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Excerpt
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Historical background and geological framework

Introduction

Today Antarctica is a continent locked in ice with nearly 98% of its current terrain covered by permanent ice and snow. Yet for the vast majority of its existence the Antarctic landmass was ice-free and supported a diversity of plants and animals. The history of the vegetation of Antarctica through geological time is intimately linked with that of the geography and climate, for both geography and climate have shaped, fashioned and controlled these high latitude ecosystems over geological timescales.

Today ice sheet and sea ice processes in Antarctica are key drivers of the oceanic circulation system. The oceanic circulation ensures the Antarctic continent remains inhospitable to terrestrial plant life through extreme cold. Yet on a geological timescale the current lack of extensive vegetation is a relatively recent phenomenon, possibly as recent as Pliocene. During the 300 million years covering the Paleozoic, Mesozoic and Cenozoic the fossil record reveals evidence of extensive forests across the high latitudes. Moreover occupying the central component of Gondwana, Antarctica played an important role in creating present day Southern Hemisphere biogeographic patterns by providing terrestrial connections between what are today widely separated landmasses. An obvious example of this is the distribution of Antarctic beech (*Nothofagus*) across South America and the southwest Pacific, which can be attributed to past terrestrial connections across Antarctica. The lack of present day terrestrial diversity however makes it difficult to integrate the Antarctic region into biogeographic studies that rely on determining relationship between extant groups. This further emphasises the importance of the Antarctic fossil record for understanding present day Southern Hemisphere diversity patterns. The interplay between supercontinent fragmentation, creation of new oceanic basins and oceanic circulation patterns, and evolution of the climate system all played a critical role in the history of Antarctic vegetation.

This book sets out to explore the interplay between geological processes and climate evolution on the evolving vegetation of Antarctica, but first, to set the book in its rightful context, we summarise the history of palaeobotanical interest in Antarctica and provide a brief summary of the geology of this southernmost continent.

History of palaeobotanical discovery

Today the Antarctic region is easily defined by strong oceanic and atmospheric features. The Antarctic Circumpolar Current, a feature observed by early explorers, effectively isolates cold surface waters of the Southern Ocean from warmer waters further to the north. The dramatic change in temperature over a short distance in surface waters (termed the Antarctic Convergence) is a major biogeographic feature that supports different assemblages of marine organisms either side of the convergence (Arntz, Gutt and Klages, 1997; Linse *et al*., 2006). Although the Antarctic region today is defined by these present day oceanographic features they have not always been present. Nevertheless, the Antarctic Circumpolar Current broadly forms a convenient boundary to discuss the early scientific expeditions of the southern high latitudes including the early voyages of Halley (1699–1700) and Cook (1772–1775) – both of which penetrated the southern polar regions yet failed to discover land.

Cook made several forays into the high latitudes in an attempt to discover land but while unsuccessful, his records played an important role in eliminating large tracts of the Southern Ocean from further exploration. These exploratory expeditions paved the way for the discovery of the continent. The voyages of Cook provided dismal descriptions of the southern polar regions depicting them simply as a frozen wasteland. Despite this, whalers and sealers continued to push further south into the southern high latitudes driven on by the depletion of sealing and whaling grounds further north. Therefore it is no surprise that sealers are acknowledged as being the discoverers of several of the Antarctic islands (e.g. Macquarie Island by F. Hasselburgh aboard the *Perserverance*; Fogg, 1992), including those lying off the Antarctic Peninsula (e.g. South Shetland Island by William Smith aboard the *Williams*; Fogg, 1992; Figure 1.1). A number of the whaling and sealing trips combined economic pursuits with science and discovery and it is amongst the records of these expeditions to the Antarctic Peninsula that the first reports of fossil plant material can be found.

