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A 50-Million-Year-Old Fossil Forest from Strathcona Fiord, Ellesmere Island, Arctic Canada: Evidence for a Warm Polar Climate

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ABSTRACT. The remains of a fossil forest are buried within a sedimentary sequence of Eocene age (approximately 50 million years old) near Strathcona Fiord, Ellesmere Island. Large petrified tree stumps are preserved in their original growth positions in coals of the Eureka Sound Group, a sequence of sandstones, siltstones and coals deposited in a delta/floodplain environment. The dimensions of 83 stumps were recorded and their positions plotted on a plan of the exposed area of coal.

The fossil stumps are roughly conical in shape, up to 1.8 m high and with roots spreading up to 5 m in diameter. They are closely spaced on the coal, some only 1 m apart. A density of 1 stump in 27 m^2 (367 stumps·Ha^{-1}) was calculated for this forest. The stumps represent large forest trees that grew in freshwater, swampy conditions between large river channels. Their buttressed roots provided extra support in the waterlogged peats. The rivers periodically shifted their courses, flooding the forests and burying them under silts and sands.

Wide growth rings in the fossil wood, in addition to evidence from associated sediments and vertebrate faunas, indicate favourable growing conditions in a mild, cool/warm temperate climate with high rainfall. Palaeolatitude studies suggest that the forest lay close to its present high-latitude position during the Eocene. Such a forest is therefore evidence that the Eocene polar climate was much warmer than today and that the trees were able to tolerate a polar sunlight regime of continuous summer sunlight followed by months of winter darkness.

Key words: fossil forest, Tertiary, Canadian Arctic, palaeoclimate, Ellesmere Island, petrified wood, Eureka Sound Group

RÉSUMÉ. Les restes fossilisés d'une forêt sont enterrés dans une séquence stratigraphique sédimentaire datant de l'éocène supérieur, soit d'environ 50 millions d'années, près du fjord Strathcona dans l'île Ellesmere. De grosses souches d'arbres sont préservées dans leur position de croissance originale dans des charbons du groupe d'Eureka Sound, soit une séquence de grès, d'aleurolites et de charbons déposés dans un environnement deltaïque ou de terraces d'alluvions. On a relevé les dimensions de 83 souches et on a reporté leur emplacement sur un plan de la surface exposée du charbon.

Les souches fossilisées ont une forme conique grossière, avec une hauteur allant jusqu'à 1,8 m et des racines s'étalant sur jusqu'à 5 m de diamètre. Les souches sont placées très près les unes des autres sur le charbon, certaines à seulement 1 m de distance. On a calculé que la densité de cette forêt était de 1 souche par 27 m^2 (367 souches·Ha^{-1}). Les souches sont représentatives des grands arbres d'une forêt qui poussait dans des marécages d'eau douce, entre de grands bras de rivière. Les racines qui s'étayaient leur fournissaient un soutien supplémentaire dans les tourbes gorgées d'eau. Les rivières changeaient périodiquement de cours, inondant les forêts et les enterrant sous des sables et des limons.

En plus de preuves fournies par les sédiments et la faune vertébrée connexes, les grands anneaux de croissance du bois fossilisé indiquent des conditions de croissance favorables sous un climat tempéré doux, de frais à tiède, avec de fortes précipitations. Les études de paléolatitude suggèrent que, pendant l'éocène supérieur, la forêt était située à proximité de sa position actuelle à haute latitude. Une telle forêt démontre donc que le climat polaire pendant l'éocène supérieur était beaucoup plus chaud qu'aujourd'hui et que les arbres étaient capables de supporter un régime d'ensoleillement polaire avec un ensoleillement continu pendant l'été et plusieurs mois d'obscurité pendant l'hiver.

Mots clés: forêt fossilisée, tertiaire, Arctique canadien, paléoclimat, île Ellesmere, bois pétrifié, groupe d'Eureka Sound

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INTRODUCTION

Petrified and mummified remains of fossil forests are preserved within Tertiary sediments in the Canadian High Arctic and represent some of the most northerly fossil forests ever recorded (Heer, 1878; Fortier *et al.*, 1963; Christie and Rouse, 1976; Basinger, 1986/87; Francis and McMillan, 1987). The remains of fossil trees present a paradoxical contrast to the treeless arctic landscape of today, where low temperatures prohibit the growth of anything but small bushes. The middle Eocene climate was obviously much warmer than today to allow such large trees to grow. These Tertiary forests grew at very high palaeolatitudes, as high as 78°N (McKenna, 1980). How the forests tolerated the polar sunlight regime of months of winter darkness followed by continuous summer sunlight may be crucial to an understanding of the evolution of the present flora.

