula, King George Island by the 2nd to the 4th Chinese Antarctic Expeditions in 1986–1988. This flora consists of at least 40 forms belonging to 16 genera and 14 families, of which 4 genera, 6 species and 2 indeterminate forms are pteridophytes, namely Osmunda sp., Gleichenia sp., Thysanopteris shenii Zhou et Li sp. nov., Alsophila antarctica Dusén, and two indet. fertile and sterile pinnules (Zhou and Li, in press a; Dusén, 1908; Berry, 1928; Tryon and Tryon, 1982; Czajkowski and Rössler, 1986); gymnosperms totalling 5 genera and 11 species: Dion antarctica Zhou sp. nov., Araucaria sp., Podocarpus (Dacrycarpus) (tertiarius) (Berry) Florin, Podocarpus (Stachycarpus) sp. 1, Podocarpus (Podocarpus) sp. 2, Podocarpus (Podocarpus) sp. 3, Podocarpus (Podocarpus) sp. 4, Acrogyne antarctica Florin, Papuacedrus shenii Zhou sp. nov. (Zhou and Li, in press b; Dusén, 1899, 1908; Berry, 1928, 1938; Florin, 1940a, b; Orlando, 1964; De Luca and Sabato, 1979; De Luca et al., 1982; Zastawniak, 1981; Zastawniak et al., 1985; Czajkowski and Rössler, 1986; Hill and Carpenter, 1989); angiosperms totalling 7 genera and 23 species: Nothofagus subferruginea (Dusén) Tanai, Nothofagus oligophlebia Li sp. nov., Nothofagus sp., Lonatia sp., Pentaneurum dusenii (Zastawniak) Li gen. et comb. nov., ?Myrtyphillum bagnalense Dusén, Rhoophyllum nordenskjoeldii Dusén, ?Oreopanax guinazui Berry, Dickytophyllum elegans Li sp. nov., Dickytophyllum latitruitubatum Zastawniak, Dickytophyllum sp. 1–10 (Li, in press; Dusén, 1899, 1908; Berry, 1925, 1928, 1938; Barton, 1964; Orlando, 1964; Czajkowski and Rössler, 1986; Tanai, 1986; Birkenmajer and Zastawniak, 1986, 1989a, b). Most of the nearest living species (or genera) of the above-mentioned fossil plants are mainly distributed in tropical Latin America and southern part of South America, corresponding to Good’s (1953) Neotropical and Antarctic Kingdoms respectively. In the present author’s opinion, the latter should be renamed the Sub-Antarctic Kingdom (Li, in press). So the Fossil Hill flora appears to have been a mixed plant assemblage composed of neotropical elements and subantarctic ones, having a close affinity to those Tertiary floras in South America and the Antarctic Peninsula (Dusén, 1899, 1908; Berry, 1938; Birkenmajer and Zastawniak, 1986). Having compared the South America floras with those from West Antarctica the present author is inclined to believe that the geological age of the Fossil Hill flora is referable to the Early Tertiary, most probably to the early to middle Eocene, a conclusion which

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is in accordance with that of Li, Z. N. et al. (1989), who determined the isotopic age of the Fossil Hill Formation and the Block Hill Formation as $52 \pm 1$ Ma – $43 \pm 2$ Ma.

**Palaeoclimatic Analysis**

Since climate is a major factor governing the distribution of vegetation, plant fossils are considered as a direct and convincing line of evidence for establishing the climate in the geological past. In order to establish the palaeoclimate, palaeobotanists usually use two different methods. One is to make a comprehensive analysis of the climatic tolerances of those extant representatives having the closest affinity to each fossil taxon (nearest living relative method) and the second (leaf physiognomy method) uses leaf size and leaf margin types as a means of determining the palaeoclimate. Wolfe (1979, p. 1) argued for the latter method as follows: “Environmental factors are continually affecting lineages to select individuals and populations that are physiognomically best adapted to that particular environment.” “Physiognomically similar forest types typically do appear in widely separated areas that have similar major climatic parameters irrespective of the lineages involved.”