In 1819, Tsar Alexander I despatched two Russian expeditions, one to the Arctic and the second to the Antarctic. Thaddeus Bellingshausen commanded the Antarctic voyage and furthered the earlier discoveries of Cook, with a circumnavigation of the Antarctic in 1820. Bellingshausen discovered several islands including Alexander Island, off the Antarctic Peninsula, and Peter I Island (Figure 1.1). More controversial is the discovery of the Antarctic continent itself. While it is clear that Bellingshausen observed the ice shelves attached to the continent, and therefore can be regarded as the discoverer of the Antarctic continent, this has been contested (Jones, 1982). The voyage of Bellingshausen made significant inroads into the discovery of Antarctica but due largely to the haste in which the voyage was put together and despatched from St Petersburg, it was poorly equipped for scientific discovery (Fogg, 1992).

The United States Exploring Expedition was a privately funded sealing trip that sailed in 1829 and returned to the United States in 1831. The naturalist on the expedition was James Eights (1833) who made geological observations on the South Shetland Islands and reported carbonised wood preserved in conglomerates, and thus penned the first scientific record of fossil plants from the Antarctic regions. However, these and other discoveries, such as the

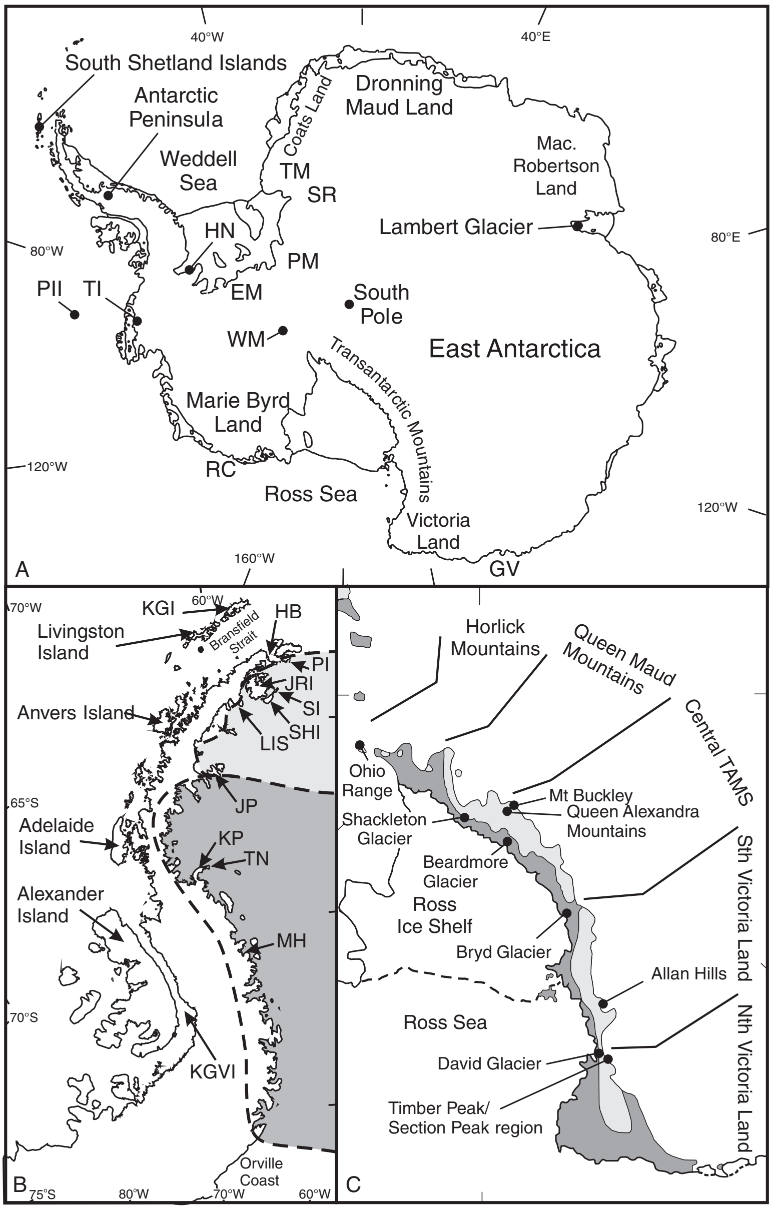

Figure 1.1 Geographic locality map showing the approximate positions of the places mentioned in the text. **A**, Antarctica. TI = Thurston Island, PII = Peter I Island, HN = Haag Nunataks, EM = Ellsworth Mountains, TM = Theron Mountains, SR = Shackleton Range, WM = Whitmore Mountains, GV = George V Coast, RC = Robertson Coast. **B**, Antarctic Peninsula region. KGI = King George Island, HB = Hope Bay, PI = Paulet Island, JRI = James Ross Island, SI = Seymour Island, SHI = Snow Hill Island, LIS = Larsen Ice Shelf, JP = Jason Peninsula, KP = Kenyon Peninsula, TN = Table Nunatak, MH = Mount Hill, KGVI = King George VI Sound. Light shading = approximate extent of the Larsen Basin, dark shading = approximate extent of the Latady Basin. **C**, Transantarctic Mountains showing main sectors and key regions mentioned in book. Dark shading shows extent of outcrop, light shading represents extent of Jurassic Ferrar Group and co-occurring Beacon Supergroup, outcrop pattern derived from Elliot and Hanson (2001).

material from the Kerguelen Islands collected by the surgeon and one of the naturalists, McCormick, on the James Clark Ross voyages of the HMS *Erebus* and HMS *Terror* (1839–1843), raised little interest scientifically and appear to have been forgotten or largely overlooked in later works. Indeed the Kerguelen material was not seriously examined for nearly another century (Edwards, 1921; Seward, 1919).

