AUSTRALIAN PALAEOCLIMATES: CRETACEOUS TO TERTIARY
A review of palaeobotanical and related evidence to the year 2000

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PREAMBLE TO 2007 EDITION

Since this monograph was submitted to CRC LEME in September 2000, *Climatic Change* has achieved a media prominence in Australia rarely if ever equalled in the past. Compelling reasons are the general acceptance of global warming as a key threat to the global community and, more locally, the impact of socially 'catastrophic' events such as Cyclone Larry (north-east) and prolonged drought (south-east), even if the nexus to global warming is unproven.

Not surprisingly, research into the predicted social and economic impact of global warming has been accompanied by renewed interest in apparently analogous warm intervals in the more recent geologic past - in particular the mid Pliocene 'warm period' some 2.5 million years ago and, more recently, the Paleocene-Eocene Thermal Maximum (PETM) about 55 million years ago. A second major stimulus has been the 'resources boom' generated by the rapid expansion of the Chinese and Indian economies.

Time constraints do not allow the text (or conclusions) of the 2000 monograph to be revised. As a compromise, this Preamble provides a selection of papers published since 2000, which in the author's opinion have the potential to improve our understanding of Cretaceous and Tertiary palaeoclimates in Australia as well as their correlation to global events (Table A). These studies range from the revision of the International Geological Timescale by Gradstein and Ogg (2004) and the biostratigraphies used to date and correlate Mesozoic-Cenozoic sequences in the marginal basins around the continent, e.g. Helby *et al.* (2004), Partridge (1999) and Monteil (2006), to 'spot samples' that provide the first detailed information on the role of Tertiary climatic change in the genesis of valuable placer deposits, e.g. de Broekert (2003), Hou *et al.* (2003a), Macphail and Stone (2004) and Paine (2005).

As in 2000, much palaeobotanical evidence continues to be generated as a by-product of hydrocarbon, mineral and groundwater exploration and the data remain 'concealed' in confidential (closed file) industry reports. Equally limiting as regards the reconstruction of terrestrial environments is the strong petroleum industries focus on marine microfossils, especially in western and northern Australia. One predictable consequence is that Tertiary spore-pollen sequences in inland northern Australia are, and will continue to be, difficult to date to a Geological Stage let alone to shorter intervals of geological time unless the host deposit is amenable to isotopic dating (discussion in Macphail and Stone 2004). The same is true of Tertiary non-marine sequences in Queensland and Plio-Pleistocene sequences in southern Australia (Dettmann and Clifford 2003, Macphail 2004a, 2006a)

North-West Australia

Micropalaeontological research, e.g. Collins *et al.* (2006), can help refine palaeotemperature trends for the northwestern margin, but virtually no additional palaeobotanical data have been formally published since 2000. Unpublished industry data indicate that Late Cretaceous floras on the North West Shelf include a significant number of angiosperm and cryptogam taxa that have not been recorded in correlative deposits in southern Australia (R. Helby and M.K. Macphail pers. observations). These, and independently dated microfloras preserved in Tertiary marine sequences, potentially provide a way to synthesize a pollen and spore-based palynostratigraphy for continental northwestern Australia.

North-East Australia

Regolith studies and marine sequences are a potential source of palaeoclimatic information, e.g. Forsyth and Nott (2003) and Conesa *et al.* (2005), but palaeobotanical reconstructions of Mesozoic-Tertiary climates continue to be constrained by limited access to proprietary data

and, for Tertiary continental sequences, by the lack of a 'local' pollen-spore based palynostratigraphy. For example in Queensland, Sajjadi and Playford's important (2002a, 2002b) reviews of Early Cretaceous microfloras in the Eromanga Basin cites numerous species described by J. McKellar (Geological Survey of Queensland in press) in an as yet (2006) unpublished analysis of correlative microfloras in the Surat Basin. Areas for which some additional palaeobotanical evidence have been published are (1) the Bundaberg Trough in coastal southeastern Queensland (Dettmann and Clifford 2003) and The St. George Basin (Lower Balonne district) in inland southeastern Queensland (Macphail 2004b). At the former site, an Early Miocene assemblage includes what appears to be the first record of the late Early to early Late Miocene zone index species *Canthiumidites bellus* in Queensland. Like its probable correlative at Mt. Coolon in central Queensland (Beeston 1994), the microflora is dominated by *Nothofagus* (*Brassospora*) spp., Casuarinaceae, Euphorbiaceae and Myrtaceae but also includes rare taxa whose Nearest Living Relatives (NLRs) occur in cool temperate rainforest as well as taxa whose NLRs occur in subtropical 'dry' rainforest. The probable Pliocene sequences in the St. George Basin indicates climates were too dry to support temperate rainforest angiosperms such as *Nothofagus* although temperate rainforest gymnosperms survived along rivers and/or the adjacent uplands.

Central Australia

A recently recognised glacial diamicton confirms glaciers had developed some time during the Berriasian to Valanginian in the Eromanga Basin (Alley and Frakes 2003). A recent PhD study uses changes in Barremian to Aptian dinoflagellate populations to infer mid Cretaceous palaeoclimates (Oosting 2004, Oosting *et al.* 2006). Otherwise, there have been few additions to the palaeobotanical database although Late Eocene macrofloras at Nelly Creek in northern South Australia continue to be a focus for macrofossil research (Hill and Cristophel 2001, Conran *et al.* 2003). Palaeontological studies have added to knowledge of Oligo-Miocene climates, e.g. Megirian *et al.* (2004), but the resolution provided by the land mammal biostratigraphy remains poor. Age control based on lithostratigraphy may or may not be reliable. For example, an organic interval within the Late Oligocene Etadunna Formation at Lake Palankarinna in northern South Australia yielded an Early Eocene microflora (M.K. Macphail unpubl. data). A possible Tertiary organic sequence intersected in a recent Northern Territory Geological Survey drillhole was discarded, despite being ear-marked for palynostratigraphic dating.

South-West Australia

Recent additions to the palaeobotanical database include detailed analyses of (1) Late Jurassic-Early Cretaceous sequences in the offshore Vlaming Sub-basin of the Perth Basin (Backhouse 2006, Macphail 2006c), (2) Late Jurassic-Cretaceous dredge samples from the offshore Bremer and Denmark Sub-basins in the western Bight Basin (Macphail and Monteil 2004, Exon *et al.* 2005), (3) Late Eocene lignites preserved in palaeochannels in southern south-west Western Australia (de Broekert 2003, Itzstein-Davey 2004, M.K. Macphail unpubl. data), (4) Early Oligocene to possibly Early Miocene carbonaceous clays underlying a highly important channel iron deposit (CID) at Yandi in the Pilbara region, northern south-west Western Australia (Macphail and Stone 2004), and (5) mid Pliocene lake sediments infilling a probable Early Cretaceous meteor impact crater at Yallalie, north of Perth (Atahan *et al.* 2004, Dodson and Macphail 2004).

The offshore data provide a detailed record of Austral Conifer Forest communities before and during the onset of rifting between Australia and Antarctica, and confirm (climate-forced) provincialism of the araucarian and cryptogam floras had developed as early as the Valanginian to Early Barremian. Microfloras preserved at Yandi demonstrate that climates at higher elevations on the Hamersley Ranges were cooler (mesotherm range) and wetter (humid

range) than now. The overlying thick CID appears to have been ferruginised in the Neogene, due to drawdown of the water table as climates became increasingly arid (Heim *et al.* 2006). The Yallalie site preserves an unusually high resolution record of local climates, including several aridity events, during the mid Pliocene warm period.

Central southern Australia

The tectonic and sedimentary histories of the eastern Eucla and Duntroon Basins have been reviewed by geologists at Geoscience Australia (references in Bradshaw *et al.* 2003, Krassay and Totterdell 2003, Blevin 2005). However, this has not resulted in drilling of offshore prospects and almost all additional palaeobotanical evidence comes from onshore sections in south-west South Australia. Examples are palaeobeach placer deposits (Clarke *et al.* 2003, Hou *et al.* 2003a, Li *et al.* 2003) and Tertiary palaeochannel sequences on the Gawler Craton (Hou *et al.* 2003b). A proposed correlation of Eocene sequences in the eastern Eucla Basin with regional sea-level events (Hou *et al.* 2006) is weakened by the large number of apparent anomalies in the palynostratigraphic dating (M.K. Macphail unpubl. comments). For example, an interval in CRAE-2, dated as late Early Eocene *Proteacidites asperopolus* Zone, includes species that first occur in the Gippsland Basin in the Early Oligocene (*Cyatheacidites annulatus*) and late Early Miocene (*Canthiumidites bellus*, *Symplocoipollenites austellus*). Whether these and other anomalies are due to downhole contamination, or reflect extended species ranges – with radical palaeoclimatic implications – is unclear.

South-East Australia

The tectonic and sedimentary histories of the Bass, Gippsland and Otway Basins continue to be reviewed by/for the earth resources industries (references in Bernecker and Partridge 2001, Partridge 2002, Blevin 2003, Holdgate *et al.* 2003a, 2003b, 2006b, McGowran *et al.* 2004, Paine 2005). The Ocean Drilling Program (ODP Leg 189) has significantly extended the existing geological and biostratigraphic database for the offshore Sorell Basin in western Tasmania, and the now deeply submerged South Tasman Rise and East Tasman Plateau (references in Boreham *et al.* 2002, Macphail 2002, Exon *et al.* 2004a, 2004b, Hill and Exon 2004). Regolith and groundwater projects have provided new information on Early Cretaceous and Late Tertiary environments in semi-arid to arid regions in eastern Australia, e.g. Hill *et al.* (2003) and Macphail (2006b). In contrast, university and museum-based research has tended to focus on lignitic deposits in Victoria and on the Southeastern Highlands of New South Wales (references in Sharp 2004, Paine *et al.* 2004, Brown 2006, Holdgate *et al.* 2006a). Piper *et al.* (2006) have reviewed Mesozoic-Cenozoic Local Faunas found in Victoria. Four recent studies of particular significance are:

1.   Revision of the *Esso-BHP* (spore-pollen) zonation for the Gippsland Basin and correlation of the zone boundaries against the Gradstein and Ogg (2004) Time Scale by A.D. Partridge (Monteil 2006). This project highlights difficulties in correlating 'local' zones defined by presence/absence criteria against the International Time Scale although the 'superzone' boundaries in this schema almost certainly reflect abrupt changes in global climate. For example the *Forcipites longus*/*Lygistepollenites balmei* Zone boundary, the *Lygistepollenites balmei*/*Malvacipollis diversus* Zone boundary and Middle/Upper *Nothofagidites asperus* Zone boundary correlate closely with the K/T Extinction Event at about 65 Ma, the PETM at about 55 Ma and opening of the Tasmanian Gateway between Australia and Antarctica at about 33 Ma, respectively (see Figure A). Studies of spore-pollen successions in other southern margin basins indicate that many species have extended or, less commonly, more restricted ranges compared to ranges recorded in the Gippsland Basin. For this reason, it is premature to assume 'equivalent' zones in the Bass, Murray, Otway and Eucla Basins have the same age limits as those inferred by A.D. Partridge (*ibid*) for the Gippsland Basin zones.

2.   Analysis of a Plio-Pleistocene lacustrine sequence preserved in the Stony Creek Basin, Daylesford in central Victoria. This site demonstrates that a number of biostratigraphically important taxa survived on the Central Highlands of Victoria some 2-5 million years after they became extinct at low elevations in the Gippsland and Murray Basins (cf. Macphail 1997, Partridge 1999, Sniderman *et al.* 2003, 2007, Macphail 2006a). Examples are (NLR in parentheses) a fern *Cyatheacidites annulatus* (*Lophosoria*) and a shrub gymnosperm *Podosporites microsaccatus* (cf *Microcachrys*). The finding highlights the need to find other palynostratigraphic criteria to subdivide Plio-Pleistocene time, e.g. by a detailed analysis of the Calival and Shepparton Formations.

3.   Analysis of Early Eocene sequences at Regatta Point and Lowana Road at Strahan on the West Coast of Tasmania. Macrofossils and microfossils preserved in these outcrops provide not only an exceptional record of the vegetation growing at high palaeolatitudes in southern Australia during this critical warm period but (Lowana Road) also preserve what may be the earliest known organic fossils of *Eucalyptus* (R. Carpenter, R.S. Hill and G. Jordan unpubl. results). It is possible that deeper intervals within the section preserve macro- and microfossils accumulating during the PETM Event itself. Carpenter *et al.* (2004) have described a broadly contemporary Early Eocene flora from near the summit (1723 m asl) of Mt. Hotham in eastern Victoria.

4.   A review of palaeobotanical evidence for the onset of climate-forced xeromorphy (Hill and Brodribb 2001). This study provides compelling evidence of the adaptive responses to aridification in two prominent and widespread Australian sclerophyll plant families during the Late Tertiary.

Regional comparisons

A highly useful review of the composition and ecology of modern tropical and paratropical rainforests, their origins in the Cretaceous and their evolution during the Cenozoic has been published by Morley (2000). This compares the Australian palaeobotanic record with those of South-East Asia and more distant landmasses, viz. Africa, India, New Zealand, South America, North America and Europe, and uses palynostratigraphic evidence to identify plant dispersal paths between these landmasses during the Tertiary.

How enduring the palaeoclimatic reconstructions inferred herein for the various regions of Australia, or indeed for any of the above continental landmasses, will be is unclear. Very recent discoveries such as the presence of glaciers in Greenland some 20 million years earlier than previously documented (Eldrett *et al*. 2007) suggests a short 'shelf life'.