In this paper both methods are adopted to analyse the Fossil Hill flora. It was found by applying the first method that the nearest living relatives (species or genera) of pteridophytes and gymnosperms in the Fossil Hill flora are largely distributed in the low and middle latitudes of the Southern Hemisphere. For example the nearest living species to *Thysanopteri shenii* is a relict form, *Thysanopteri elegans* which is only found on the Juan Fernandez Islands (ca. 33°3S, 80°W) in the southeast Pacific Ocean, i.e. in the neotropical plant region. However, representatives of this genus had a worldwide distribution in the geological past. The records of the meteorological station on Robinson Crucoe Island (33°37'S, 78°52'W), one of the Juan Fernandez Islands, show that the annual mean temperature is 16°C, with a mean temperature for the warmest month of 19°C, and a mean temperature for the coldest month of 12°C (Table 1). The representatives of *Nothofagus*, a dominant genus of angiosperms both in number of species and specimens in the Fossil Hill flora, have their nearest living relatives in the southern part of South America and New Zealand, being major members of temperate rainforests in these regions. It is worth noting that the fossil leaves of *Nothofagus* are much bigger in size than those of their living relatives, which shows that the climatic conditions at that time were somewhat warmer and more humid. Other common forms among the fossil angiosperms are *Pentaneurum dusenii* and *Lomatia* sp. the former belonging to the Melastomataceae, with tropical South America as its present-day centre of distribution, whereas the latter is very similar to an extant species being distributed in Chile. It may be assumed from the distribution of these nearest living species, especially from the meteorological data in the region where the genus *Thysanopteris* occurs, that these plants once lived in a warm temperate rainforest, with a rather low mean annual range of temperature but with abundant precipitation.

Statistics show that the leaf physiognomy has a close relation with the prevailing climatic conditions (Wolfe, 1979). The most important aspects of the physiognomical features available for palaeoclimatic analysis are the leaf margin types (dentation or an entire margin). As revealed by Wolfe (1979), Wolfe and Upchurch (1987), Upchurch and Wolfe (1987), in mesic east Asian environments, the percentage of dicotyledonous species that are entire-margined closely parallels mean annual temperature: an increase of 3 percent entire-margined species correlates with an increase of 1°C in mean annual temperature, i.e. a leaf margin percentage of about 60% approximates the 20°C isotherm. Since the modern vegetation of the Southern Hemisphere has higher percentages of entire-margined species than that of the Northern Hemisphere, the relation appears to be about 4%/1°C (Wolfe, 1979). In the Fossil Hill flora, entire-margined leaves amounted to 40%. This suggests that the flora existed at a mean annual temperature of about 10°C, or higher, considering the above-mentioned results of the nearest living relative analysis.

Of the non-deciduous species from the Fossil Hill flora, small-sized leaves are common. This may reflect the high-latitudeal zone in which the plants were growing (Smith and Briden, 1977), the consequent lower temperatures in summer, and the very small amount of sunlight in winter.

The main conclusions from these palaeobotanical studies are: (1) in the early-middle Palaeogene, a temperate to warm-temperate rainforest had developed in the Fossil Hill region of King George Island; (2) these forests were dominated by *Nothofagus, Podocarpus, Araucaria* and *Papuaecrus*, with an undergrowth consisting of *Thysanopteris*, a kind of tree fern, the cycad *Dion* etc.; (3) a mean annual temperature slightly higher than 10°C, but lying at a high altitude, where the sunlight was very weak in winter, the temperature was far from high in summer, and the mean annual range of temperature was quite low while there was abundant rainfall.

**Table 1.** Data from Meteorological Station of Robinson Crusoe Island, Juan Fernandez Islands (based on “World Climatic Data”, 1972).

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$T$ = temperature; $R$ = precipitation.

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A New Explanation for the Warm Climate during Early and Middle Palaeogene

In the early-middle Palaeogene, it was relatively warm in both Antarctica and the Arctic, as evidenced by the plant and animal fossils. For example, many discoveries have been reported from north of the Arctic Circle, including amphibians, reptiles (such as crocodiles), birds, mammals as well as big trees such as Ceratophyllum, Juglans, Ginkgo, etc. (West et al., 1977; Basinger, 1989). It has further been confirmed from the data on oxygen isotopes that in early and middle Palaeogene, it was much warmer in the high and middle latitudinal areas than it is today (Shackleton, 1984). What was the reason for the occurrence of such a warm climate at that period of time in the high latitudes? Jefferson (1983) had put forward the following four points in order to explain the apparent anomaly as to why Antarctica, lying at high latitudes (65°–80°S), witnessed a warm climate from late Permian to early Palaeogene:

1) **Global warming.** As evidenced by δ¹⁸O, an increase of sea water temperature on a global scale was believed to be the principal reason.

2) **Over-reliance on uniformitarianism.** Jefferson held that it is not correct to have faith in the theory of uniformitarianism without more supporting evidence.

3) **Inaccurate palaeolatitudes.** The palaeolatitude in a specific region and at a specific geological time is determined by means of palaeomagnetic data. In the process of geological history, the palaeomagnetic pole and the palaeogeographic pole were possibly not so closely related to each other, with the latter being more closely related to the palaeoclimate.