Scientific interest in polar palaeofloras began in the late 1800s with the discovery of extensive fossils in the Arctic resulting in works such as those by Oswald Heer (1868–1883), which documents Cretaceous and Cenozoic floras. This demonstrated that the northern polar regions had not always been frozen and virtually devoid of plant life, but rather during the past had supported extensive and diverse forests. The implications of a much warmer world excited scientific debate, and the diversity and composition of the Arctic Cenozoic floras led Heer to suggest that the northern temperate flora arose in the Arctic region and spread southwards, and the Arctic was thus a centre of origin for the modern flora (Heer, 1868, 1874). These ideas gained considerable momentum in the late 1800s (e.g. Nathorst, 1884) and spurred further exploration to and discovery in the Arctic. Indeed this thinking contributed greatly to the misleading interpretations of the Cenozoic fossil floras of New Zealand (von Ettingshausen, 1887, 1891), Australia (von Ettingshausen, 1888) and South America (e.g. Dusén, 1899; Engelhardt, 1891, 1895), where fossil plant material were nearly always assigned to modern northern temperate taxa with scant regard to the fact that the local flora differed markedly in floristic composition. The fossil plant discoveries in the Arctic raised the question whether floras might have been present in the south, and if so, whether these showed similar patterns to those in the Arctic.

Two expeditions were instrumental in the next phase of Antarctic palaeobotanical discovery. In 1892, Captain C. A. Larsen aboard the *Jason*, led a Norwegian whaling and sealing expedition to the Antarctic Peninsula. This expedition was primarily for commercial purposes but Larsen harboured an interest in scientific exploration. The *Jason* reached Seymour Island in November 1892 and, after first sailing south along the edge of the Larsen Ice Shelf, returned to Seymour Island in December of that year (Larsen, 1894). On December 4th a small party, including Larsen himself, landed on Seymour Island with the aim of looking for seals, but while ashore they discovered abundant fossil shells and wood, and so began the first of many collections of fossils from Antarctica (Larsen, 1894).

At the same time as Larsen's expedition was heading south another whaling party, the *Dundee Antarctic Expedition 1892–1893* was also underway. This was a much larger expedition comprising four vessels (*Active*, *Balaena*, *Diana* and *Polar Star*). Although essentially a commercial expedition, two surgeons (C. W. Donald and J. Bruce) with interests in natural history were appointed and scientific instruments were provided by the Royal Geographical Society of Edinburgh and the Metereological Office. In spite of the greater scientific weight of the *Dundee Antarctic Expedition 1892–1893* commercial interests thwarted the efforts of the naturalists. This lack of support served only to frustrate both scientists (Fogg, 1992; Zinsmeister, 1988).