Table A: **20001-2007 literature (subject in parentheses)**

Chronostratigraphy

Aubry *et al*. 2005 [nomenclatural clarification of the Neogene and Quaternary]
Cooper 2004 [NZ Geologic Time Scale]
Gradstein and Ogg 2004 [Geologic Time Scale 2004]
Husing *et al*. 2006 [Neogene geological timescale]
Monteil 2006 [updates of Mesozoic-Cenozoic palynostratigraphies in terms of the 2004 Time Scale]
Ogg 2004 [status of divisions of the International Time Scale]
Walsh 2006 [critique of proposed subdivision of the Cenozoic Era]
Watchman and Twidale 2002 [relative and absolute dating of landsurfaces]
Zalasiewicz *et al*. 2004 [chronostratigraphic terminology]

Climatic models and palaeoclimatic studies

Alley and Frakes 2003 [Early Cretaceous glaciation, South Australia]
Alley *et al*. 2003 [abrupt climatic change]
Andersson *et al* 2002 [mid Pliocene temperature record, Southern Ocean]
Atahan *et al*. 2004 [Pliocene charcoal record, SW Western Australia]
Demicco *et al*. 2003 [Cenozoic atmospheric ρCO_2]
Dodson and Ramrath 2001 [mid Pliocene aridity events, SW Western Australia]
Dodson and Macphail 2004 [mid Pliocene climates, SW Western Australia]
Eldrett *et al*. 2007 [Eocene-Oligocene continental glaciation of Greenland]
Erbacher *et al*. 2001 [Aptian anoxic event linked to increased continental runoff]
Exon *et al*. 2002 [climatic consequences of opening of the Tasmanian Gateway, Tasmania]
Frakes and Barron 2001 [Phanerozoic general circulation model for Australia]
Fujioka *et al*. 2005 [Pliocene initiation of stony deserts, central Australia]
Gallagher *et al*. 2003 [Pliocene climates, SE Australia]
Gibbs *et al*. 2006 [PETM warming events]
Jahren *et al.* 2001 [Early Cretaceous analogue of the PETM].
Katz *et al*. 2001 [triggers for the PETM]
Lawver & Gahagan 2003 [opening of Drake Passage]
Lourens *et al*. 2005 [PETM warming events]
Megirian *et al*. 2004 [Oligo-Miocene climates, central Australia]
Petrozzo 2002 [Late Cretaceous palaeoclimates, Exmouth Plateau]
Sniderman *et al*. 2007 [Plio-Pleistocene climates, SE Australia]
Warnaar 2006 [Eocene-Oligocene opening of the Tasmanian gateway to deepwater circulation]
Zachos *et al*. 2003. [tropical sea surface temperatures during the PETM]

Palaeoclimatic proxies

Burnham *et al*. 2001 [leaf margins]
Huff *et al*. 2003 [leaf architecture]
Nathan *et al*. 2002 [long distance dispersal of seeds by wind]
Osborne and Beerling 2002 [CO_2 and tree growth]
Royer *et al*. 2002 [CO_2 and freezing sensitivity]
Schimel and Baker 2002 [wildfires]
Shakesby and Doerr 2006 [wildfires]
Taylor and Shirtliff 2003 [weathering],
Van Bergen and Poole 2002 [stable carbon isotopes]

Basin and related studies

Anand and Paine 2002 [regolith geology, Yilgarn Craton, Western Australia]
Bernecker and Partridge 2001 [Late Cretaceous sedimentation in the Gippsland Basin, Victoria]
Blevin (Compiler) 2003 [Cretaceous-Tertiary Bass Basin, Bass Strait]
Blevin 2005 [Bremer and Denmark Sub-basins, SW Australia]
Boreham *et al*. 2002 [Sorell Basin, W Tasmania]
Bradshaw *et al.* 2003 [Jurassic-Cretaceous Bight Basin, SW Australia]
Brown 2006 [Tertiary drainage, SE Highlands, New South Wales]

Table A (cont.)

Basin and related studies (cont.)

Cathro and Austin 2001 [mid Miocene karstification, Carnarvon Basin, Western Australia]
Cecil and Edgar 2003 [climate controls on stratigraphy]
Clarke *et al.* 2003 [Middle-Late Eocene stratigraphy, Eucla Basin, South Australia]
Clarke *et al.* 2004 [Neogene, St. George Basin, southern Queensland]
Collins *et al.* 2006 [Miocene carbonates, NW Western Australia]
Conesa *et al.* 2005 [Miocene palaeoenvironments, Marion Plateau, NE Queensland]
de Broekert 2003 [regolith, Yilgarn Craton, Western Australia]
Exon *et al.* 2001 [deepwater basins around Tasmania]
Exon *et al.* 2004a [Cretaceous-Holocene history of the Tasmanian Gateway, Tasmania]
Exon *et al.* 2004b [Cretaceous-Oligocene tectono-sedimentary history, Tasmanian region]
Exon *et al.* 2005 [submarine canyons, Bight Basin, SW Australia]
Forsyth and Nott 2003 [drainage evolution, Cape York Peninsula, NE Queensland]
Gammon and James 2001 [Eocene nearshore environments, Bremer and western Eucla Basins, Western Australia]
Heine and Muller 2005 [Late Jurassic rifting, North West Shelf, NW Australia]
Hill and Exon 2004 [basin development, Tasmanian Offshore Zone, Tasmania]
Hill *et al.* 2003 [palaeovalley systems, Broken Hill, New South Wales]
Holbourn *et al.* 2004 [Middle Miocene evolution, NW and SW margins]
Holdgate *et al.* 2001 [Tertiary coals, Torquay Basin, Victoria]
Holdgate *et al.* 2003a [Plio-Pleistocene tectonics and eustasy, Gippsland Basin, Victoria]
Holdgate *et al.* 2003b [Latrobe Group, Gippsland Basin, Victoria]
Holdgate *et al.* 2006a [palaeoriver systems, Central Highlands, Victoria]
Holdgate et al. 2006b [Middle Miocene Yallourn coal seam, Gippsland Basin, Victoria]
Hou et al. 2003a [Tertiary beach deposits, eastern Eucla Basin, SW Australia]
Hou *et al.* 2003b [Tertiary palaeovalleys, South Australia]
Hou *et al.* 2006 [Eocene stratigraphic succession in the Eucla Basin, South Australia]
Jaques *et al.* 2002 [mineral systems of Australia]
Jones 2006 [Cenozoic landscape evolution, central Queensland]
Kelley *et al.* 2001 [Oligo-Miocene Torquay Group, SE Australia]
Krassay and Totterdell 2003 [Late Cretaceous sedimentation, Bight Basin, SW Australia]
Latimer and Filippelli 2002 [opening of Drake Passage, SW Atlantic Ocean]
Li *et al.* 2003 [Middle-Late Eocene lithostratigraphy, Great Australian Bight, SW Australia]
Macphail 2001 [comparison of the Gippsland and Taranaki Basin (NZ)]
McGowran *et al.* 2004. [Cenozoic stratigraphic succession in southern Australia]
Mavromatidis 2006 [burial/exhumation histories, Cooper-Eromanga Basins, central Australia]
Molina-Garza and Fuller 2002 [Cenozoic palaeomagnetic data, Australia]
Paine 2005 [Late Miocene-Pliocene beach deposits, Murray Basin, SE Australia]
Paine *et al.* 2004 [Pliocene strandlines, SW Victoria]
Partridge 2001 [stratigraphy of the Sherbrook Group, Otway Basin, SE Australia]
Partridge 2002 [chronostratigraphy of the Otway Basin, SE Australia]
Pickett 2003 [post Middle Miocene laterite formation, coastal New South Wales]
Pidgeon *et al.* 2004. [Late Miocene laterites, Darling Range, Western Australia]
Sandiford 2003 [Late Neogene tectonics, Otway Ranges, SE Australia]
Sharp 2004 [Cenozoic stream derangement, SE Highlands, New South Wales]
Sutherland *et al.* 2006 [Cretaceous-Tertiary sediments, Tamar Trough, N Tasmania]
Taylor and Gentle 2002 [Tertiary palaeodrainage, Victoria]
Twidale 2002 [origin of etchplains]
Wei 2004 [opening of the Australia-Antarctic Gateway, Tasmania]
Wopfner, H. and Twidale 2001 [origins of Australian desert dunes]
Young and McDougall 2004 [Cenozoic stream derangement, SE Highlands, New South Wales]
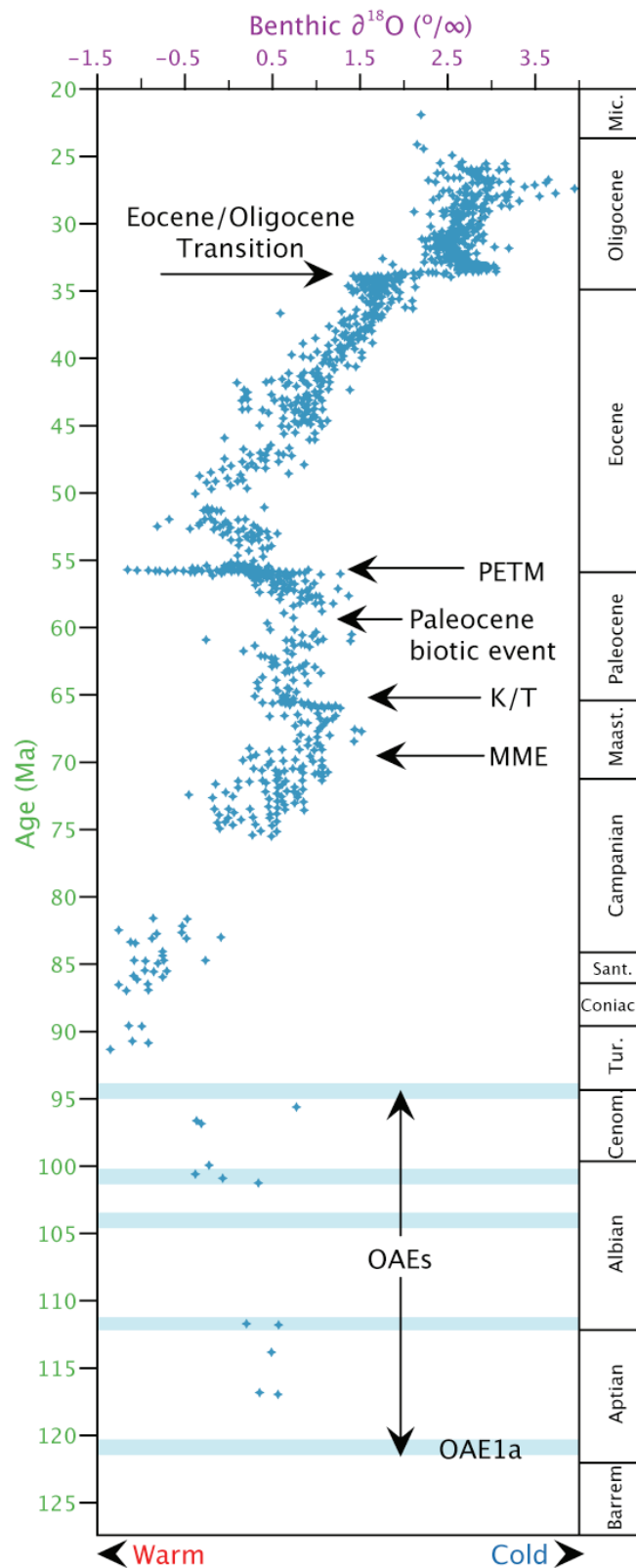
Table A (cont.)

Biostratigraphy

Backhouse 2006 [Albian Gearle Siltstone, southern Carnarvon Basin, Western Australia]
Crouch *et al*. 2001 [PETM event]
Jordan and Hill 2002 [Cenozoic plant macrofossil sites in Tasmania]
Laurie and Foster 2001 [Mesozoic plant microfossils]
Macphail 2002 [Tasmanian Offshore Zone, Tasmania]
Macphail, 2004a [palynostratigraphic data, Denmark and Bremer Sub-basins, SW Western Australia]
Macphail, 2004b [palynostratigraphic data, St. George Basin, SE Queensland]
Monteil *et a*l. 2004 [palynostratigraphic data, Otway Basin]
Oosting 2004 [Barremian-Aptian dinoflagellates]
Oosting *et al*. 2006 [interhemispheric correlation of Barremian-Aptian dinocyst assemblages]
Partridge *et a*l. 2003 [palynostratigraphic data, offshore Tasmania]
Quilty 2001 [Australia-Antarctic correlation]
Sajjadi and Playford 2002a [Late Jurassic-earliest Cretaceous palynostratigraphy, Eromanga Basin, Queensland]
Sajjadi and Playford 2002b [Late Jurassic-earliest Cretaceous palynostratigraphy, Eromanga Basin, Queensland
Sinclair and Monteil 2004 [palynostratigraphic data, Otway Basin]
Taylor and Haig 2001 [Barremian foraminifera, Carnarvon Basin, Western Australia]
Tosolini *et a*l. 2002 [correlation using Early Cretaceous megaspore assemblages]
Williams *et al*. 2004 [Late Cretaceous-Neogene dinocyst events in the Southern Ocean]

Palaeobotany, palaeontology, palaeoecology

Archer *et al*. 2001 [vertebrate palaeoecology]
Barnes *et al*. 2001 [Tertiary Cunoniaceae]
Brooks *et al* 2003 [long term control on floodplain vegetation]
Burslem *et al*. 2001 [diversity of modern rainforests]
Carpenter *et al*. 2004 [Early Eocene flora, Mt. Hotham, eastern Victoria]
Dettmann and Clifford 2002 [Tertiary Anacardiaceae]
Dettmann and Clifford 2003 [Miocene flora, Bundaberg Trough, SE Queensland]
Greenwood *et al*. 2001 [Tertiary *Banksia*, central Australia]
Hill 2001 [*Nothofagus* evolution and palaeoecology]
Hill and Brodribb 2001 [onset of xeromorphy in the Casuarinaceae and Banksieae]
Hill and Paull 2003 [Tertiary Cupressaceae in Tasmania]
Hill and Whang 2000 [Miocene Podocarpaceae]
Hocknall 2005 [Late Cenozoic faunas, Queensland]
Itzstein-Davey 2004 [Late Eocene Proteaceae]
Levin 2004 [ecological speciation]
Mackensen *et al*. 2003 [decomposition rates of woody detritus]
Macphail and Hill 2001 [Australian Tertiary Mimosaceae]
Macphail and Hill 2002 [Poaceae]
Martin 2001 [Tertiary Convolvulaceae]
Martin 2002 [Tertiary Malpighiaceae]
Martin 2003 [Tertiary Onagraceae]
McLaughlin 2001 [floristic impact of the break-up of Gondwana]
Morley 2000 [evolution of tropical and paratropical rainforests]
Piper *et al*. 2006 [Mesozoic-Early Quaternary mammal faunas of Victoria]
Poole 2002 [Cretaceous-Tertiary *Nothofagus*]
Read *et al*. 2005 [phytogeography and climatic analysis of *Nothofagus* subgenus *Brassospora*]
Roshier *et al*. 2001 [temporary wetlands in arid Australia]
Sniderman et al. 2003 [Plio-Pleistocene vegetation, Central Highlands, Victoria]
Swenson *et al*. 2001 [*Nothofagus* biogeography]
Wignell 2001 [volcanism and wildfires]

Figure A: **Generalised climatic curve of the Cretaceous and Palaeogene derived from deep-sea oxygen isotope data (from Zachos *et al.* 2001). Note: Gradstien and Ogg. 2004. have shifted the age ranges some stages.**

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PREFACE

Brief

In late 1997, the author was contracted by the Cooperative Research Centre for Landscape Evolution and Mineral Exploration (CRC LEME) to review published palaeobotanical evidence for changes in continental climates in Australia during the Cretaceous and Tertiary Periods, an interval that covers the last ~145 million years of geological time. Limited opportunities were provided to extend the palaeobotanical database by analysing fossiliferous deposits preserved in areas of particular interest to CRC LEME, e.g. the Yilgarn goldfields. The monograph required some thirty months to complete, nine of which were funded by CRC-LEME.