The remains of several forests are preserved within sediments of the Upper Cretaceous-Eocene Eureka Sound Group, a suite of non-marine and marine sandstones, siltstones, mudstones and interbedded coals. At Strathcona Fiord, the Eureka Sound Group includes sediments representative of deltaic environments, with the forests growing in swampy areas on the delta plain (Miall, 1986; Ricketts, 1986). An important feature of the Strathcona Fiord fossil forest is that the trees are preserved as upright stumps in their positions of growth, rather than as drifted logs in marine sediments, the state in which fossil wood is commonly found. Such *in situ* forests provide essential information required to reconstruct a realistic picture of the forest environment, such as the stump spacing and forest density, root dimensions and habit, and the types of trees that grew adjacent to each other. In addition, the preserved fossil soils and the surrounding sediments document the history of the forest. Growth rings in the wood provide both palaeoclimate information and the means for estimating the production rate of woody organic material in the forests, a potential source of hydrocarbons.

This paper focusses on one particular petrified forest near Strathcona Fiord, Ellesmere Island, and reports field observations and measurements taken at this site during the 1987 field season.

GEOLOGICAL SETTING

The Strathcona Fiord forest is exposed on slopes on the eastern banks of the Fossil Forest River, approximately 6 km south of the southern shores of Strathcona Fiord (latitude 78°37′N, 82°50′W) (Fig. 1). The sedimentary sequence consists of fine-grained sandstones and siltstones interbedded with coal seams containing fossil wood. The sediments form part of the Eureka Sound Group, a sequence of mainly non-marine deposits that filled the Sverdrup Basin (Ricketts, 1987). Presumably both the

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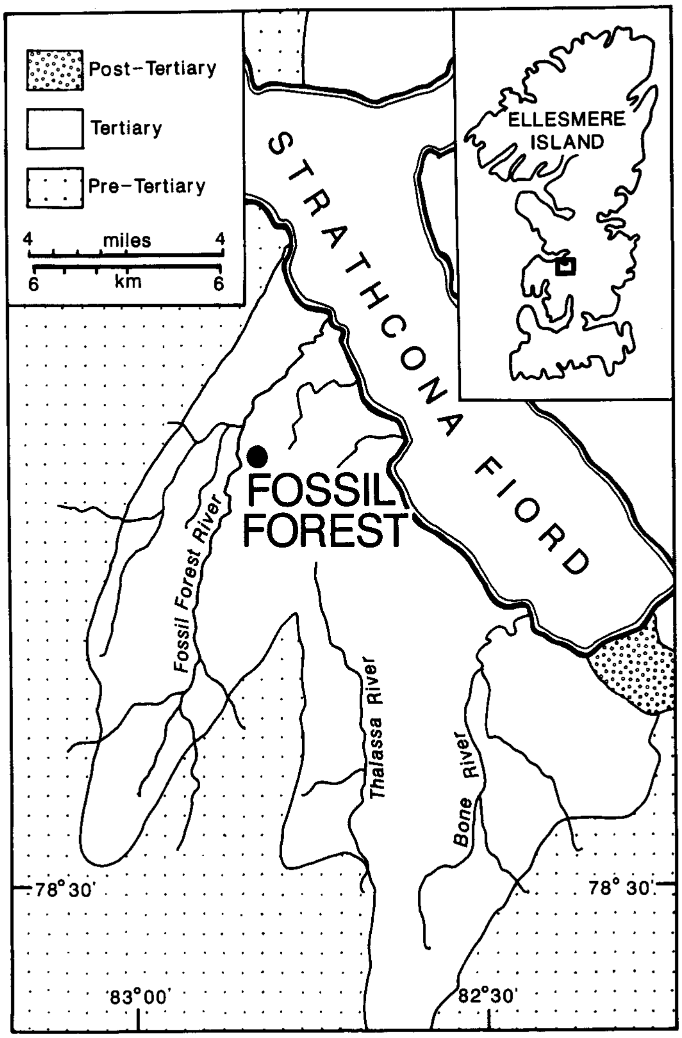

FIG. 1. Location map of the Strathcona Fiord area showing the position of the fossil forest on the banks of the Fossil Forest River. Inset shows the location of the area on Ellesmere Island. (Informal geographic names proposed by West *et al.*, 1981.)

highlands, which were the source of the clastic sediments, and the basin margins were vegetated and the plant debris then contributed to the coals, either as drifted plant matter or as *in situ* remains.