From the published records of both expeditions it is unclear when the parties from the *Jason* and the *Dundee Antarctic Expedition* first met (Zinsmeister, 1988). However, the meeting on the 28th December 1892 was important since the *Jason*, which had been at sea for several months, was running low on stores particularly tobacco (Aagaard, 1930). A frustrated Bruce, joined a few days later by Donald, decided to trade tobacco for most of the fossils collected by the crew members of the *Jason*, and as a result these fossils made their way back to Scotland and were later described by Sharman and Newton (1894, 1898). However, not all the fossils collected on Seymour Island by Larsen and his crew were traded. Captain Larsen's personal collection ended up in Oslo although some specimens are also housed in the Swedish Museum of Natural History in Stockholm. In 1894 Larsen returned to the Antarctic, made other landings on Seymour Island (Larsen, 1894) and explored further inland, reporting the copious presence of fossil wood. Later Zinsmeister (1988), through fieldwork on Seymour Island and detective work of published records, determined the area described by Larsen as being the head of Cross Valley, an area now known to be rich in Paleocene wood and leaves.

When describing the fossils collected by Larsen from his two trips to the Antarctic region, Sharman and Newton (1898) followed the conventional thinking of the time regarding the origin of the Earth's biota. They noted the importance of these discoveries, and catalogued the similarities of the southern flora and fauna to those in the northern latitudes. Larsen's discoveries were also influential in the major discoveries made by the *Swedish South Polar Expedition 1901–1903* (Figure 1.2). Otto Nordenskjöld, whose uncle had been a polar explorer and the first to navigate the Northeast Passage in the Arctic Basin, led the expedition. Between 1895 and 1897 Otto Nordenskjöld had already explored southern South America before making trips to Alaska in 1898 and East Greenland in 1900. The *Swedish South Polar Expedition* aimed to further the discoveries of Larsen, and Larsen was thus selected to captain the vessel, *Antarctic*, south. In the annals of Antarctic exploration the *Swedish South Polar Expedition* was an epic, and testament to the endurance and perseverance of these early explorers and scientists.

The expedition first called at the South Shetland Islands on the west side of the Antarctic Peninsula prior to sailing to Seymour Island on the east side. The initial landing on Seymour Island at Penguin Point was disappointing as the rocks lacked fossils and this influenced Nordenskjöld's decision not to build his wintering base here (Nordenskjöld and Andersson, 1905) but rather on nearby Snow Hill Island (Figure 1.2A) – a decision strongly influenced by the discovery of ammonites made during a reconnaissance landing. However, this was a decision that Nordenskjöld later came to rue once he realised the wealth of palaeontological material on Seymour Island (Nordenskjöld and Andersson, 1905; Zinsmeister, 1988). The following summer, largely due to thick ice conditions, Larsen was unable to reach the Snow Hill base to pick up the over-wintering party. As a result Dr Gunnar Andersson, Lt Duse and Seaman Grunden were put ashore at Hope Bay with the intention of sledging to Snow Hill Island to advise Nordenskjöld of the difficulties in access, and to suggest they travel to Hope Bay (Figure 1.1). However, and somewhat ironically, the sea ice had by this time broken up, and the party was unable to reach Snow Hill Island, and so returned to Hope Bay to await the return of the *Antarctic*. Unbeknown to the Hope Bay party the *Antarctic* had become trapped in the ice, and drifted for over a month before being crushed and sinking to the east of Paulet