Credentials

The author is a palynologist/palynostratigrapher, specialising in the Mesozoic and Cenozoic palynostratigraphy and palaeoecology of the Australasian region. Relevant industry and academic research experience over the past 20 years includes the revision of the *Esso-BHP* palynostratigraphy (with A.D. Partridge) and the development of regional palynostratigraphies for the Cenozoic Murray-Darling Basin (Macphail and Truswell 1989, 1993, Macphail 1999) and analysing correlative sequences in western, central southern and northwestern Australia (Macphail 1996c, 1997a, unpubl. results).

The palaeobotanical and palaeoenvironmental data generated by this research and the studies of colleagues working on Australian macrofloras and microfloras over the past 30 years form the basis of this review.

Relationship to CRC LEME objectives

This review forms part of the CRC LEME mission to:

1. Develop a framework for the three dimensional evolution of the Australian landscape.

2. Translate this knowledge into improved mineral exploration methods for Australia.

The study is part of Program 4 [Synthesis] with applications in Program 1 [Shield Regions], Program 2 [Tasman Fold Belt] and Program 3 [Basins]. Recent studies exploring the relationship between regolith evolution, minerals, climate (and vegetation) include Butt (1998), Hill *et al.* (1998), Hughes *et al.* (1998), Pain *et al.* (1998) and Taylor (1998).

Disclaimer

In common with previous reviews, the resolution of Cretaceous-Cenozoic climatic change is limited by the serendipitous factors of sampling and preservation, the uncertain relationship between many plants and their environment in the past, and the varying reliability of the chronostratigraphic schema by which the palaeobotanical events are correlated. Put another way, the biased distribution and uneven sampling of fossiliferous deposits, and the complex response and resilience of individual plants and the communities in which they coexist, are as much a fact of life in Australia as elsewhere (Macphail *et al.* 1994). The author is not a palaeoclimatologist and no attempt has been made to interpret inferred palaeoclimates in terms of present or past synoptic patterns (cf. Gentilli 1972, Bowler 1982)

EXECUTIVE SUMMARY

This review presents 'first pass' palaeoclimatic reconstructions for seven geographic regions, which encompass mainland Australia and Tasmania, and eleven time slices, which cover Berriasian to Late Pliocene time.

These regions usually encompass a range of bioclimates whilst the individual time slices may encompass more than one climatic excursion. For this reason, the climatic synopses (see Summary Tables) should be treated as working hypotheses only.

The palaeoecological and other relevant data upon which the palaeoclimatic inferences are based are summarised in Section 5 [Early Cretaceous], Section 6 [Late Cretaceous] and Section 7 [Tertiary]. The primary data are analysed in Appendix 1 (Cretaceous) and Appendix 2 (Tertiary).

The analysis of the Australian palaeobotanical database is supported by discussion on:

- The complex interaction between climate and plants, the role of climatic change as an agent in regolith development, and the nature and limitations of the palaeobotanical and associated geochronological evidence [Sections 1-4].

- The global framework against which climatic change occurred in Australia during the Early Cretaceous, Late Cretaceous and Tertiary [Sections 5.1, 6.1 and 7.1].

The review concludes by proposing ways by which (1) the existing palaeobotanical database may be extended and (2) suggesting quantitative techniques that will maximise the retrieval of palaeoclimatic information from the extant database [Section 8].

I. GENERAL CONCLUSIONS

At present plant fossils, especially pollen and spores, provide the only cost-effective, moderately reliable means for dating continental sedimentary sequences and reconstructing the climates under which they accumulated *over the range of terrestrial environments* present in Australia during the Cretaceous and Tertiary.

Palaeoclimatic inferences can be made using presence/absence data but statistically reliable quantitative data are essential if the maximum information is to be extracted from the palaeobotanical (and related) database.

Oxygen isotope data, minerals such as glendonites and palaeogeographic data provide the most robust evidence for past temperatures. In most instances, the palaeobotanical data provide a reliable indication of past temperature and rainfall regimes.

Changes in palaeotemperature correspond well with general trends in global temperature. However, conditions inferred for coastal regions are a relatively poor guide to environments occurring inland or on upland sites.

At no time during the Cretaceous or Tertiary have uniform conditions existed across the continent although environmental gradients may have been weaker during the Early Cretaceous to Late Tertiary. `The orientation of some latitudinal gradients will have changed as the Australian continent rotated around the geographic South Pole during the Cretaceous.

Epicontinental seaways helped maintain high humidity in the interior of the continent during the Aptian and Albian. Orographic effects (uplands) and rivers and groundwater (lowlands) helped maintain humid microclimates during the Late Tertiary aridification of the continent.

i. Early Cretaceous climates

None of the nearest living relatives (NLRs) of Cretaceous plants growing at high to polar latitudes are adapted to prolonged darkness and mild conditions and, with few exceptions, the existing palaeobotanical evidence does not permit Early Cretaceous climates to be reconstructed in unambiguous terms. This is due to the uncertain ecology of most commonly occurring taxa and the lack of objectively expressed (quantitative) data for many sites.

Photoperiod

Low light intensities, including prolonged darkness during winter months, are likely to have shaped the composition and structure of Cretaceous plant communities in palaeo-central and southern Australia.

Temperature

Conceptualising Early Cretaceous climates as 'warm' is misleading despite the undoubted presence of timber-sized trees at high to polar latitudes.

On present indications, Berriasian-Albian temperatures in palaeo-southern and central Australia were cool-cold (lower mesotherm to microtherm range). Temperatures in palaeo-northern Australia appear to have been relatively warm (upper mesotherm). Because of rotation of the continent about the geographic South Pole, these regions do <u>not</u> correspond with modern central southern and northern Australia.

Rainfall

Apart from present-day northwestern Australia where climates may have been seasonally dry during the Berriasian-Barremian, humid to perhumid climates extended across the continent throughout Early Cretaceous time. 'Maximum' humidity occurred during the Aptian-Albian, possibly due to the presence of extensive epicontinental seas.

Seasonality

Comparisons of the Early Cretaceous data imply that seasonal variations in temperature were higher in the interior of the continent.

ii. Late Cretaceous climates

Palaeobotanical evidence becomes increasingly reliable as proxy-climatic data during the Late Cretaceous. By Maastrichtian time, the continent had more or less attained its present-day orientation with respect to the South Pole although the continent was located at middle to high palaeolatitudes.

Photoperiod

Low light intensities continued to influence the composition and/or structure of plant communities growing in southern and central Australia but probably not in regions further to the north.

Temperature

Climates in palaeo-southern Australia appear to have cooled (lower mesotherm-microtherm). Warmer (upper mesotherm) conditions are recorded in palaeo-northern Australia (present-day northwestern Australia).

Rainfall

Precipitation may have decreased (humid range) or become more seasonal in southeastern Australia.

Seasonality

Seasonal contrasts in temperature are likely to have remained strong due to the location of the continent at high palaeolatitudes.

iii.   Tertiary Climates

With few exceptions, only Late Neogene climates can be reconstructed in quantitative terms.

Photoperiod

Low light intensities ceased to be an important forcing factor during the Late Paleocene.

Temperature

Warming during the Paleocene culminated in maximum Tertiary warmth during the early Early Eocene when very warm to hot (upper mesotherm-megatherm) temperatures are recorded in northwestern, central, southwestern, central southern and southeastern mainland Australia and, locally, in western Tasmania. The clearest indication of the impact of abrupt warming during the PETM is the presence of a tropical mangrove palm (*Nypa*) at a palaeolatitude of 66^0 S in Macquarie Harbour on the West Coast of Tasmania.

Locally warm (mesotherm range) climates persisted into late Early Eocene time in Macquarie Harbour and in the Gippsland Basin in southeastern Victoria, and into Middle-Late Eocene time in the Polda and St. Vincent Basins in southwestern South Australia. Temperatures in coastal northeastern Queensland were relatively cool (lower mesotherm) during the Early Eocene, possibly due to cool currents flowing northwards along the eastern margin.

Very warm to hot (megatherm range) climates persisted in northwestern Australia throughout the Middle-Late Eocene and similar (upper mesotherm) conditions first developed in northeastern Australia during the Oligo-Miocene. Temperatures in northern Australia are likely to have remained very warm to hot throughout the Neogene due to rapid northward drift of the continent, despite the global cooling trend.

Temperatures in central and southern Australia decreased (mesotherm range) during the Middle Eocene although there is weak evidence for temporary warming in southeastern Australia during the late Eocene

Abrupt cooling associated with the development of the Circum-Antarctic Current is recorded in southeastern Australia during the Eocene-Oligocene transition. The effects were most severe in Tasmania where the event is associated with transient glaciation (Lemonthyme Glaciation) on the north-west Central Plateau. The same event is reflected in major impoverishment of the temperate rainforest flora in the Gippsland Basin. Temperatures in central southern and southwestern Australia remained relatively warm (lower mesotherm), probably due to warm water 'gyres' within the Bight.

Conditions in southern Australia appear to have been milder (mesotherm range) during the Early Miocene than during the Early to Late Oligocene or Middle to Late Miocene.

Climates in coastal southwestern and central southern Australia were warmer (mesotherm range) during the Early Pliocene than during the Late Pliocene or Quaternary. The warm phase correlates with the mid Pliocene warm event recorded elsewhere at middle-high latitudes.

Rainfall

Precipitation appears to have increased during the Paleocene. The Early Eocene warm period is associated with wet to very wet (perhumid) conditions across the continent, including in central and northwestern Australia where rainfall may have become strongly seasonal (possibly monsoonal). Similar conditions persisted into Middle-Late Eocene time except that rainfall became more variable (possibly less reliable) in central and southwestern Australia and more uniformly distributed (or more reliable during summer months) in southeastern Australia.

By Oligo-Middle Miocene time, subhumid conditions prevailed in north-west Australia and there is limited evidence for a decrease in rainfall (humid range) in central and southwestern Australia. Rainfall remained perhumid in the north-east, central south and south-east mainland Australia and in Tasmania.

There is weak evidence for wetter conditions in central southern and southwestern Australia, and relatively strong evidence for wetter conditions on the Southeastern Highlands, during the Mid Pliocene warm phase. One site in south-west Western Australia (Yallalie) provides unequivocal evidence for three periods of aridification, at 2.9 Ma, 2.59 Ma and 2.56 Ma, during the same period. The vegetation response is broadly similar to that observed during Quaternary glacial-interglacial cycles, and parallels the development of continental ice sheets in the Northern Hemisphere. By Late Pliocene time, essentially modern bioclimatic regimes were in existence.

Seasonality

Seasonality, measured by the seasonal distribution and, in central and northwestern Australia, the reliability of rainfall, increased markedly during the Late Palaeogene and Neogene. The trend included a steep increase in the lapse rate (decrease in air temperature with increasing elevation), which may have been associated with decreasing CO_2 levels.

II.   FUTURE DIRECTIONS

For most geological epochs, the Australian palaeobotanic record is commensurate with records preserved on other landmasses in the Southern Hemisphere. Two Australian sequences however, preserve exceptionally detailed records for short periods of geological time. These are (1) the 34 m long Lemonthyme Creek sequence in north-west Tasmania, which is likely to correlate with the development of the Circumantarctic Current during the Eocene-Oligocene transition, and (2) the 110 m thick Yallalie sequence in south-west Western Australia, which correlates with the initiation of continental ice-sheet development in the Northern Hemisphere. Early Eocene sequences preserved at Regatta Point near Strahan in western Tasmania, may preserve a detailed record of the PETM as well as its continuing impact at this high palaeolatitudes site throughout the Early Eocene.

Application of objective (statistical) techniques used to extract palaeoclimatic data from Late Quaternary palynosequences is likely to improve the reliability of Cretaceous and Tertiary climate reconstructions in Australia. These are *Isopollen Mapping* (Birks and Birks 1980), *Biome Analysis* (Prentice and Webb 1998) and *Principal Components Analysis*, respectively.

SUMMARY OF INFERRED CRETACEOUS PALAEOCLIMATES

Meteorological parameter	INFERRED PALAEOCLIMATE						
	North-West	North-East	Centre	South-West	central southern	South-East	Tasmania
TIME SLICE K-1: BERRIASIAN to BARREMIAN 141-115 Ma							
temperature	lower mesotherm?	microtherm range	microtherm range	lower? mesotherm	lower mesotherm	microtherm range?	no record
rainfall	humid?	humid	humid-perhumid	humid	humid	humid-perhumid	
seasonality	strong (temperature)	strong (temperature)	strong (temperature)	strong? (temp.)	strong? (temp.)	strong (temperature)	
TIME SLICE K-2: APTIAN to ALBIAN 115-97.5 Ma							
temperature	mesotherm range	microtherm range	microtherm range	lower mesotherm	microtherm range	lower microtherm	no record
rainfall	humid	humid-perhumid	humid	humid	humid-perhumid	perhumid	
seasonality	weak?	strong (temperature)	strong (temperature)	weak?	strong? (temp.)	strong (temperature)	
TIME SLICE K-3: CENOMANIAN 97.5-91 Ma							
temperature	upper mesotherm	mesotherm range	upper microtherm	lower mesotherm	micro-mesotherm	micro-mesotherm	no record
rainfall	perhumid	humid	humid	subhumid?	humid	humid	
seasonality	strong? (rainfall)	strong? (rainfall)	weak (temperature)	strong (rainfall)?	weak (temperature)	weak (temperature)	
TIME SLICE K-4: TURONIAN to SANTONIAN 91-83 Ma							
temperature	upper mesotherm?	no record	no record	no record	lower mesotherm?	upper microtherm	microtherm range
rainfall	humid-perhumid				humid-perhumid	humid-perhumid	humid-perhumid
seasonality	strong (rainfall)				±uniform (rainfall)	±uniform (rainfall)	strong (temperature)
TIME SLICE K-5: EARLY CAMPANIAN 83-70 Ma							
temperature	upper mesotherm	no record	no record	no record	micro-mesotherm	microtherm range	no record
rainfall	humid-perhumid				humid	perhumid	
seasonality	strong? (temp.)				weak (rainfall)?	±uniform (rainfall)	
TIME SLICE K-6: LATE CAMPANIAN to MAASTRICHTIAN 70-65 Ma							
temperature	meso-megatherm	no record	no record		upper microtherm	upper microtherm	upper microtherm
rainfall	no record		variable (rainfall)		humid	humid	humid
seasonality	strong (rainfall)				strong (rainfall)	strong (rainfall)	strong (rainfall)