The sedimentary sequence near Strathcona Fiord was identified as Member 1V by West *et al.* (1981) and assigned to the Margaret Formation by Miall (1986). The units were considered to represent delta-front/delta-plain environments and have yielded many vertebrate fossils, including lizards, tortoises and crocodiles. These fossils have been used to date the unit as late Early Eocene to mid-Eocene, although plant fossils in the sediments are considered to be more characteristic of late Paleocene assemblages (West *et al.*, 1981). In his revision of the lithological units Ricketts (1986) included Member 1V in the Iceberg Bay Formation of Middle or Late Paleocene to Middle Eocene age.

THE PETRIFIED TREES

Petrified wood is preserved in several coal beds on the banks of the Fossil Forest River, but the *in situ* fossil stumps occur in one prominent band exposed intermittently on the slope. The stumps are conspicuous because of their large size and their orange/yellow weathering colours, which contrast with the background of black coal (Fig. 2). The dimensions of 87 trees (83 stumps and 4 logs) were recorded from one area. More stumps are present to the south, but the relationship between the two areas is unclear due to poor exposure.

Most of the stumps consist of the basal part of the trunk, the root stock and part of the spreading roots (Fig. 3). The roots are typically conical in shape and, rather than branching and trailing

FIG. 2. An area of the fossil forest showing large permineralised tree stumps on black coal layer. Figure for scale.

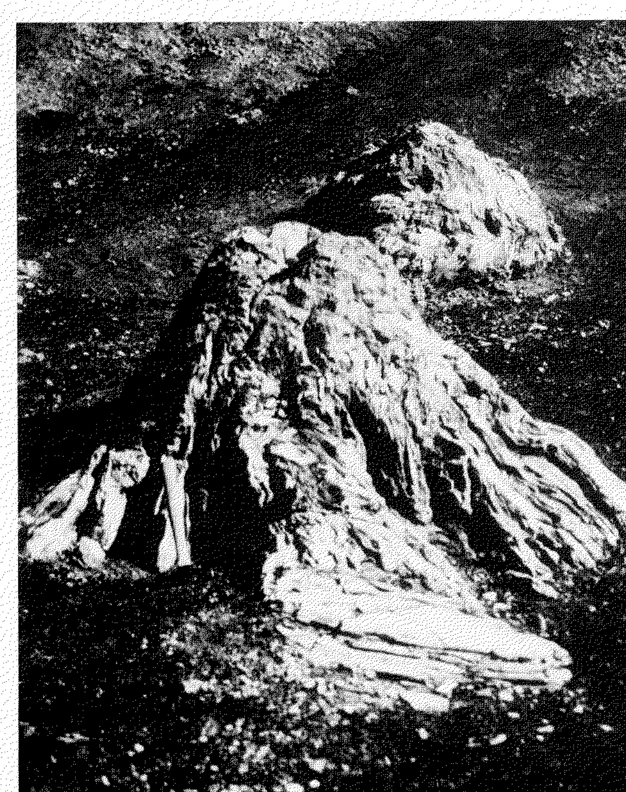

FIG. 3. Large conical fossil tree stumps. The diameter of the stump in the foreground is 1.50 m and the height 0.98 m.

away from the base of the trunk, as do many tree roots, they form a dome-like sheath around the lower part of the trunk (Fig. 4). The roots have the appearance of a buttressed system that develops on trees requiring extra anchorage in unstable, swampy conditions. Every tree in the Strathcona Fiord forest that has the roots well enough preserved has this type of root structure. A few logs lie on the surface of the coal. These probably represent trunks and fallen branches from the nearby tree stumps, though it is notable that logs are relatively rare, presumably most having been washed away when the forest was flooded.