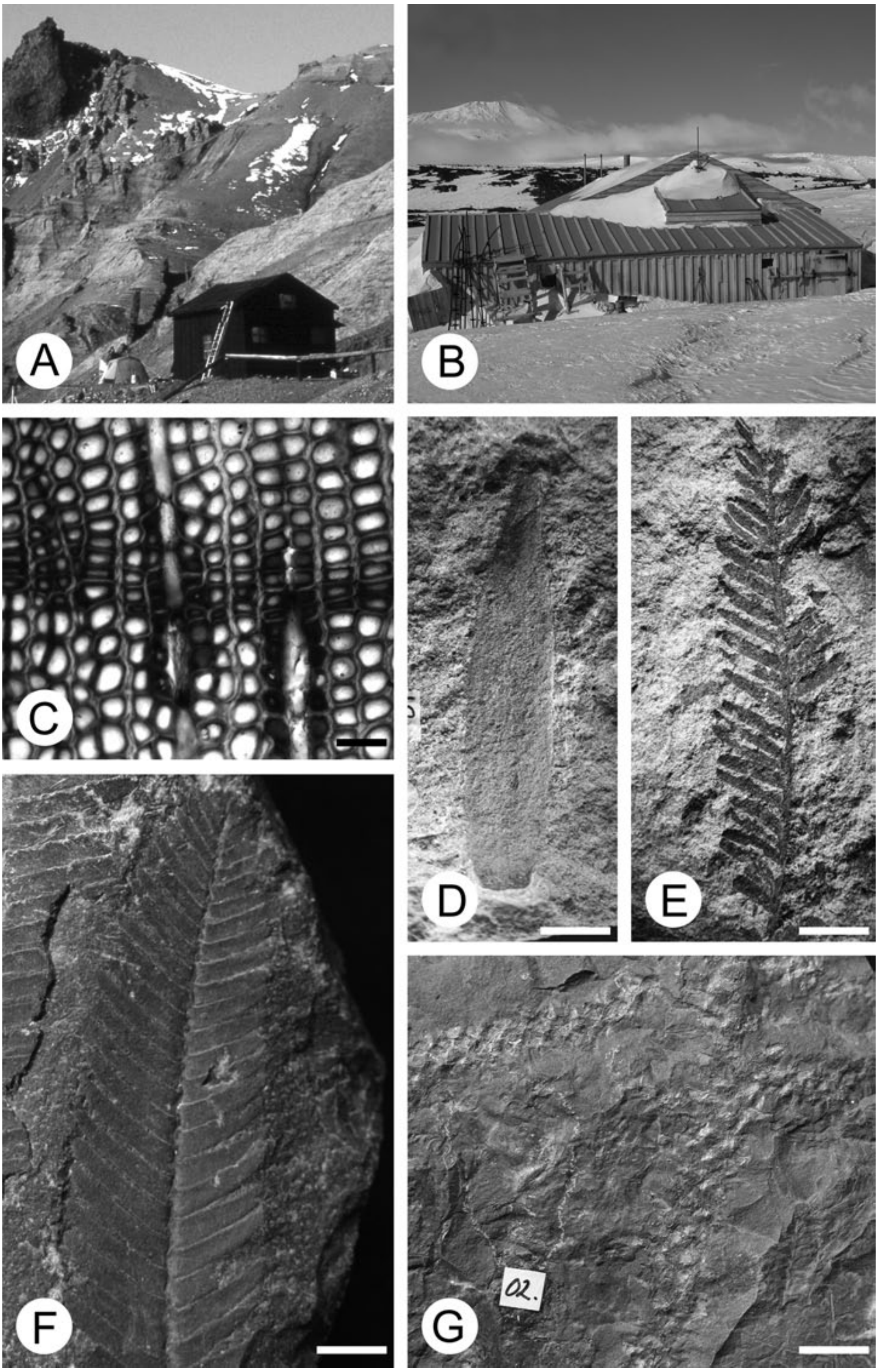

Figure 1.2 Historic bases and fossil plant collections. **A**, *Swedish South Polar Expedition 1901–1903* Base on Snow Hill Island. Nordenskjöld's expedition discovered Jurassic, Cretaceous and Cenozoic

Island. Larsen and his crew took to the lifeboats, and managed to reach Paulet Island where they spent a miserable winter in a stone hut that they had built. All three parties spent winter in the Antarctic: Nordenskjöld at his base on Snow Hill Island (Figure 1.2A); Larsen and crew on Paulet Island; and Gunnar Andersson, together with Duse and Grunden, in a small stone hut at Hope Bay. Remarkably all parties survived the winter with the Hope Bay party finally making it to Snow Hill Island to meet Nordenskjöld the following spring. The Paulet Island party arrived on Snow Hill Island just as the relief vessel sent from Argentina was due to depart. In spite of the adversity faced by Nordenskjöld and the expedition members the *Swedish South Polar Expedition* should be regarded as one of the most successful scientific expeditions during this period of initial exploration and discovery. The scientific results of this expedition were published between 1908 and 1933 in a series of comprehensive volumes (Conrad, 1999).