SUMMARY OF INFERRED TERTIARY PALAEOCLIMATES

Meteorological parameter	INFERRED PALAEOCLIMATE						
	North-West	North-East	Centre	South-west	central southern	South-East	Tasmania
TIME SLICE T-1: PALEOCENE 65-54.8 Ma							
temperature	upper mesotherm	lower mesotherm	mesotherm range #	upper mesotherm *	lower mesotherm	lower mesotherm	upper microtherm
rainfall	subhumid-?humid	humid-perhumid	humid	subhumid-humid	humid-perhumid	humid-perhumid	perhumid-humid
seasonality	strong (rainfall)	weak (rainfall)	weak (rainfall)	strong (rainfall)	weak (rainfall)	±uniform (rainfall)	±uniform (rainfall)
TIME SLICE T-2: EARLY EOCENE 54.8-49 Ma							
temperature	megatherm range *	mesotherm range	upper mesotherm	upper mesotherm *	upper mesotherm *	upper mesotherm *	mesotherm range *
rainfall	perhumid	humid-perhumid	perhumid	perhumid	humid-perhumid	humid-perhumid	perhumid
seasonality	strong (rainfall)	weak (rainfall)	weak (rainfall)	strong (rainfall)	weak (rainfall)?	weak (rainfall)	weak (temperature)
TIME SLICE T-3: MIDDLE to LATE EOCENE 49-33.7 Ma							
temperature	megatherm range *	mesotherm range *	mesotherm range	mesotherm range	mesotherm range *	mesotherm range	micro- mesotherm
rainfall	humid-perhumid	perhumid	humid-perhumid	humid-perhumid	perhumid	perhumid	perhumid
seasonality	strong (rainfall)	weak (rainfall)	variable (rainfall)	variable (rainfall)	weak (rainfall)	weak (rainfall)	±uniform (rainfall)
TIME SLICE T-4: OLIGOCENE to MIDDLE MIOCENE 33.7-11.2 Ma							
temperature	megatherm range	mesotherm range *	lower mesotherm	lower mesotherm	lower mesotherm	mesotherm range	microtherm range
rainfall	subhumid-semiarid	perhumid	humid	subhumid-humid	perhumid	humid-perhumid	perhumid
seasonality	strong (rainfall)	weak (rainfall)	variable (rainfall)	variable (rainfall)	weak (rainfall)	variable (rainfall)	±uniform (rainfall)
TIME SLICE T-5: LATE MIOCENE to PLIOCENE 11.2-1.78 Ma							
temperature	megatherm range	upper mesotherm	lower mesotherm	mesotherm range	mesotherm range	mesotherm range	microtherm range
rainfall	subhumid-semiarid	humid-perhumid	subhumid-humid	subhumid-humid	subhumid-semiarid	humid-perhumid	perhumid
seasonality	strong (rainfall)	strong (rainfall)	strong (rainfall)	strong (rainfall)	strong (rainfall)	weak (temperature)	strong (temperature)

possibly Early Eocene
* *Nypa* present

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INTRODUCTION

Mineral resources, whether precious or base metals, hydrocarbons or groundwater, continue to underpin the Australian economy.

In most cases, the geologic environment controls mineral formation. Minerals found in alluvium (placer deposits) or weathered bedrock (saprolite deposits), and groundwater and hydrocarbon reserves are exceptions in that these have indirect or direct links to past climates and/or vegetation.

This report reviews palaeobotanical and related data for climatic change in continental Australia during the Cretaceous (141-65 Ma) and Tertiary (65-1.78 Ma).

Amongst the more unmistakable indicators of climatic change are the fruits and foliage of trees whose nearest living relatives (NLRs) are confined to tropical rainforest, and the skeletal remains of freshwater crocodiles, dolphins and turtles preserved in the (now) arid north of South Australia. The fossil cysts of algae and the spores and pollen of the higher plants provide less obvious but much more widespread evidence of past climates. The same microfossils also provide a cheap, relatively precise means of dating the host sediments.

The relationships between plants, climate and other elements making up ancient or 'hidden' (Fortey 1993) landscapes remain speculative. However, it is certain that environmental forces in the past included extreme (catastrophic) terrestrial and extraterrestrial events as well as more gradual changes in rainfall and temperature (Budyko 1999). The relative importance of the individual processes can be difficult to unravel. Nonetheless, there is every reason to suppose that ecological relationships were varied during the Cretaceous and Tertiary as they are now, and many organisms were able to reproduce and disperse under less than optimal conditions.

For these reasons, this monograph briefly discusses the strengths and weaknesses of palaeobotanical and other forms of proxy-climatic evidence, as well as modern bioclimatic relationships. These relationships provide benchmarks for inferring regional trends in temperature and rainfall during the Cretaceous and Tertiary.

Sloan and Morill (1998) claim that terrestrial palaeotemperature is the key to understanding the past. In Australia, rainfall is equally or more important and trends in the amount and seasonal distribution of rainfall in the past is a primary focus of the review.

A.   RELATIONSHIP OF THIS STUDY TO PREVIOUS REVIEWS

a.   Previous reviews

Numerous papers and monographs purporting to review the evolution of the Australian environment during the Mesozoic and/or Cenozoic are in print. In spite of ambitious titles that imply an Australia-wide coverage, reconstructions published before about 1990 are almost always based on specific deposits (usually in southeastern Australia) that represent relatively short intervals of geologic time.

This situation changed dramatically in 1994 with the publication of *History of the Australian Vegetation: Cretaceous To Recent* (Hill 1994a) for two reasons. Firstly, the majority of articles did attempt to review all published data on a continent-wide basis, e.g. Quilty (1994) and Taylor (1994). Secondly, for the first time a concerted attempt was made to incorporate unpublished data generated by the earth resources industries, e.g. Dettmann (1994) and

Macphail *et al*. (1994). Equally importantly, the book was instrumental in re-establishing fossils as a primary source of information on past environments.

Since then, several syntheses of Australian Phanerozoic climates have appeared, including three during the preparation of this review. These are: (1) the *Evolution of Australian environments* by L.A. Frakes (1999), (2) the *Evolution of the Australian flora: fossil evidence* by R. S. Hill, E.M. Truswell, S. McLoughlin, and M.E. Dettmann (1999) and (3) the *Palaeobiology of Australian faunas and floras*, edited by A.J. Wright, *et al*. (2000). The first two overviews appear in the revised *Introduction Volume* of the *Flora of Australia* Series (ABRS/Environment Australia). The last overview comprises a number of related synopses of Mesozoic-Cenozoic floras and faunas published by the Association of Australasian Palaeontologists. A monograph by S. McLoughlin titled *The break-up of Gondwana and its impact on the pre-Cenozoic floristic provincialism* is in press (Australian Journal of Botany 49: 271-300, 2001).

Significantly these syntheses were prepared in response to requests by the biological, not earth, sciences community even though much of the data (or samples) were 'by-products' of geological exploration.

Hill (1992a), Hill *et al*. (1996), Swenson *et al*. (2000), Hill and Scriven (1998) and Hill and Brodribb (1999) have reviewed the history of *Nothofagus* and the three major Southern Hemisphere gymnosperm families Araucariaceae, Cupressaceae and Podocarpaceae, respectively. Hill *et al*. (1999) and Greenwood *et al*. (2000) have reviewed fossil evidence for Tertiary vegetation in Tasmania and Victoria, respectively. Otherwise, the most recent reviews, which specifically focus on palaeobotanical evidence for Cretaceous-Tertiary floras and environments, are: Dettmann and Jarzen (1988, 1990, Kershaw (1988), Hill (1992b, 1994a), Truswell (1993), Dettmann (1994), Kershaw *et al*. (1994), Macphail *et al*. (1994), Martin (1994), Specht and Dettmann (1995), Macphail (1997a, 1997b) and Martin (1998a). Earlier but still valuable overviews are Kemp (1978), Barlow (1981), Dettmann (1981), Nix (1982), Lange (1982) and Truswell and Harris (1982).

Useful analyses of the present-day vegetation and environments in Australia and neighbouring landmasses are provided by Webb *et al*. (1984), Jeans (1986), Floyd (1989), Adam (1994), Boland *et al*. (1994), Groves (1994, 1999), Enright *et al*. (1995), Specht and Dettmann (1995), Donoso (1996), Ogden *et al*. (1996), Read and Brown (1996), Read and Hope (1996), Veblen *et al*. (1996) and Fox (1999). Blevin (1991), Quilty (1994), Taylor (1994), Wilford and Brown (1994), Langford *et al*. (1995) and Stagg *et al*. (1999) provide valuable reviews of the tectono-sedimentary histories of the continental margin basins where much of the palaeobotanical evidence is preserved.

b.   This review

This review differs from the above studies in three respects: (1) As far as is known, it is the first of its type in Australia to be explicitly part-funded by the mineral resources industry. (2) The author has attempted to review all accessible unpublished industry and government reports known or likely to include information on Cretaceous-Tertiary floras, as well as the formally published literature up to 2000 (see Section 9). (3) Within the time constraints of the project, additional material has been located (often with difficulty) and quantitatively analysed to fill known gaps in the chronostratigraphic record.

Visits to the Geological Surveys of New South Wales, South Australia and Western Australia uncovered a plethora of unpublished palaeontological reports spanning the last 120 years. Some important material continues to be held by private individuals. For example, Late Cretaceous environments in the Pilbara region in the north of south-west Western Australia are inferred from a single sample donated 'out of interest' some 25 years ago to Emeritus

Professor B. Balme (Geology Department: University of Western Australia). Industry colleagues, in particular Drs. R. Helby (Sydney) and A.D. Partridge (Melbourne) provided important information on the few open file samples from the North West Shelf, which preserve diverse Late Cretaceous and Tertiary terrestrial spores and pollen in dinoflagellate-dominated microfloras.

Conversely only old reports, general comments and informal 'notes' seem to have been have been archived regarding microfloras recovered from Tertiary sub-basins in northern Tasmania (cf. Evans 1970a, 1970b, Forsyth 1979a, 1979b). Samples from the important Paleocene-Eocene Kings Park Shale (onshore Perth Basin), which had been sought for a previous review (Macphail *et al*. 1994), arrived too late to be analysed for this review. Shedding of experienced palaeontological staff within the State and Commonwealth geological organisations has resulted in the loss of many unrecorded observations as well as irreplaceable samples. An example is the only non-marine Late Cretaceous sediment found so far in New South Wales. Similarly, much potentially fossiliferous drillcore and cuttings samples have been discarded to minimise storage costs and some important core holdings have survived only because they were stored in remote locations, e.g. the Lemonthyme Tillite sequence in Tasmania (Macphail *et al*. 1993).

Few organisations now support in-house drilling rigs and it is unlikely that any of the sites will be re-drilled in the foreseeable future. For this reason, the review concludes by suggesting techniques that will improve the 'extraction' of palaeoclimatic information from the existing palaeobotanical database.

c.   Methodology

The procedure used in this review is similar to the chronostratigraphic column (time series) method used by Langford *et al.* (1995) to reconstruct the Cenozoic palaeogeography of Australia. The six key steps are:

1.   Subdivision of the Australian continent into broad bioclimatic regions.

2.   Subdivision of the Cretaceous and Tertiary Periods into time slices that are commensurate with the existing age control.

3.   Identification of sections and drill-holes that have yielded Cretaceous and/or Cenozoic fossil sequences, using published and unpublished reports.

4.   Revision of all accessible palaeobotanical and other relevant proxy-climatic evidence for each geographic region and time slice, including where possible, the analysis of additional material to fill known gaps in the chronostratigraphic or geographic record.

5.   Use of a modified version of the NLR method to reconstruct past vegetation and climate patterns (references in Hill 1994a, Macphail *et al*. 1994).

A related proposal, to plot the palaeoclimatic interpretations onto the palaeogeographic baseline maps of Langford *et al*. (1995), could not be undertaken in the time available.

d.   Format

The review is made up of nine separate sections that may be consulted or passed over as required. Sections 1-4 provides background information on climate and climatic change. Sections 5-7 summarise published and unpublished evidence for climatic change during the Early Cretaceous, Late Cretaceous and Tertiary, respectively. Section 8 presents general conclusions and recommendations. Section 9 provides a comprehensive list of palaeobotanical and related publications. Plant names and distributions follow Mabberley (1989) and Hnatiuk (1990).

Section 1 (Definitions)

This section defines and discusses climate and climatic change, as natural phenomena and as agents in regolith development. It includes a review of modern relationships between climate and major vegetation types (*biomes*) on the global and regional scale.

Section 2 (The nature of fossil evidence)

This section lists the types of palaeobotanical and related fossil evidence that are available in Australia. It includes a discussion of their strengths and weaknesses as proxies for reconstructing past climates in qualitative and (if possible) quantitative terms.

Section 3 (Chronostratigraphy)

This section briefly discusses chronostratigraphic methods by which fossiliferous terrestrial sediments are tied to the International (Geological) Time Scale.

Section 4 (Boundaries in space and time)

This section defines the geographic and time slices in which the palaeobotanical evidence is discussed.

Section 5 (Early Cretaceous climates)

This section reviews published evidence for global climatic change and summarises evidence for climates and climatic change in Australia during the Early Cretaceous. Detailed analyses of palaeobotanical and other proxy-climatic evidence are given in Time Slice K-1 (Berriasian-Barremian) and Time Slice K-2 (Aptian-Albian) in Appendix 1.

Section 6 (Late Cretaceous climates)

This section reviews published evidence for global climatic change and summarises evidence for climates and climatic change in Australia during the Late Cretaceous. Analyses of the palaeobotanical and other proxy-climatic evidence are given in Time Slice K-3 (Cenomanian) to Time Slice K-6 (Late Campanian-Maastrichtian) in Appendix 1.

Section 7 (Tertiary climates)

This section reviews published evidence for global climatic change and summarises palaeobotanical and related evidence for climates and climatic change in Australia during the Tertiary Period. Detailed analyses of the relevant palaeobotanical and other proxy-climatic evidence are given in Time Slice T-1 (Paleocene) to Time Slice T-5 (Late Miocene-Pliocene) in Appendix 2.

Section 8 (Conclusions)

This section summarises (a) patterns of climate change in space and time inferred in Sections 5-7 and (b) suggests ways additional information can be recovered from the existing palaeobotanical data.

Section 9 (References)

The section provides a comprehensive bibliography of relevant climatic, biological and geological literature up to and including the year 2000.

Appendices

Appendix 1 (Cretaceous)

Palaeobotanical and other relevant data for the Early and Late Cretaceous Periods are reviewed in Time Slice K-1 to Time Slice K-2 and Time Slice K-3 to Time Slice K-6, respectively.

Appendix 2 (Tertiary)

Palaeobotanical and other relevant data for the Tertiary Period are reviewed in Time Slice T-1 to Time Slice T-5.