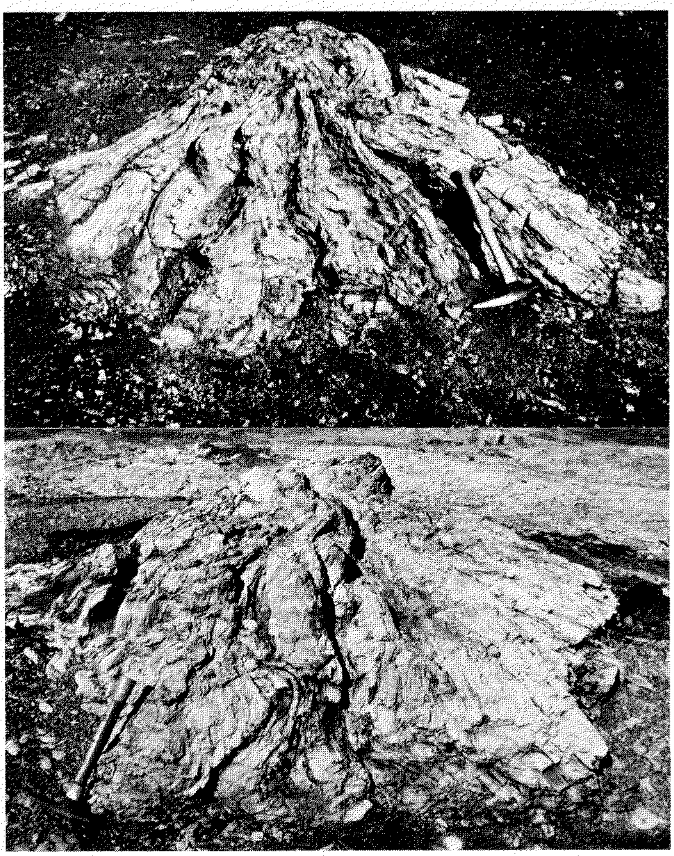

FIG. 4. Large permineralised fossil tree stumps, illustrating the conical shape of the roots. Hammer for scale is 30 cm long.

DIMENSIONS OF THE TREES

Several dimensions of the stumps were measured, including the preserved height and the maximum diameters of the whole stump in both north-south and east-west directions. If the basal part of the trunk was still preserved above the root flare, the trunk height and diameters at this position were also measured. Preservation is variable and several stumps have been eroded to rounded blocks. Because of the rather steep dip of the beds (approximately 30°) and of the outcrop slope (about 20° in the same direction), the stumps protrude at an angle to the slope rather than being vertical and many have been covered on the upslope side by slumped mud and sand. The east-west diameter measured on wood that is partially covered is therefore much smaller than the north-south diameter, which is generally well exposed and more representative of tree size. For all petrified stumps the measured diameter is always somewhat less than the former tree size due to compaction and loss of bark and soft outer parts upon burial. Many of the stumps have deteriorated into fragments, with the central trunk missing. However, the root parts are still in place, giving an approximate measure of the size of the tree.

The most remarkable feature of these trees is their enormous size. A dome-shaped root stock of over 5 m in diameter was measured for the largest tree, and 37 of the stumps had preserved root stocks of over 1 m in diameter. The height of the stumps ranges from 0.15 to 1.80 m, 5 stumps being over 1 m tall. The common height ranges from 0.20 to 0.70 m, though the top parts of the smaller trees have obviously been eroded since being exposed. Eighteen stumps are very well preserved and retain a small portion of trunk above the root stock. The diameters of the trunks are generally between 40 and 60 cm, although 2 are over 1.00 m.

DENSITY OF THE STUMPS

The stumps on certain areas of exposed coal are positioned very close to one another, with only about a metre or two between them (Fig. 2). To quantify these observations, the stumps and the area of exposed coal were mapped. A baseline was laid out across the slope, and the distance of each stump and the exposed edges of the coal from the line were measured. Once plotted (Fig. 5), the total area of exposed coal bed was calculated. Eighty-three petrified stumps were noted in an area of coal of 2261 m^2 (2.261 Ha), giving a density of 1 stump in 27 m^2 (367 stumps$\cdot$$Ha^{-1}$). The density varies somewhat from area to area due to the pattern of exposure; for example, a few stumps are spread out along long, narrow bands of exposed coal (Fig. 5). The most extensive area of coal (area F in Fig. 5) contains many (50) closely spaced stumps, giving a density of 1 stump in 22 m^2.

Growth rings are apparent on the eroded cross-sections of the stumps (Fig. 6). Where not compressed, in several trees they are notably very wide, and ring widths of up to 10 mm were measured in the field.

PRESERVATION

The tree stumps are permineralised by calcite. The interior parts are black due to the inclusion of woody organic matter. The exterior of each stump has been bleached yellow-orange, but the wood grain is still visible on the outside and growth rings are present on the trunk cross-section (Fig. 6). However, the trunk cross-section, which should be nearly circular in shape, is often deformed, indicating that the trees underwent compaction, both vertically and horizontally, while the woody material was still soft prior to permineralisation. The terminations of roots, which are spread out in the coal, grade from being well permineralised near the trunk to very flattened and coaly distally. The distal roots were probably greatly flattened during burial, which prevented the infiltration of permineralising solutions.