Three significant palaeobotanical discoveries were the legacy of the *Swedish South Polar Expedition*. In spite of the meagre rations, and having to survive on penguins over the winter, the Hope Bay party discovered Jurassic plant fossils at Mount Flora (Halle, 1913a, 1913b; Nathorst, 1904, 1906; Figure 1.2F, G). The Hope Bay Flora was described in detail with extensive comparisons to other Jurassic floras known at the time (Halle, 1913a, 1913b). The quality of the monograph (Halle, 1913a, 1913b) ensured it became a reference flora for dating Jurassic Southern Hemisphere floras. Although in recent times the Hope Bay flora has been variously regarded as Early Jurassic (Rees, 1993; Rees and Cleal, 2004) to Early Cretaceous (Gee, 1989; Stipanicic and Bonetti, 1970) recent radiometric dating has confirmed an early Middle Jurassic age (Hunter *et al*., 2005).

From Snow Hill Island several Late Cretaceous plants were also described (Halle, 1913b) along with a diverse leaf flora of Paleocene age from Seymour Island (Dusén, 1908) (Figure 1.2D, E) – although the treatment later received some criticism from experts on Southern Hemisphere Cenozoic floras (e.g. Berry, 1913). The third contribution focused on the fossil wood from the Cretaceous, Paleocene and Eocene from Snow Hill and Seymour islands (Gothan, 1908; Figure 1.2C). Together these monographs illustrated Antarctica not as a frozen continent, but as with the deposits from the Arctic, point to the land having once been warm and vegetated.

Caption for Figure 1.2 (cont.)
floras in the northern Antarctic Peninsula. **B**, *British Antarctic Expedition (Terra Nova Expedition) 1911–1913* base with Mount Erebus in background. The polar party carried back 35 lb of rock that included specimens of *Glossopteris*. **C–G**, examples of material collected by members of the Swedish South Polar Expedition. C, thin section of fossil wood described by Gothan (1908) as *Araucarioxylon pseudoparenchymatosum*. S4061. D, leaf of *Araucaria imponens* described by Dusén (1908) from the Paleocene of Seymour Island. S132021_01. E, *Elatocladus heterophylla* S132020 from the Upper Cretaceous of Snow Hill Island. F, *Otozamites hislopii* described by Halle (1913b) from Hope Bay, S020114. G, *Pagiophyllum feistmanteli* described by Halle (1913b) from Hope Bay, S020135a_01. Scale bars C = 50 µm, D–G = 1cm. D–G courtesy of S. McLoughlin and Department of Palaeobotany, Swedish Museum of Natural History.

Whilst Nordenskjöld and the *Swedish South Polar Expedition* had been overwintering on the Antarctic Peninsula, on the other side of the continent, Captain Robert Falconer Scott was leading the *British National Antarctic Expedition 1901–1904*. The young geologist on this expedition, Hartley Ferrar, established the basic stratigraphy of the Transantarctic Mountains. He described them as a basement complex of igneous and metamorphic rocks overlain by a horizontally bedded sedimentary sequence, which was in turn intruded by dolerite sills (Ferrar, 1907). Traces of plant life were recorded (Arber, 1907) but the significance was not recognised for a further 20 years when Edwards (1928) split the samples to reveal fragments of the large, woody, seed-bearing arboreal seed plant, *Glossopteris*, confirming a Permian age for the strata. Perhaps the most well-known discoveries were made on Scott's second expedition the *Terra Nova Expedition* (1911–1913) based out of Cape Evans (Figure 1.2B). On the return journey from the South Pole the ill-fated polar party discovered beautifully preserved leaves at Mount Buckley. These were examined by Seward (1914) and again identified as *Glossopteris*. One can only speculate, had the *Glossopteris* leaves from Scott's first expedition been discovered prior to Scott's second expedition, whether the polar party would have carried the 35 lb of rock specimens from Mount Buckley. If the polar party had not carried the specimens they may have reached One Ton depot and survived, instead of succumbing to the cold some 11 miles short. The importance of the fossils from both of Scott's expeditions were realised in subsequent studies by Du Toit (1937) and the formulation of his ideas on continental drift.