SECTION 1 (DEFINITIONS)

1.1 Climate and climatic change

1.1.1 *Climate*

Climate is the condition of the atmosphere (*weather*) averaged over one to several decades on geographic scales that can range from the local to global. It incorporates both meteorological averages and extremes. Many geological and biological phenomena are profoundly influenced by less common meteorological events, e.g. cyclones and severe droughts.

The principal elements of weather that make up climate are: (1) insolation (the energy input from the sun), (2) sea surface and air temperatures, (3) precipitation and evapo-transpiration, (4) atmospheric pressure and water content (relative humidity), (5) the origins and latitudinal trajectories of air masses and ocean currents, (6) land and ocean heating differences (determining the type and intensity of weather disturbances), (7) wind speed and direction (exposure) and (8) cloud cover.

Except for sub-alpine and alpine regions where limits on plant growth include low air temperatures and extreme events such as out-of-season glazing storms, the key factor limiting plant growth in Australia is *effective precipitation* [rainfall minus (run-off plus evapo-transpiration)].

Like temperature, rainfall varies diurnally and seasonally, as well as with latitude and elevation. Over the geological time-scale, the two other factors that have changed dramatically in Australia since the end of the Jurassic are light intensities (*photoperiod*) during winter and the concentration of carbon dioxide in the atmosphere.

All climates are *seasonal* to the extent that precipitation, air temperature and other factors such evaporation, photoperiod and the direction and strength of prevailing winds varies quasi-systematically throughout the year. Although *seasonality* strictly refers to changing day lengths during the year (Christopherson 1997), the term is more commonly used in palaeoecology to denote the variation in temperature and rainfall between the coolest/warmest and wettest/driest quarters of the year.

For much of Australia, an appropriate measure of seasonality is the reliability and amount of precipitation received in the driest month (moisture surplus or deficit) irrespective of whether this occurs in summer (winter rainfall zone) or winter (summer rainfall zone). For highland areas, snow and mists may be an important contribution to the total annual precipitation whilst evaporation is reduced by the orographic cloud cover (Jackson 1999, Weathers 1999). Mean monthly temperatures may be of less biological importance than maximum and minimum values.

During the Cretaceous and Paleocene, regions south of palaeolatitudes 70-80°S experienced partial to total darkness during winter and up to twenty-four hours sunlight during summer.

1.1.2 *Climatic change*

Climatic change is any change in *long-term* weather patterns (external boundary conditions *sensu* Chappell 1983) that are sustained over periods longer than several decades. Conversely, climatic catastrophes, which may have equal or more profound geological and biological consequences, are short-lived perturbations of the 'boundary conditions' (Budyko 1999). An important *caveat* is that climatic change is never spatially uniform and changes in the local or regional landscape or fauna do not necessarily vary congruently with changes in

vegetation. Moreover, individual taxa are usually less resilient to environmental stresses than the communities in which they co-exist (cf. Montuire *et al*. 1998).

1.1.3 *Climatic regions*

The earth naturally experiences a wide range of climatic conditions although these can be grouped into broad climatic types or 'regions', many of which appear to be associated with characteristic suites of landforms (*climatic geomorphology*) or vegetation types (*bioclimates*).

At the most general level, climates are classified into (1) *continental climates*, which are characterised by a relatively wide range of maximum and minimum temperatures, and (2) *maritime climates* where the temperature range is moderated by the oceanic influences. For this reason changes in *relative sea level* (eustatic or tectonic) influence the regional climates along the continental margins. Evidence is increasing that vegetation *per se* also can have a profound effect on the climates of inland regions, e.g. via aerosols (Kavouras *et al*. 1998).

1.1.5 *Classification of world climates*

The most widely used classification of global climates is the empirical *Köppen* System (Christopherson 1997). A modification of this system, the *Köppen-Geiger* System, categorises world climates using mean monthly temperatures, mean monthly precipitation and total annual precipitation to designate climatic zones by latitude from the equator to the pole. Deserts are unique in being classified primarily on precipitation and, like highland and polar regions, are considered to be special cases. Other criteria may be used within individual regions.

1.1.6 *Classification of Australian climates*

Gentilli (1972, 1986) uses synoptic climatology to subdivide the continent into climatic 'response' zones. Warner (1986) uses the ratio of precipitation to evapo-transpiration to identify the hydrologic regimes that are believed to enhance geological weathering.

1.2   Weathering

1.2.1 *Weathering processes*

Weathering is the process by which surface and subsurface rocks disintegrate (*physical weathering*) or dissolve (*chemical weathering*).

Rates of weathering are influenced by the composition (*lithology*) and fabric (bedding, jointing) of the rock as well as by climate. The fragmented material that overlies unaltered bedrock is termed *regolith* whether it is *in situ* or transported (Ollier 1991). Rocks which are weathered *in situ* but still retain evidence of the original fabric are termed *saprolite*. Soil, which usually consists of a number of discrete horizons, is the uppermost 'layer' of the regolith. Chemical weathering can produce hard, chemically precipitated deposits collectively known as duricrust (*bauxite, calcrete, silcrete, ferricrete*), which cap igneous rocks, lithified sediments and soil profiles across the continent (Ollier 1991, Anand *et al*. 1994, Eggleton and Taylor 1998).

Lithological factors aside, the depth of weathering is controlled by annual precipitation, temperature (especially freeze-thaw cycles), fluctuations in the depth of the water table, topography (especially slope orientation) and rates of stripping (erosion). Not surprisingly, physical weathering processes predominate in drier, cool to cold climates and chemical weathering predominates in wetter, but not necessarily warmer, climates.

Due to complex tectonic processes, the 'age of exposure' (Taylor 1994) only provides a rough guide to the depth of the weathering profile across Australia (Figure 1). For example, Tertiary igneous and volcanoclastic rocks on the Southeastern Highlands of New South Wales have developed a deep regolith (and fertile soils) whilst Precambrian quartzites and Palaeozoic limestones in Tasmania are characterized by thin regoliths (and highly infertile soils).

1.2.2 *Role of plants*

Plants contribute to the weathering processes (and CO_2 levels in the atmosphere) by the physical action of roots or via organic acids and methane released by living and decaying plant matter.

Aluminium or iron-rich crusts (bauxite, ferricrete, laterite) reflect the preferential leaching of silica under tropical (usually rainforest-supporting) climates. The same phenomenon can occur in much colder climates. For example in basaltic areas of Iceland, the weathering release of Ca^{2+} and Mg^+ to streams is two to five times higher in vegetated areas than in barren areas (Moulton and Berner 1998). Conversely, Meunier *et al.* (1999) have noted that a significant part of the silica (SiO_2) dissolved from the parent rock is retained in soils as (biogenic) phytoliths.

Figure 1:   Age of exposure of landsurfaces (from Taylor 1994)

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1.3   Flora, vegetation and climate

1.3.1 *Flora*

An important distinction exists between flora and vegetation. A *flora* comprises the plant species present in an area irrespective of their relative abundance or life form. *Vegetation* denotes the abundance and structural arrangement of the taller or more common species. *Plant community* is used to denote relatively stable associations between particular species, which in combination make up particular *vegetation types*. Species making up the major vegetation types in Australia are given in Specht (1970, 1982).

1.3.2 *Vegetation*

Vegetation has a staggering potential to alter global and regional environments in the short-term and over geological time. For example, on average plants contain less than 0.5 g carbon cm^3 and form a 'veneer' that is less than 100 m thick between the 100 km deep lithosphere and 10 km high atmosphere. Nevertheless, the global vegetation manages to cycle 60 gigatonnes (60×10^{15} g) of carbon between the lithosphere, biosphere and atmosphere each year (Naeem 1999).

Similarly, methane produced by the bacterial decomposition of organic matter in wetlands has been implicated as a major factor in global warming. A brief but intense period of global warming and massive perturbation of the global carbon cycle during the Paleocene-Eocene transition (Paleocene-Eocene thermal maximum) almost certainly was due to the catastrophic release over ~20 ka of methane, which previously had been 'frozen' as hydrates in sea floor sediments (Rohl *et al*. 2000).

1.3.3 *Biomes*

Biomes are defined as broad stable ecosystems of plants and animals, which occupy climatic regions defined by unique combinations of precipitation and temperature, and seasonal variation in these parameters. *Plant biomes* are broad vegetation classes defined by combinations of dominant physiognomic character (life form, leaf-form, phrenology).

Terrestrial and most aquatic ecosystems are underpinned by plants whose life-forms/size (trees, shrubs, herbs), growth rates and distributions are shaped not only by the prevailing climate but also by soil fertility, drainage and moisture status (*edaphic factors*).

Global biomes

The strong association of particular life forms with particular climatic regimes allows plant biomes to be defined using a combination of climatic, physiognomic and physiological characters (Christopherson 1997). Because of functional convergence between unrelated plants growing under the same physical environment, it is possible to use *ecophysiological* data to compare or combine data from regions with taxonomically different floras (Prentice *et al*. 1992).

Eleven terrestrial plant biomes can be recognised globally (Table 1). Most biomes are named after the tallest/most abundant (*dominant*) plant stratum present, i.e. the one most exposed to climate. They are rainforest, savannah (grasslands with scattered trees), grassland (grasslands lacking woody species), shrublands, desert and tundra. Each is characterised by a distinctive flora with equally distinctive morphological and ecophysiological adaptations. The transition between biomes is recognisable by changes in the physiognomic character of the vegetation as a whole, in the relative proportions of the component plant communities, or in the relative abundance of the dominant plant species.

Table 1: Biological and Climatic Characteristics of the Major Terrestrial Biomes (After Christopherson 1997)

BIOME	VEGETATION CHARACTER	CLIMATE	ANNUAL RAINFALL	MEAN TEMPERATURE	WATER BALANCE
Evergreen Tropical Rainforest	tropical broadleaf forest with vines, epiphytes, palms and tree-ferns	consistent daylength (12 hrs)	1600-1800 mm [> 60 mm/month]	always warm [21^0-30^0C]	surplus all months
Tropical Seasonal Forest, and Scrub	tropical monsoon forest and scrub, tropical semi-deciduous forests	low and erratic rainfall with heavy summer downpours	1300-2000 mm with <40 rain days during driest 4 months	variable, > 18°C	deficit driest months
Tropical Savannah	thorn scrub and woodland, tropical grassland	tropical climates, with <6 months receiving rain	90-1500 mm	variable, > 10°C	variable deficit, fire/drought-prone
Mid latitude Broadleaf and Mixed (Conifer) Forest	subtropical deciduous forests, temperate broadleaf forests, temperate conifer forests	mesothermal climates with humid, warm-hot summers, cool to cold, dry winters	750-1500 mm	temperate with cool-cold season	winter deficit
Conifer Forest and Montane Forest	taiga and boreal forest, montane and highland forests	microthermal climates with humid warm-cool summers	300-1000 mm	short summer, cold winter	mild deficit
Mid-High Latitude Evergreen Temperate Rainforest	temperate and subantarctic rainforest [cryptogam-rich understorey]	mesothermal climates with humid warm-cool summers, without dry season (oceanic)	1500-5000 mm	mild summers, cool-cold winters 4 months >10^0C	large surplus all months
Mediterranean Shrublands	sclerophyll forests and woodlands sclerophyll scrub and heath	mesothermal summer-dry climates, drought-prone	250-650 mm	dry summers	summer deficit, winter surplus
Mid Latitude Grasslands	temperate grasslands, sclerophyll shrubland	microthermal and meso-thermal summer-dry climates	250-750 mm	temperate continental climates	more or less in equilibrium
Warm Desert and Semi-desert	subtropical desert, steppe shrubland	dry arid and semi-arid climates at low to middle latitudes	< 20 mm	extreme temperature range (av. 18°C)	rainfall <50% evapo-transpiration
Cold Desert and Semi-desert	mid latitude desert, mid-latitude shrublands and steppe	arid and semi-arid climates	20-250 mm	average 18°C	rainfall >50% evapo-transpiration
Arctic and Alpine Tundra	tundra	polar and highland climates	150-800 mm	<10°C	frozen or surplus

TABLE 2: Classification of vegetation types in Australia (after Specht 1970)

Life-form and height		Foliage projective cover of canopy stratum (%)			
		100-70%	70-30%	30-10%	<10%
tall trees	>30 m	tall closed forest (rainforest)	tall open forest (wet sclerophyll forest)	not extensive in Australia	not extensive in Australia
medium trees	10-30 m	closed forest (rainforest)	open forest (dry sclerophyll forest)	woodland (sclerophyll woodland)	open woodland (savannah woodland)
low trees	<10 m	low closed forest (rainforest)	low open forest (dry sclerophyll forest)	low woodland (sclerophyll woodland)	low open woodland (savannah woodland)
tall shrubs	> 2 m	closed scrub (wet scrub)	open scrub (eucalypt mallee scrub)	tall shrubland (acacia scrub)	tall open shrubland (acacia scrub)
low shrubs	< 2 m	low closed shrubland (subalpine rainforest)	heathland	low shrubland (chenopod shrubland)	low open shrubland (chenopod shrubland)
hummock grasslands and sedgeland	-	hummock sedgeland (buttongrass sedgeland)	hummock sedgeland (buttongrass sedgeland)	hummock grasslands	not extensive in Australia
grasses/graminoids	-	closed tussock grasslands	tussock grassland	grasslands (rangelands)	open grasslands
herbs (forbs)	-	herbfield (chiefly subalpine/alpine)	herbfield (chiefly subalpine/alpine)	fell-field	open forb-field (fell-field)

<u>Australian 'biomes'</u>

Although biome terminology is widely used in Australia, the vegetation is more usually classified in terms of *formations* made up of distinct *communities* or *associations*. For example, Specht (1970) has used plant community *structure* (height and spacing of the dominant *stratum*) to classify the vegetation (Table 2). Particular types have been further subdivided using other characters. Webb (1959, 1968) and Webb *et al*. (1984) have used leaf size and structural relationships to subdivide rainforest formation growing in regions with adequate rainfall in all seasons but subject to different temperature regimes.