The coal in which the stumps stand represents the remains of the forest floor peaty litter and possibly drifted plant material. The organic matter underwent sufficient compaction to have lost the outlines of the original plant material, unlike the "mummified" leaf litter layers in the fossil forests at Geodetic Hills, Axel Heiberg (Basinger, 1986/87; Francis and McMillan, 1987). Leaf impressions are, however, apparent on the bedding sur-

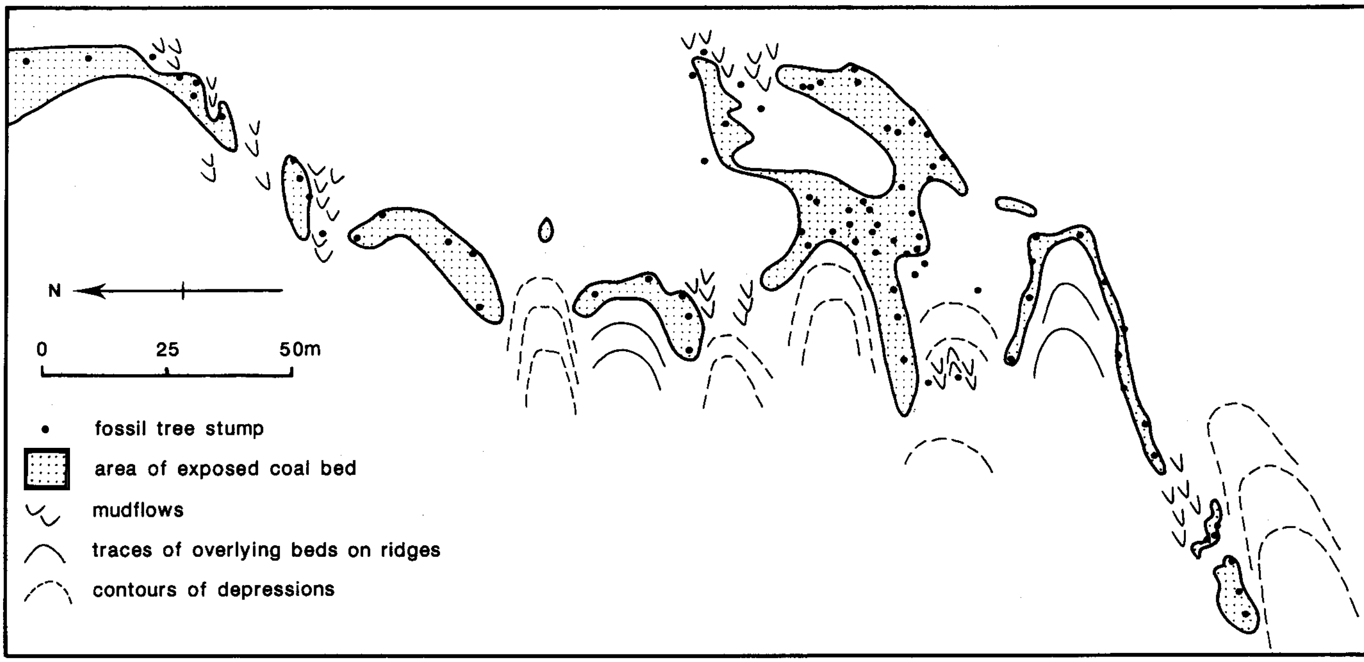

FIG. 5. Plan of the measured area of fossil forest floor at Strathcona, showing position of fossil tree stumps and area of exposed coal bed.

FIG. 6. Transverse cross-section of part of a stump revealing wide, slightly contorted growth rings. Scale bar represents 5 cm.

faces of adjacent sandstones. Also, very little fossil resin was observed in these coals, in contrast to the abundance of resin at Geodetic Hills.

DISCUSSION

A tentative picture of the Strathcona Fiord forest on Ellesmere Island can be obtained from the field data. The sedimentary environment was a lowland delta plain with active and abandoned distributary channels separated by lakes, swamps or marshy areas (Miall, 1986). Fairly dense forests with large trees grew in marshy, interdistributary areas, and layers of peaty leaf litter formed below and around the trees. The trees seem to have been tolerant of waterlogged soils and had large, buttressed roots for support and stability. Sedimentary features indicate that the water was fresh, and there is no evidence that the trees had to tolerate saline water.