With the increase in interest in the Antarctic, coupled with the increase in the number of expeditions to this region, further discoveries that included abundant fossil plant material were being made by other National Expeditions (e.g. *British Antarctic Expedition 1907–1909*; Truswell, 1991). Examples include the wood discoveries on South Georgia during Shackleton's last expedition (Gordon, 1930) and the plant fossils on Alexander Island reported by the *British Graham Land Expedition 1934–1937* (Fleming, 1938; Stephenson and Fleming, 1940). The Alexander Island material was thought to be Middle Jurassic based on similarities with the floras described from Hope Bay until recent research showed that they were from the Cretaceous (Aptian) part of the succession (Taylor, Thomson and Willey, 1979).

The next major advance in knowledge of the Antarctic fossil floras was made during the *Trans-Antarctic Expedition 1955–1958*. An extensive geological programme covering a broad geographic area made further discoveries of plant fossils of Devonian, Permian, Triassic and Jurassic. These extensive collections coupled with a review of the earlier discoveries enabled Plumstead to provide the first synthesis of Antarctic fossil floras (Plumstead, 1962) and this remained the only synthesis for nearly 30 years.

The establishment of permanent bases since the late 1940s has led to ongoing research and discovery, and thus to a dramatic increase in our knowledge of the natural history of Antarctica. The International Geophysical Year (IGY, 1957–1958) marked the beginning of this permanent presence in the Antarctic for many nations. The IGY acted as a watershed for Antarctic research as it shifted national focus from territorial claims to scientific purposes. This ultimately resulted in the formation of the Antarctic Treaty which put territorial claims into abeyance and made Antarctica a region for scientific research. International committees such as the Scientific Committee for Antarctic Research (SCAR) played, and continue to play, a role in coordinating and setting collaborative research directions. Palaeobotanical research was very much a by-product of geological reconnaissance and mapping efforts with new discoveries being passed on to international experts for research and publication. For example, British Antarctic Survey geologists made several discoveries in the 1960s and 1970s in the course of geological mapping. These included Permian floras from Dronning Maud Land (Plumstead, 1975) and the Theron Mountains (Lacey and Lucas, 1981a), a Mesozoic flora from the South Shetland Islands (Lacey and Lucas, 1981b; Orlando, 1968), and several Cenozoic floras from King George Island (e.g. Lucas and Lacey, 1981). The collaborative nature of research from the IGY continued so that it was not unusual for countries to lend material for study to scientists from other nations who had also been involved in the IGY (e.g. United Kingdom to Argentina; Orlando, 1968).

In principle, those discoveries deemed to be the most significant at the time were passed on for further research and there are many other reports of plant fragments scattered within publications focusing on the geology of specific regions (e.g. Thomson, 1975). It is only in recent decades that the British Antarctic Survey has initiated in-house palaeobotanical expertise in the field through studentships (e.g. Jefferson, 1981; Rees, 1990), and more recently through employees and joint research projects within certain British universities. These studies have resulted in a significant advancement in our understanding of the palaeobotany of Antarctica. In parallel with the development of a palaeobotanical capability was an expansion into the field of palynology, firstly through the commissioning of a pilot study (Dettmann and Thomson, 1987), followed by the appointment of staff palynologists (e.g. Duane, 1996) and joint collaborations with the British Geological Survey (e.g. Pirrie and Riding, 1988; Riding *et al*., 1998). Other nationalities, such as Australia, have also made significant palaeobotanical and palynological collections, particularly whilst undertaking field mapping studies, which were then passed on to experts to document. These include the discoveries of Permian plant macrofossils (White, 1962, 1973) and pollen (e.g. Kemp, 1973) from the Prince Charles Mountains.