A number of the terms used to qualify temperature regimes, viz. *tropical*, *subtropical* (*paratropical*), *temperate*, *subalpine* and *alpine*, have geographical as well as thermal connotations. In recognition of this, Nix (1982, 1991) has proposed an ecophysiological classification, which relates plant growth response (and therefore competitive ability) to the major climatic variables of insolation, air temperature and seasonal precipitation. Three major thermal response categories are distinguished (mean air temperatures in parentheses) where precipitation does not limit plant growth in any season – *megatherm* ($>24^{\circ}$C), *mesotherm* (14°C -24°C) and *microtherm* ($<14^{\circ}$C) (see Table 3a). Analogous categories for rainfall (Table 3b) are *perhumid* (wet to very wet), *humid* (wet), *sub-humid* (dry) and *semi-arid - arid* (very dry) although these are much more difficult to quantify in Australia because of the strongly seasonal distribution of rainfall.
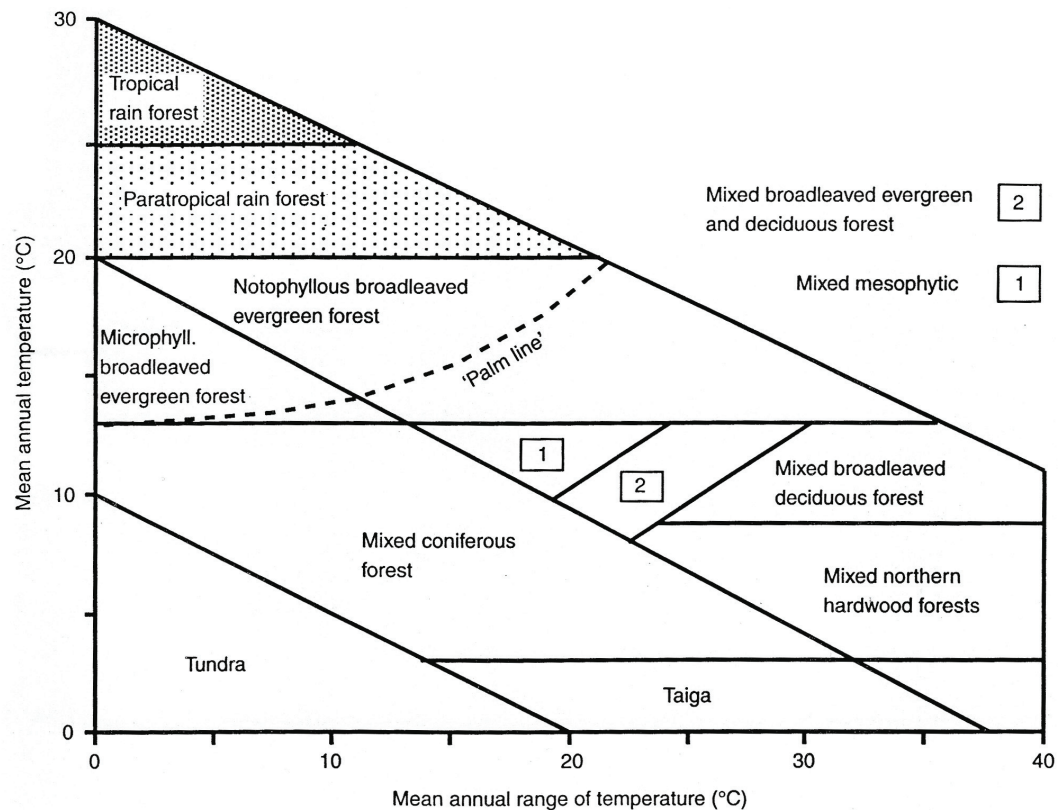
For example temperate rainforest is the dominant plant formation in western Tasmania where mean annual rainfall exceeds ~1200 mm pa, whereas the same annual rainfall in southwestern Western Australia only supports dry sclerophyll forest. The critical difference is the amount of rainfall received during summer months – greater than 200 mm per month in western Tasmania (where summer rainfall is not limiting), and less than 70 mm per month in Western Australia (where summer rainfall is limiting).

TABLE 3:   **Temperature and rainfall regimes**

TABLE 3a: TEMPERATURE*			TABLE 3b: RAINFALL		
CATEGORY		**RANGE**	**CATEGORY**		**RANGE (approx.)**
cold	lower microtherm	$<10^{0}$C	wet-very wet	perhumid	> 1200 mm pa
cool	upper microtherm	$10\text{-}14^{0}$C	±wet	humid	900-1200 mm pa
warm	lower mesotherm	$14\text{-}18^{0}$C	±dry	subhumid	600-900 mm pa
very warm	upper mesotherm	$18\text{-}24^{0}$C	very dry	semi-arid	300-600 mm pa
hot	megatherm	$>24^{0}$C	arid	arid	< 300 mm pa

  * These values differ that those inferred by Wolfe (1987) from temperature relationships of major forest types in East Asian forests (Figure 2), which may be more appropriate for warm periods during the Palaeogene.

Figure 2:   **Relationship of different bioclimates to mean annual temperature and mean annual range of temperature (from Morley 2000)**

1.3.4 *Diversity*

In general, rainforests are more diverse (*floristically rich*) than sclerophyll and herbaceous vegetation types unless another factor such as low soil fertility prevents one to several species having a distinct competitive advantage over other species. Analogues of modern warm temperate, subtropical/paratropical and tropical rainforest communities and some wet sclerophyll communities can be identified at least as far back as the Late Paleocene (Truswell 1993, Macphail *et al.* 1994, Macphail 1997a, 1997b) and possibly the early Late Cretaceous (Specht *et al.* 1992).

1.3.5 *Response and resilience*

Because different plant species have different responses and resilience to changes in their habitat (including climatic change), plant communities are dynamic entities whose composition and structure will naturally alter over time (*ecological succession*).

Many rainforest and wet sclerophyll species cannot regenerate without some form of natural disturbance such as flooding or wind-throw of over-mature tall trees. Other species may be able to survive long periods of adverse conditions by virtue of life-spans that exceed 500-1000 years, e.g. tall gymnosperms. Plants able to coppice from underground stems such as rhizomes and lignotubers may be long-lived.

Many plants can be replaced by any one of a number of species with similar ecological tolerances. Accordingly community composition tends to shift over time. This leads to the regional vegetation becoming spatially heterogeneous (*patterned*) on the local to regional

scale. Replacement communities are usually more diverse or structurally complex than the communities they succeed (*secondary succession*). In rare instances, e.g. following volcanic eruptions, major landslips, severe flooding and hot fires, the succession will be *primary* in that the pioneer plants have to colonise bare rock surfaces or mineral soils.

1.3.6 *Ecology and ecophysiology*

Fox (1999) has reviewed environmental influences on the Australian vegetation. The only information available on the ecological preferences of most plant species is empirical, i.e. is based on their distribution along known gradients in precipitation, temperature and soil fertility, e.g. Jackson (1968, 1999). In exceptional cases, objective techniques such as BIOCLIM, which use trend surface analysis of plant distribution data (Nix 1982, 1991), have been used to estimate climatic envelopes. Examples are *Nothofagus* (Busby 1986) and some Miocene floras (Kershaw 1995). This technique is not particularly successful in predicting species distributions in mountainous terrain, where microclimates can vary rapidly over short vertical and horizontal distances. As noted for some *Eucalyptus* spp. on the Southeastern Highlands of New South Wales (M. Austin pers. comm.), thriving stands do not always occupy sites having the optimal climatic regime and this can make it difficult to determine the relative importance of the presumed environmental controls.

A more reliable method is to study the physiological response(s) of phytosociologically important species to controlled variations in the environment, particularly light intensity, water-stress and low temperatures. For example, Read and Hill (1985), Hill *et al*. (1988), Read and Hope (1989), Read (1990) and Read and Francis (1992) have prepared ecophysiological profiles for several canopy dominants in lowland rainforest. Brodribb and Hill (1997, 1998, 1999) have studied the physiological adaptations and responses of selected Southern Hemisphere gymnosperms to low light intensities and water-stress. Eamus (1999) has analysed the ecophysiological traits of evergreen trees with 100% (deciduous), >50% (semi-deciduous) and <50% leaf fall (brevi-deciduous) in seasonally dry tropical habitats.

1.3.7 *Climatic forcing and biological thresholds*

Climate is widely accepted as being the primary determinant of vegetation on the geographical scale or over periods of time exceeding several millennia (Hill 1994a) and sustained shifts in community dominance are likely to reflect regional changes in climate. Exceptions are specialized plant communities that are (a) subject to strong edaphic control, e.g. swamp forests, or (b) dependant on repeated tectonic disturbance, e.g. some *Nothofagus* rainforest communities.

Changes on this scale imply that either or both effective precipitation and mean temperatures have crossed a *biological threshold*, resulting in the previously dominant species becoming less competitive relative to the replacement species (cf. Wilbanks and Kates 1999). Because local conditions tend to vary systematically across a region, i.e. along *climatic gradients*, the replacement of one species by another also is likely to be ±systematic (*time-transgressive*) rather than ±erratic (*diachronous*).

Adams *et al*. (1999) note the last million years (Quaternary Period) has been punctuated by many rapid climatic transitions, often over periods of less than a thousand years, and conclude that long term climatic change occurs in sudden 'jumps' rather than by incremental changes (*abrupt climatic change*). Many of the mechanisms invoked to explain rapid changes in regional and global climate, e.g. ocean current circulation patterns, biological productivity, atmospheric CO_2 and dust particles, and snow and ice cover, are not unique to the Quaternary. For this reason, it is likely that Cretaceous and Tertiary climates will also exhibit sudden stepwise instability ('*switching*') on time scales of decades to a few centuries, even if the 'switching events' are concealed by broad age determinations (Zachos *et al*. 1993).

Accordingly, only at sites with exceptional resolution will short-term changes be preserved in the fossil record. Australian examples are rhythmites at Lemonthyme Creek, north-west Tasmania (Early Oligocene), and Yallalie, south-west Western Australia (mid Pliocene). High levels of *biodiversity* seem to be restored by ~10 million years after major extinction events (cf. Erwin 1998, 2000; Gaston 2000).

1.3.8 *Fire and soil fertility*

Over shorter periods of time, the role of climate becomes more ambiguous whilst the influence of other factors such as soil drainage, soil fertility and the frequency/intensity of wildfires and other disturbances become more pronounced on the local to regional scale (references in Fox 1999 for mainland Australia, Jackson 1968, 1999, Macphail 1979, 1980 for Tasmania, Ogden et al. 1996 for New Zealand, Read and Hope 1996 for New Guinea and New Caledonia, Peres 1999 for South-East Asia, and Veblen *et al.* 1996 for South America).

Hill (1998a, 1998b) has restated the distinction between the morphological response of plants to low levels of soil nutrient such as phosphorus (*scleromorphy*), and low soil moisture levels (*xeromorphy*), but notes that these forcing factors and wildfires have 'genuinely overlapped' in Australia since Late Eocene times and scleromorphic and xeromorphic plants are well adapted to the ubiquitous presence of fire in the modern landscape ('fire-requiring and promoting' species).

Low intensity wildfires may help increase regional rainfall in that low concentrations of smoke particles help water droplets form. However, recent forest fires over South-East Asia have confirmed that very dense smoke haze 'turns off' normal tropical rainfall due to over-saturation of the atmosphere with small particles (Adler 1999). For this reason, anthropogenic wildfires are suggested to be partly responsible for the decline in rainfall seen in the tropics over the past century. Periods of intense volcanic activity and/or meteor impact almost certainly will have had similar consequences on the local to regional scale (Kerr 2000).

1.3.9 *Vagility and vicariance*

Plants differ greatly in their ability to disperse propagules such as spores and seeds into the surrounding landscape (*vagility*).

The relatively high levels of endemism (*vicariance*) in Australasian rainforest floras is attributed to the low vagility of many rainforest species (Barlow 1981, Dawson 1986, Hartley 1986, Morat *et al.* 1986, Thorne 1986, Webb *et al.* 1986, Whiffen and Hyland 1986). Nevertheless, fruits, seeds and seedlings of mangroves and other strand plants are routinely found on the beaches on cays in the south Coral Sea, confirming that plant propagules can drift from as far away as Fiji, Vanuatu and New Caledonia to Australia (Smith 1992).

Similarly, palynostratigraphic evidence confirms that many woody and some herbaceous plants have been able to cross wide ocean gaps, including to New Zealand and Ninetyeast Ridge in the Indian Ocean (Kemp and Harris 1977, Macphail *et al.* 1994). These data demonstrate that chance dispersal events, many of which are of intrinsically very low probability due to the low vagility of the species concerned, have occurred during Early Tertiary when Australia was surrounded by wide oceans. Conversely during the Late Tertiary when Australia has been close to South-East Asia, only limited floristic interchange has taken place due to the lack of suitable 'target' habitats in northern Australia (Macphail 2000).

SECTION 2 (THE NATURE OF FOSSIL EVIDENCE)

Fossils are the traces of once-living organisms that have been buried by natural processes and subsequently preserved in whole or in part.

This definition covers skeletal and cell wall material of any size, whether chemically unaltered, reduced to mineral carbon, replaced by other minerals such as silica, calcite, limonite and pyrite or reduced to impressions (casts and moulds), as well as excreted material, and tracks, trails and borings. Microanalytical and geochemical techniques allow some fossil organisms to be identified from organic residues (*organic trace fossils*). Examples include marine algae such as acritarchs and dinoflagellates, and C_4 grasses, which possess distinctive biochemical 'signatures'.

As an adjective, 'fossil' is used more widely, to cover any entity of perceived geological antiquity whether or not the object is extant. Examples include fossil ice wedges (sedimentary casts of ice wedges) and 'living fossils' such as Wollemi Pine (Macphail *et al*. 1995).

2.1   Taphonomy

Taphonomy encompasses the post-mortem history of the organisms. Taphonomic processes include the decomposition phase after death (*necrophysis*), the sedimentological history of fossil remains (*biostratinomy*), and chemical and physical changes in the fossil between burial and collection (*diagenesis*).

2.1.1   *Fossil assemblages*

With few exceptions, the individual accumulations of fossils (*assemblages*) represent geologically instantaneous records of past life. Stratified sequences, which cover much longer periods of geological time, may provide a *time series* record of past life.

The value of a fossil assemblage as *proxy-climatic* evidence depends on the degree to which the individual fossils can be associated directly to past environments or indirectly via living relatives whose ecological relationships are known. Preservation and geological age are important constraints. In most instances, the palaeoclimatic inferences are qualitative, e.g. warmer and wetter or, if quantitative, are expressed as a range (*climatic envelope*). Geologic evidence such as glendonites and the ratios of naturally occurring isotopes can provide more or less precise quantitative evidence of past climates.

2.1.2   *Palaeobotany*

Palaeobotany is the study of plant remains. The discipline may or may not be distinguished from *palaeontology*, which can encompass animal remains only (colloquial usage) or all fossils (dictionary definition/industry usage) according to context.

Palaeobotanical evidence is subdivided into two main classes according to the size of the remains: *macrofossils* (chiefly stems, foliage, flowers and fruits) and *microfossils* (chiefly algal cysts, spores and pollen grains). The two forms of evidence are complementary in that they usually reflect different elements in the palaeovegetation. It is important to note that good preservation of plant macrofossils is no guarantee that microfossils of the same plants will have been preserved or can be identified to the same taxonomic level (and vice versa).

2.1.3 *Palaeoecology*

Palaeoecology is the study of the interactions of organisms with one another and with their environment in the past. It differs from the *ecology* of living organisms in that incomplete preservation usually prevents direct observation of many aspects of the biota.