The trees were large, with trunks up to at least 1 m and root stocks up to 5 m in diameter. The fossil remains indicate that the trees were monopodial, with one main trunk, possibly attaining heights of 40-50 m. Although the wood type has yet to be identified, the most common leaf type in the arctic Tertiary forests is *Metasequoia* (Dawn Redwood), and it is highly likely that the fossil trees of Strathcona Fiord were of this type. Living *Metasequoia*, found today only in relict communities in China (Chu and Cooper, 1950), are deciduous, a feature that helps explain the abundance of such foliage in fossil leaf litter layers. If it is assumed that all the fossil stumps in the Strathcona forest layer are of the same generation, then the forest was quite dense, with trees as closely spaced as 1 m. For comparison, modern cypress swamps in the Alabama wetlands have tree densities of only $169 \cdot Ha^{-1}$ (Lugo, 1984). Even if some stumps represent dead trees of an earlier generation, they were clearly standing erect between living trees, so the forest floor would have appeared crowded. The height of petrified stumps in other fossil forests has been considered an indicator of the water depth that drowned the trees, the trunks having rotted off near the water level (Jefferson, 1982; Francis, 1983). In this case, the depth of water that covered the Strathcona trees may have been up to 1.5 m.

The interbedding of coals with fluvial silts and sandstones was due to periodic floods, which would have buried the forests. One of these floods may have killed the trees and sealed in the layers of peat. The lack of petrified horizontal logs in the fossil forest suggests that fallen trunks and branches were either washed away by the flood waters or rotted and compacted into the coal very quickly. Subsequent invasion of the vegetation into the area gave rise to re-established forest conditions.

Some idea of the nature of the local climate can be obtained from both the fossil trees and the sediments. Deltaic, shallow water floodplain environments are extremely sensitive to climatic influences. Clearly, a wet climate with plenty of rainfall prevailed during the Eocene on Ellesmere Island, allowing the formation of swampy areas and peat. The large sizes of the forest trees implies that the climate was warm and favourable for growth. Had it been too cold, much smaller, tundra-like plants would have resulted. The well-defined and wide growth rings in the stumps indicate that the trees grew rapidly in a favourable forest environment and that the climate was markedly seasonal and warm, at least during the growing season, and the rainfall ample for fast growth. A warm/cool temperate climate with high rainfall is therefore envisaged for this forest. From sedimentary evidence, Miall (1984) proposed that the Eocene climate of Ellesmere Island was warm and moist to support dense vegetation and extensive coal swamps. Nearby elevated highlands would have influenced sedimentary facies (Miall, 1984) and may have created climates that locally favoured forest growth. The terrestrial vertebrates (including tortoises, flying lemurs, salamanders and alligators) that lived in the forests probably required an equable climate with little more than brief periods of freezing winter temperatures (West *et al.*, 1981).

These forests of large trees, growing well in a warm, wet climate so close to the North Pole, represent a special environment for which there is no modern analogue. Yet temperate forests in high latitudes beyond 70° were not uncommon in the Tertiary (or even earlier in other warm phases in the Phanerozoic), as indicated by other fossil floras in arctic Canada (Hills *et al.*, 1974), Spitsbergen (Schweitzer, 1980) and even near the South Pole in Antarctica (Jefferson, 1982; Kemp and Barrett, 1975). During the Eocene, climates were globally much warmer than at present (Frakes, 1979). The poles were free of permanent ice. Broad-leaved evergreen vegetation extended to latitudes of 60°N and broad-leaved deciduous plants lay at even higher palaeolatitudes. Deciduous conifer forests occupied the most northern environments but spread to lower latitudes during cooler intervals during the Eocene (Wolfe, 1985).

Even with an Eocene climate much warmer than the present, the existence of substantial vegetation at high latitudes illustrates a tolerance of the polar sunlight regime of months of winter darkness followed by constant summer sunlight. In the past, a reduction in the tilt of the earth's axis of rotation was proposed to allow a more even annual distribution of sunlight (Wolfe, 1980). However, reduced obliquity would probably have caused lower temperatures and a less seasonal climate in polar regions (Barron, 1984), inconsistent with the geological evidence. It seems more likely that the plants were suitably adapted to long periods of winter darkness and summer sunlight and underwent metabolic shutdown during the dark times, then grew continuously during the summer (Axelrod, 1984). The large sizes and the density of the trees in the Strathcona Fiord forest provides clear evidence that forests grew well in polar areas under these conditions in the past.

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