In contrast, research institutes such as the Byrd Polar Research Center (formerly Institute for Polar Studies) located within Ohio State University have had direct access to palaeobotanical expertise. James M. Schopf reported on the fossil plant findings of expeditions (Schopf, 1962, 1968) and participated in several Antarctic field seasons. Schopf also realised the significance of the discoveries made by Mercer and Gunning of permineralised peats (Schopf, 1970a) and took part in several expeditions to collect material including Triassic peats (Schopf, 1970b). Permineralised peats are now known to be from several localities in both the Permian and Triassic of the Transantarctic Mountains. These deposits have formed the focus of palaeobotanical research by researchers from the United States of America in the Transantarctic Mountains since the 1970s, firstly through the work of J. M. Schopf, and more recently through T. N. and E. L. Taylor and members of their research group. The unique permineralised peats of Permian and Triassic ages have yielded copious amounts of information both on the morphology and anatomy of the plants themselves (e.g. Schopf, 1978; Smoot and Taylor, 1986a; Smoot, Taylor and Delevoryas, 1985), as well as the biology (e.g. Smoot and Taylor, 1986b) of the plants growing in such high latitude ecosystems. Recent discoveries of peat in the Prince Charles Mountains (Neish, Drinnan and Cantrill, 1993) further extended our knowledge of the occurrence of these palaeobotanically rich deposits.

While palaeobotanical material is known from many regions of the Antarctic it will become clear that two areas, namely the Transantarctic Mountains and the Antarctic Peninsula (particularly the northern Antarctic Peninsula region) are of prime importance due to the extensive outcrop and geological history. The expansion of Antarctic Treaty nations, and the desire for a number of nationalities to have a physical presence on the continent, saw an increase in the number of bases, particularly during the 1980s, in the northern Antarctic Peninsula. Countries such as Argentina, Chile, Poland and Russia who originally had bases in this region were joined by countries such as Brazil, Uruguay, Peru, China and Korea, making the northern Antarctic Peninsula one of the most densely occupied and cosmopolitan regions of the continent. The increased presence went hand in hand with an expansion in palaeobotanical discovery and research. This phase of investigation began in the 1980s with geological mapping of the volcano-sedimentary strata of King George Island resulting in rediscovery and documentation of Late Cretaceous (e.g. Birkenmajer and Zastawniak, 1986, 1989a, 1989b; Zastawniak, 1994) and Cenozoic floras (e.g. Li, 1994; Torres, 1984; Zastawniak, 1981). Interpretation of the stratigraphy and age of these Late Cretaceous and Cenozoic sequences was not without controversy due to problems with resetting of radiometric dates (Soliani and Bonhomme, 1994). The succession of floras has now been synthesised (Dutra and Batten, 2000). Whilst numerous publications began to appear focusing on the King George Island floras other regions were also being investigated. The initial work on the Early Cretaceous flora of Byers Peninsula, Livingston Island (Fuenzalida, Araya and Hervé, 1972) and nearby Snow Island was expanded to include palynology (Askin, 1983; Duane, 1996) and macrofossils (Cantrill, 2000; Cesari *et al.*, 1998, 1999; Torres *et al.*, 1997, 1998) including wood (Torres, Valenzuela and Gonzalez, 1982). The presumed Triassic flora from Williams Point (Livingston Island) was revisited and shown to be Cretaceous (e.g. Chapman and Smellie, 1992; Rees and Smellie, 1989). Other regions, such as the flora described by Halle from Mount Flora at Hope Bay, have also been revised (Gee, 1989) based on new collections (e.g. Ociepa, 2007; Ociepa and Barbacka, 2011; Rees and Cleal, 2004). Interestingly, whilst new material and further discoveries continue to be made within existing floras, relatively few new fossiliferous regions have been found and studies have largely built upon the pioneering work of previous researchers.

Perhaps the most dramatic, and certainly the most controversial fossil discovery in recent years were those of *Nothofagus* wood (Carlquist, 1987) and leaves (Hill, Harwood and Webb, 1996; Hill and Truswell, 1993; Webb and Harwood, 1993) from glacial deposits (Sirius Formation) in the Beardmore Glacier region. These were assigned a Pliocene age based on diatoms from the base of the sequence (Webb *et al.*, 1984). The Pliocene age coupled with the interpreted growth form and implied growing conditions suggested a much warmer Antarctica, and consequently a decreased ice volume and less stable ice sheet (see Chapter 9). This created controversy and considerable debate within the Earth Science community regarding the stability of the ice sheet (Burckle and Pokras, 1991) especially in