2.2 Plant macrofossils

Plant macrofossil assemblages (*macrofloras*) constitute a highly detailed record of past vegetation that is strongly biased towards plants growing close to water, e.g. on the banks of sluggish rivers or around lakes (Burnham 1989, Christophel and Greenwood 1987a, Greenwood 1992, 1994, Alexander *et al*. 1999).

2.2.1 *Taphonomic constraints*

Plant remains are subjected to a number of processes between the time of abscission and their burial in sediments where conditions may or may not lead to long-term preservation. For example, cellulose and lignin, which are the major compounds making up cell walls, are the food source for many fungi and soil invertebrates. Similarly, the size of many plant remains makes them susceptible to physical attrition during transport and deposition, especially by water and wind. Accordingly, except under anoxic conditions, only the more robust plant parts such as roots, stems, twigs and leaves are preserved in an unaltered state. The most commonly found remains are leaves, particularly those of species with naturally dehiscent foliage such as deciduous trees.

2.2.2 *Taxonomic constraints*

The taxonomic level to which plant macrofossils can be identified using foliage or wood is high, often to genus or species level, since many of the taxonomic characters are the same as the characters used to identify modern plant species or genera. For example, leaf cuticle is chemically stable, and microscopic features such as the distribution of stomata and presence of trichomes (plant hairs) allow small fragments to be compared with those of living species with great accuracy, even when primary taxonomic evidence such as flowers and fruits are absent. Similarly the arrangement of the various types of cells making up wood (xylem) allows some stem remains to be assigned to modern genera. If such characters are not preserved, e.g. in impressions and casts, it can be difficult or impossible to determine phylogenetic affinities accurately (Jordan and Hill 1999).

The resistance to decay of wood and leaf cuticle is similar to that of fossil spores and pollen and both are major components of the finely disseminated (acid-resistant) detritus (*kerogen*) preserved in sedimentary rocks (cf. Rowett 1993a).

2.3 Plant microfossils

Fossil pollen and spores (*miospores*) together with phytoliths and algal cysts are by far the most abundant and widespread of all plant remains. Although dispersed by much the same transport processes, the distinction between spores and pollen is an important one in plant migration, and therefore how the palaeobotanical record mirrors past climates:

- *Spores* are produced by fungi, mosses, liverworts, fern allies and ferns (collectively termed *cryptogams*) and are functionally equivalent to the seeds of flowering plants in that they germinate to produce the next generation of plants. Dispersal is by wind and/or water, less commonly by foraging insects.

- *Pollen* are gametes produced by both gymnosperms and angiosperms, and are functionally equivalent to animal sperm. Dispersal is by wind, animals and/or water, with some common insect-pollinated species dispersing pollen by two or more pathways.

The other major classes of plant microfossils are (a) silica cells (*phytoliths*) produced by many of the higher plants, and (b) the cysts produced by freshwater and marine algae, e.g. diatoms, acritarchs and dinoflagellates (*dinocysts*), and coccoliths (*nannofossils*). Whilst these can be common in freshwater or marine sediments, only microfossils with organic (as opposed to calcareous and siliceous) walls survive the processing techniques used to recover spore-pollen from sediments or rocks.

Marine algae and microfauna such as planktonic foraminifera (forams) underpin the global chronostratigraphy (Harland *et al.* 1990) but are not considered in this review except as evidence for past sea surface temperatures (SSTs).

Unlike plant macrofossils, miospore assemblages (*microfloras*, *palynofloras*) represent distant plant communities as well as plants growing close to the site of deposition (Macphail *et al.* 1994). Reasons include their wide dispersal and resistance of the cell walls to physical or chemical decay.

2.3.1 *Taphonomic constraints*

Spores, pollen and algal cysts are produced and dispersed in astronomical numbers. The cell walls, made of sporopollenin, are highly resistant to natural oxidative process and for this reason, miospores are by far the most commonly found fossils in fine-grained sediments accumulating in onshore and nearshore sedimentary basins.

The main agencies transporting miospores over long distances are wind (*anemophily*) and water. Batten (1984) has proposed that 'lightly sculptured' (psilate-scabrate) pollen grains are an adaptation to dispersal by wind since anemophily is best developed in open canopied vegetation types such as savannahs, open woodlands and deciduous forests. Many but not all of these vegetation types inhabit regions with strongly seasonal climates.

Because of their small size, fossil pollen and spores are subject to the same sorting processes during transport and deposition as very fine sand and silt particles. For the same reason, present-day relationships between elevation, basin size, and the area and types of plants represented by microfossils, are likely to apply to Cretaceous and Tertiary palynofloras (Dettmann 1994, Macphail *et al.* 1994, Woo *et al.* 1998). Empirical and experimental pollen trapping data indicate:

- The overwhelming majority of plants in Australia are under-represented in that their miospores are produced in limited numbers or dispersed only short distances (<10 m) into the surrounding landscape, unless water-transport is involved. The pollen or spores of these *under-represented* species can be found in large numbers when the source plants species grew close to, or (riparian plants) upstream of the site. The category includes most tropical and subtropical rainforest trees, most shrubs and herbs, and many ferns and fern allies.

- A few trees, shrubs and herbs produce miospores in very large numbers and disperse these over long distances into the surrounding landscape (*well- to over-represented* species). Unlike under-represented taxa, it can be difficult to determine whether large numbers of their pollen or spores represent a few individuals growing close to, or large stands growing at some distance from, the site. The category includes most

wind-pollinated trees and shrubs but only some herbs. Examples are the Araucariaceae, Cupressaceae and Podocarpaceae (gymnosperms), and Casuarinaceae, Chenopodiaceae-Amaranthaceae (usually abbreviated to Chenopodiaceae), Nothofagaceae and Poaceae (angiosperms). A few insect-pollinated angiosperms are well-represented because of open flowers with numerous anthers or because of their very wide distribution. Australian examples are wattles (*Acacia*) and eucalypts (*Eucalyptus*). A comparison of macrofossil and microfossil data at the Oligo-Miocene Pioneer site in northeastern Tasmania shows that that *Nothofagus* (*Brassospora*) spp. are over-represented, and *Nothofagus* (*Lophozonia*) spp. are likely to be under-represented in the Tertiary pollen record (Hill and Macphail 1983).

- Microfloras recovered from sediments accumulating towards the centre of larger (>200 m diameter) lakes, in estuaries, and marine depositional environments, tend to be dominated by the pollen of wind-pollinated trees, in particular gymnosperms (*Neves Effect*) and/or miospores produced by light-requiring ferns, shrubs and trees lining waterways (cf. Birks and Birks 1980).

- Microfloras recovered from coals, lignites and other backswamp sediments deposited in smaller diameter basins tend to be dominated by locally growing (often under-represented) plants and often include pollen or spore types not found in sediments accumulating away from the shoreline in larger basins.

2.3.2 *Taxonomic constraints*

Miospores are conservative plant organs in terms of evolution. Because of their small size (10-120 μm), taxonomic characters that might allow one type to be distinguished from another using scanning electron microscopy, are difficult to resolve using bright field light microscopy. For this reason, modern pollen, spores and algal cysts should only be identified to genus or family level unless only one species of parent plant occurs within the pollen source area. Tasmanian examples are the Huon Pine (*Lagarostrobos franklinii*) and alpine creeping pine (*Microcachrys tetragona*). This can be presumed in the case of Late Quaternary fossil spores and pollen types but Tertiary examples almost certainly represent more than one species or ecotype (Macphail *et al*. 1994).

The further back in time, the less confidently can a spore or pollen be related to a modern taxon unless the degree of morphological specialisation is exceptional (Truswell and Marchant 1986, Collison 1990). Accordingly, a very large number of Cretaceous and Tertiary miospores cannot be assigned to any living genus or family. In many instances, it is improbable that living descendants exist.

For pragmatic reasons, only the most morphologically distinctive or biostratigraphically important miospore types are formally described as fossil genera (*form genera*) or species (*form species*). Most fossil species encompass a wide range of morphologies and often are linked to other fossil species via intermediate *morphotypes*. This has two important consequences for the reconstruction of past vegetation and climates. (1) The range of morphotypes assigned to a given fossil species tends to increase over time. (2) Geographic variation between microfloras is obscured by broadly defined fossil species.

2.4. Reconstruction of past vegetation and climates

Plant macrofossils and microfossils are direct but partial evidence of past floras only, although some indication of community dominance and structure is provided by their relative abundance (Gestaldo and Ferguson 1998). In practice, inferences on palaeohabitat are usually made by combining palaeoecological with other types of evidence, e.g. lithostratigraphy (*clastic facies analysis*).

It is noted that the climatic response classification developed by Nix (1991) has proved useful in classifying some Eocene and younger rainforest communities at sites where moisture availability is not limiting (Greenwood 1994, Macphail *et al.* 1994). How relevant modern communities are as analogues for other Cretaceous and Tertiary communities is less clear given that southern Australia was at high to polar latitudes (>60°S) and therefore subject to prolonged darkness during winter months. For this reason, categorising past plant communities in terms of the highly detailed classifications developed for the modern Australian vegetation, e.g. Specht (1970), is considered premature unless supported by plant macrofossil evidence.

Much of the palaeobotanical evidence of Cretaceous and Tertiary climates in Australia come from continental margin basins in southern Australia, in particular the Bass, Gippsland and Otway Basins in the south-east, and epicontinental basins that were inundated by marine transgression during the Early Cretaceous, e.g. the Perth, Eromanga and Surat Basins, or during the Late Tertiary, e.g. the Eucla and southern Murray Basins (Figure 3). A surprising number of onshore depositional environments are due to uncommon events. Examples include meteor craters, e.g. at Goats Paddock in the Kimberley region and Yallalie near Perth, and lakes dammed by Tertiary tectonism or volcanism on the Eastern Highlands.

Figure 3: **Epicontinental and continental margin basins (from Palyfreyman 1984)**

2.4.1 *Palaeovegetation*

The relationship between plant fossil assemblages and the parent or source vegetation is spatially complex and variable in time (Birks and Birks 1980, Macphail *et al.* 1994, Chaloner and McElwain 1997). Three important *caveats* are:

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1. The usual practice of equating the relative abundance of macrofossils or microfossils with the physical or numerical prominence of the parent plants involves several questionable assumptions. For example, many tall or common (phytosociologically important) genera and some plant families are severely under-represented by pollen or spores. This class includes almost all warm temperate to tropical rainforest trees, many sclerophyll shrubs and most herbs. Some important rainforest trees are 'blind-spots' in the fossil record in that their pollen are seldom preserved, and macrofossils are the only direct evidence of their past existence. Examples are Lauraceae and Juncaceae. Similarly, plants that have non-dehiscent foliage or are confined to dry/interfluve habitats, are unlikely to be represented in the macrofossil record whether or not they are well represented by pollen or spores.

2. Unless unequivocal evidence such as tree-trunks in growth position is present, plant community structure is deduced by analogy when the floristic composition of a fossil community appears to agree with a modern one. However, such analogies can be misleading given the wide range of life forms present in most plant families and genera and the observation that many tall tree species can survive as low shrubs in unfavourable habitats. Modern Tasmanian examples are the Huon Pine (*Lagarostrobos franklinii*) and Myrtle (*Nothofagus cunninghamii*), both of which occur as low-growing shrubs in the alpine zone and along riverbanks but also grow into 30-40 m tall trees in lowland temperate rainforest.

3. The assumptions that the fossil plants had approximately the same ecological preferences as their modern equivalent(s) is difficult to confirm for Tertiary taxa, and highly suspect for the few Cretaceous taxa with known close descendants. The clearest evidence found so far for this assertion comes from an Early Quaternary site in western Tasmania, where macrofossils of the present-day alpine creeping pine *Microcachrys tetragona* are preserved in association with other shrubs that are confined to warm temperate and subtropical rainforest (Macphail *et al*. 1993, Jordan 1997a, 1997b). In other instances, the present day geographic range of a species or genus appears to reflect past rather than modern day climates, and therefore is of limited palaeoclimatic value (Coates and Kirkpatrick 1999).

In spite of the above caveats, palaeobotanical reconstructions of Cretaceous and Tertiary climates are almost always based upon the present-day spatial distribution of their NLRs, augmented by palaeogeographic and sedimentological data. For example, Hill and Scriven (1997) have found a moderately good correspondence between the (hypothesised temperature-forced) distribution of commonly-occurring macrofossil taxa in Tasmania during the Oligo-Miocene and the altitudinal distribution of their NLRs. Horrell (1991) has claimed that modern NLR data allows the equivalents of ten modern plant biomes to be recognised across the globe during the Late Maastrichtian, although it is noted that biozones characterised by year-round high humidity or semi-arid to arid conditions had to be defined by geological evidence, viz. the distribution of thick coal and evaporate sequences, respectively.

More generally, the value of past plant communities as proxy-climatic evidence is reduced by the low taxonomic resolution of pollen or spores produced by the dominant species. For example, it is not possible to use pollen to distinguish between shrub species that dominate modern xerophytic vegetation, e.g. *Acacia*, Casuarinaceae, Gyrostemonaceae or Myrtaceae, and their tree-sized relatives that occur in modern and Tertiary wet forest types (Macphail *et al*. 1994). In such cases, the probable source may be able to be 'identified' by the presence of associated taxa that produce distinctive pollen or spores (cf. Martin 1997a). These associates need not be higher plants; Lange (1976, 1978a) has used the remains of Tertiary epiphyllous fungi as evidence for the former presence of rainforest in arid northern South Australia.

An alternative approach is to use the architectural characteristics of leaves (size, type of margin and stomatal arrangement) and wood anatomy (growth rings) as evidence of past climate (*foliar physiognomic analysis*). This allows proxy-climatic information to be obtained from Cretaceous and Tertiary plant clades that are extinct, or whose NLRs are unknown. For example, the presence of a 'drip tip' analogous to those found on the leaves of extant rainforest trees has been used to infer warm and very wet climates (Greenwood 1992, 1994). Uhl and Mosbrugger (1999) propose that leaf venation density has proxy-climatic value. Whether it is possible to use foliar physiognomic analysis to make reliable *quantitative* estimates of past rainfall or temperature continues to be debated (Greenwood and Wing 1995, Jordan, 1996, 1997b, Wing and Greenwood 1996, Wiemann *et al.* 1998a, Wilf *et al.* 1998).

Leaf morphology in sclerophyllous plants is equivocal proxy climatic evidence because of the convergent effects of low soil nutrient levels (scleromorphy) and dry soils (xeromorphy). Hill (1998b) concludes that the two can be distinguished via differences in foliar adaptations that protect the leaf from excessive wetting (cuticular striations, dense covering of trichomes) and those that reduce water loss (stoma enclosed in pits or within raised structures, revolute leaf margins). However, plants with xeromorphic characters are inherently unlikely to occur at sites conducive to fossilisation.