4) **Changes in axial obliquity.** According to Williams (1972), in the Mesozoic, reduced axial obliquity of the Earth would result in small polar circles and explain the occurrence of “mid-latitude” vegetation at high latitudes. Although a slight change in the amount of inclination of the Earth’s axis has been widely accepted, such a change, either significant or gradual, has so far not been supported by astronomical theories.

The present author believes that points 1) and 3) of the above-stated explanations merit our further consideration. What is deficient about point 1) is that it fails to explain the factor(s) causing the sea water to become warmer. Point 3) has been generally recognized that there was a certain distance between the palaeomagnetic pole and the palaeogeographic pole, but how the positions of the palaeogeographic pole in different geological times should be determined remains a very difficult problem. Besides, as mentioned by Creber and Chaloner (1985), the increasing content of CO₂ in the atmosphere by the Mesozoic and Palaeogene may have been the primary cause for the warm climate at that time. It was Dorn (1989) who put forward the hypothesis of polar wandering, a hypothesis which remains to be verified.

In this paper an alternative explanation is put forward for the occurrence of a warm and humid climate in King George Island during the early and middle Palaeogene. The present author considers the chief cause for the warm climate in this area at that time to be the relative palaeoposition of some plates in the Southern Hemisphere, and a consequent southern Pacific oceanic circulation quite different to that of today. The reasoning is as follows.

It was learnt through the study of palaeomagnetism that during the period ranging from the Late Cretaceous to the early Palaeogene, Antarctica remained in the high-latitudinal zone (Smith and Briden, 1977). During the Cretaceous period, Gondwana effectively separated the South Pacific Ocean from the other oceans and continents. The South Pacific Ocean was separated from the Indian Ocean by the East Antarctic-Australian craton. There was a shelf sea connection between the southern part of South America and the Antarctic Peninsula which may have allowed only limited amount of interchange with the Atlantic Ocean. Moreover, the South Pacific Ocean at that time was only half the breadth of the present Pacific Ocean (Zinsmeister, 1982). Under these conditions, it has been suggested that the circulation of the southern Pacific Ocean resembled that of the present-day North Pacific Ocean, with a mainly counterclockwise circulation (Zinsmeister, 1982). It was under the influence of the south Circum-Pacific warm current, flowing from the equator that a warm and humid climate developed, as inferred from the plant fossils present in Gondwana or at least on its marginal zone close to the South Pacific Ocean. As pointed out by Ziegler et al. (1984, p. 4), “… at any given time, the climatic boundaries typically deviate from being parallel to latitude by 10 to 15° due to such effects as poleward transportation of warm water by western boundary current like the Gulf Stream.” The specific heat of the atmosphere accounts for only 1/3257 that of water, in other words, if the temperature of the top 1 cm of the surface water temperature dropped by 1°C, the heat released would be capable of raising the temperature of the atmosphere by 1°C to a height of about 33 m (Chen, 1979). To sum up, we maintain that it would have been feasible for a warm south-flowing oceanic current to have made the climate in the parallic area of Gondwana become warmer in the early and middle stages of the early Palaeogene than would be expected from its latitude. Moreover, if we take into account that the palaeomagnetic pole might have been at some distance from the palaeogeographic pole at that time then it becomes easy to explain why a midlatitudinal climatic environment should have existed in the high-palaeomagnetic latitude locality of King George Island during the early and middle Eocene. Palaeobotanical studies reveal that the mean annual temperature at that time was not so high; the mean annual range of temperature not so great; the mean temperature of the coldest month was not very low and that of the warmest month not so high, whereas the amount of rainfall was rather abundant, etc. All these characteristics can be considered to be the direct result of a warm oceanic current in the high latitudinal area.

By the end of the Eocene (38 Ma), following the advent of a shallow water environment between Australia and Antarctica and the initiation of the Circum-Antarctic Ocean current (Kennett et al., 1975; Shackleton and Kennett, 1975; Kemp, 1978), the Antarctic region witnessed for the first time and all of a sudden what was possibly a global climatic deterioration, caused by the changes in the entire ocean current system on the Earth’s surface. At the end of Oligocene epoch (23.5 Ma), the Drake Passage between South America and...
Antarctica came into being, known as the deep-water environment (Barker and Burrell, 1977). From then on, following the initiation of the circum-Antarctic deep water ocean current, the climate in Antarctica underwent a cooling which eventually led to the specific climatic pattern which characterizes the landmass nowadays.

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