Modern relationships between climate and wood anatomical features in North American, South American, African and Malaysian floras have been used to develop a method for inferring past climates from fossil wood (Wiemann *et al.* 1998b). More recently Falcon-Lang (2000) has challenged the uncritical use of growth rings in fossil conifer wood as a tool for reconstructing seasonality, citing a strong inverse relationship between leaf longevity and the growth ring architecture ('ring markedness'). Other recent studies have investigated the value of phytoliths in identifying *Nothofagus* (*Lophozonia*) in the Tertiary fossil record (Whang and Hill 1995) and reviewed the use of fungal germlings as evidence for past humidity (Wells and Hill 1993).

2.4.2   Other proxy-climatic evidence

Away from the continental margin basins, erosion and/or prolonged periods of non-deposition or deep weathering of the regolith have destroyed much of the organic matter deposited during the Cretaceous and Tertiary. Hence the continental landscape largely is a palimpsest of erosional and weathering features developed under varying climatic regimes, especially in the cratonic regions of central and Western Australia.

Most erosional features of the landscape are difficult to use as proxy-climatic data for several reasons: (1) Landforms may or may not change abruptly at thresholds in the climatic continuum (Chappell, 1983). (2) In many regions, climate-driven processes have changed in intensity rather than in character during the geologic past. (3) The time(s) of formation of most landforms almost always are poorly constrained.

Using a mathematical model in which climate fluctuated sinusoidally between wet and dry states, Rinaldo, *et al.* (1995) found that both end states left detectable geomorphologic signatures in the landscape only when there was no active tectonic uplift. Where uplift had occurred, the topography was found to track the prevailing climate, but only those features developed during the wet state were likely to be preserved. Probable examples are the dissected pediments and cemented soil horizons (*duricrust*) now found across much of inland Australia. A more favourable situation exists in aggradational terrain where mineralogy, lithostratigraphy, stratal patterns (*facies architecture*) and animal remains reflect past climates although, once again, such evidence is often difficult to date.

1.   Palaeontological evidence

Like plant tissues, animal remains may be found ±chemically unaltered, replaced by other minerals, or occurring as impressions and casts. Two of the more commonly found remains preserved in terrestrial deposits are mollusc shells and skeletal remains of land vertebrates.

The majority of faunal remains have been transported by water, wind and/or dismembered by scavengers prior to burial. Taphonomic biases are similar to plant macrofossils in that the body parts that are most likely to be preserved are the more robust bones and teeth of animals living by or in streams and lakes. Examples are herbivores, particularly those that grazed in herds, burrowing rodents, fish, crocodiles, turtles and water birds. Empirical evidence confirms that carnivores and other life-forms that are rare in living faunas, are equally rare in the fossil record. Under-utilised sources of proxy-climatic data are vertebrate tracks (Lockey 1998) and insects (cf. Rozefelds 1988, Wilf and Labandeira 1999).

Australian fossil mammal assemblages extend back into Early Cretaceous time, such as at Lightning Ridge (Archer *et al.* 1994), and many of these marsupial clades underwent adaptive radiation following the diversification of flowering plants in the mid Cretaceous and aridification of the continent in the Late Tertiary. However, only rarely can the faunal assemblages (*Local Faunas*) be directly dated using geochronometric techniques, or indirectly by plant microfossils (Macphail 1996a, 1996b, 1996c). Lateral facies variation, and the geographically restricted extent of most distinctive strata usually restrict the use of lithostratigraphy to correlate faunal assemblages with distant, more easily dated rock formations.

At present, most Tertiary faunas are assigned to Local Faunas, which are correlated using superposition and stage-of-evolution criteria (Megirian 1994). This approach assumes that relative position within a given clade is evidence of geological age. Turnover, used to define the boundaries of these faunal biochrons, occurs mostly at the species level. At present marsupials, which appear to have evolved rapidly in their morphology and also dispersed rapidly over large geographic areas, provide the highest resolution. However 'Mammal (strictly speaking Marsupial) Ages' have not been defined for Australia due to the highly fragmented nature of the faunal record and also because of minimal immigration due to prolonged isolation of the continent during the Tertiary.

A study of Late Paleocene faunas in Wyoming indicates that climatically-forced changes in the vegetation can have abrupt and long-lasting effects on the evolution of mammalian communities (Clyde and Gingerich 1998). Similarly, many aspects of the history and structure of Australian herbivores are adaptations to the harvesting and consumption of particular plant groups (Archer *et al*. 1994). For this reason, it is possible to use anatomical features such as dentition to infer some aspects of their diet and therefore past vegetation and climates.

2.   Isotopes

Stable isotopes of carbon ($^{12}C/^{13}C$) and oxygen ($^{16}O/^{18}O$) are widely used to reconstruct palaeotemperatures, in particular sea surface temperatures (SSTs), and can be used to infer palaeosalinities. $^{16}O/^{18}O$ ($\delta^{18}O$) can be used for terrestrial sediments as well as for any calcareous fossils. For example Bird and Chivas (1993) have used the oxygen-isotope composition of clay minerals to develop a broad-brush weathering chronology and circumscribe the conditions under which deep weathering of the regolith occurred during the Mesozoic and Tertiary across Australia.

The use of carbon isotopes to reconstruct terrestrial palaeotemperatures depends on the observation that the three types of photosynthetic pathways found in the higher plants, designated as C_3, C_4 and CAM, provide different competitive advantages under different

climates. For example, grass species utilising the C_4 photosynthesis pathway are most numerous in regions where summers are hot and wet. Their relative abundance declines in regions where mean annual temperatures and/or summer rainfall are relatively reduced (Hattersley 1983, 1987). Connin *et al*. (1998) have used $\delta^{13}C$ variation in herbivore tooth enamel to evaluate patterns of C_4 plant abundance, and therefore infer trends in summer rainfall, in the southwestern United States.

3.   Minerals

A number of minerals form under highly specific conditions and these (or their casts) can provide direct or indirect information on past climates.

An example is glendonite, which provide unequivocal evidence of seasonal freezing of seawater in the Eromanga Basin during the Early Cretaceous (Frakes *et al*. 1995). Gibson *et al*. (2000) have used a spike in kaolinite-dominated mineral assemblages to infer intensified weathering due to increased precipitation and temperatures on the north-east Atlantic coast of the United States during the Late Paleocene. Other widely used environmental indicators include evaporite minerals that form onshore only under arid and semi-arid conditions, e.g. anhydrite, gypsum and halite (cf. Bowler 1976). These are at the dry end of a spectrum of mineral indicators whose wet end are lignites and coal (Rees *et al*. 1999). Between these end members are clays such as illite, which indicate weathering under temperate conditions, and smectite, which indicates weathering under warm and semi-arid conditions. Uranium-lead dating of zircons has been used to provenance sands reworked into Quaternary sand dunes (Pell *et al*. 1997) and the same technique can be applied to pre-Quaternary contexts (B. Pillans pers. comm.).

4.   Palaeosols

Fossil soils (*palaeosols, paleosols*) developed across former landsurfaces are indirect evidence of past climates and climatic change (Catt *et al*. 2000). Recent reviews of the terminology and taxonomy of palaeosols include Nettleton *et al*. (2000) and Reuter (2000).

In Australia, considerable attention has been paid to the local conditions under which major cementing minerals in duricrust are transported by, and precipitated from, circulating groundwater. Examples are iron/aluminium sesquioxides (ferricrete), secondary silica (silcrete) and carbonates (calcrete) (Arakel 1991, Bourman 1993, Anand 1997).

These and related studies indicate: (1) Ferricrete is best developed under climates with a seasonally variable rainfall (Milnes *et al*. 1985, Butt 1981, cited in Clarke 1994). (2) Silcrete requires acid-weathering conditions within the soil but otherwise cannot be linked to specific environmental conditions (Milnes and Twidale 1983). (3) Gibbsite, one of the major minerals found in bauxite, implies mean annual temperatures were above $22^{\circ}C$, unless drainage and parent rock characteristics were unusually favourable (references in: Price *et al*. 1997, Price 1998, Taylor 1998). (4) Calcrete may form under sub-humid to semi-arid climates although one form (pedogenic calcrete) preferentially occurs in winter rainfall regions such as southwestern Western Australia whilst the other form (groundwater calcrete) preferentially occurs in regions receiving summer rainfall. (5) Saprolite can develop under almost any humid climatic regime although rates of 'deep weathering' will vary. More generally, Christopherson (1997) proposes that heavily weathered soils with distinctive iron and aluminium oxide horizons (*oxisols*) reflect seasonal- and non-seasonal wet tropical climates, respectively. Ekart *et al*. (1999) have used palaeosol carbonates to estimate atmospheric ρCO_2 levels over the past 400 million years.

5. Facies architecture and lithostratigraphy

Many sediments and sedimentary sequences are the result of cyclic processes operating under particular environments (Schwarzacher 2000). The environmental signatures of these processes may be physical, geochemical or architectural.

An example of a sediment type that has well-defined climatic implications is aeolian dust preserved in the Late Cenozoic regolith in arid and semi-arid south-west Western Australia (Glassford and Semeniuk 1995). Cool water shelf carbonates provide evidence for SSTs along the southern margin during the Oligo-Miocene (references in Nelson and James, 2000). Elsewhere, Alley *et al*. (1999) have used sediments infilling palaeodrainage systems to reconstruct a weathering history for central southern Australia; Dingle and Lavalle (1998) have used chemical weathering and maturity of sediments to infer palaeoclimates in western Antarctica during the Late Cretaceous and Cenozoic; and Pederson *et al*. (2000) have shown that sediment production and delivery to piedmont fans can be correlated with climatic change during the Mio-Pliocene in tectonically quiescent areas.

Sequence stratigraphy concepts have revolutionised the interpretation of sedimentary sequences infilling continental margin basins (cf. Haq *et al*. 1987, Miall 1995, Bohacs and Suter, 1997). Gammon *et al*. (2000) and Li *et al*. (2000) provide examples of the role of oscillating sea levels in determining sedimentation patterns (and therefore stratal architecture) in the Eucla and Otway Basins, respectively. However, sequence stratigraphy concepts are difficult to apply inland where deposition may not be directly linked to changes in relative sea level (McCarthy and Plint 1998, McCarthy *et al*. 1998).

6. GCM Modelling

General Circulation Models (*GCM*s), which simulate past climates, increasingly are being used as an alternative to reconstructions founded on proxy-climatic data. For example, GCMs have been used to model conditions during Quaternary glacial and interglacial cycles and to predict how sensitive regional climates will be to future changes in atmospheric CO_2. Similar models have been used to reconstruct mid Cretaceous and Early Eocene climates for the Australian region (Frakes 1997, 1999), or the globe as a whole (cf. Sloan 1994, Barron *et al*. 1995, Sloan and Rea 1995, Price *et al*. 1998, Haywood *et al*. (2000).

Climatic predictions, however, may be difficult to test, e.g. because of uncertainties in the boundary conditions such as the extent of the East Antarctic Ice Sheet during the middle Pliocene. At present, the resolution provided by GCM simulations is too coarse to accurately predict past environments at the regional geographic scale. A recent example is a model that failed to 'predict' the formation of bauxite deposits in Tertiary Australia (Price *et al.* 1997, Price 1998, Taylor 1998). Thus palaeobotanical and related evidence are likely to remain an essential part of the data used to define and test boundary conditions used in modelling experiments (Thompson and Fleming 1996, O'Brien 1998).

SECTION 3 (CHRONOSTRATIGRAPHY)

Few rock sequences are suitable for isotopic dating. For example, the potassium/argon (K/Ar) method is of limited use in Australia due to the restriction of suitable volcanic rocks to the eastern margin, Tasmania and the Kimberley region. Other sequences have to be dated via their fossil content or their stratigraphic relationships to other strata that preserve fossils. This inevitably leads to circular reasoning when the same fossils are used as evidence of both age and palaeoenvironment. In most instances however, age determinations can be validated via correlation with other sections that can be dated by chronometric techniques.

3.1 Palynostratigraphic dating

Most of the zonation schema that use fossil pollen and spores to date and correlate Cretaceous and Cenozoic sediments in Australia were developed by or for the petroleum exploration industry. An exception is the Murray-Darling Basin in southeastern Australia where the driver has been groundwater and salinity management.

In almost all instances, the zone boundaries are defined by the observed First (FO) and Last (LO) occurrences of selected species (Concurrent Range zones). Computer models that can simulate the fossil record have been used to analyse potential discrepancies (offsets) in the FO and LO of a species in the stratigraphic record *versus* the probable earlier times of migration and later extinction of the parent taxa (cf. Holland and Patzkowsky 1999, Nowak *et al*. 2000). Offsets explain occasional anomalously early or late occurrences of particular fossil species.

The microfossils that are most useful as zone indicator species (*zone index species*) tend to be relatively large and distinctively shaped/ornamented types that are easily seen using low magnification or bright field microscopy. Many of the parent plants were small, rare or under-represented plants that grew in the subcanopy or ground stratum, or in water. Examples are two liverwort spore types, *Foraminisporis wonthaggiensis* and *Cingulatisporites bifurcatus* whose FOs define the base of the Valanginian and Late Miocene in southeastern Australia, respectively.

For these reasons, zone index species may be restricted to one sedimentary basin or geographic region. An example is a fern now restricted to South America (*Lophosoria*) whose fossil spores (*Cyatheacidites annulatus*) are widespread in Oligo-Miocene sediments across southeastern Australia but are not known to occur in correlative sediments in northern Queensland, central Australia or Western Australia; *Foraminisporis wonthaggiensis* is common in Early Cretaceous sequences in eastern Australian but has not been recorded in Cretaceous sequences in south-west or north-west Western Australia (M.K. Macphail and A.D. Partridge pers. observations). Similarly, the age range (*time distribution*) and maximum relative abundance (*acme*) of commonly occurring species will tend to vary from basin to basin because of differences in local to regional environments. An example is an extinct species of the rainforest genus *Anacolosa* whose fossil pollen (*Anacolosidites acutullus*) first appears in northwestern Australia in the Late Cretaceous, but is not recorded southeastern Australia until the Late Paleocene.

3.1.1 *Cretaceous*

Formal spore-pollen and dinoflagellate-based palynostratigraphies have been available since the 1960s, e.g. Burger (1980) and Morgan (1980) for the Eromanga and Surat Basins, which cover much of northern South Australia, central Queensland and northwestern New South Wales respectively; Dettmann (1963), Stover and Evans (1973) and Stover and Partridge (1973) for the Otway and Gippsland Basins in southeastern Australia; and Balme (1964) and Backhouse (1988) for the Perth, Carnarvon and Canning Basins in Western Australia.

Subsequent developments include melding of the above schema into a pan-Australian palynostratigraphy covering the Late Jurassic-Cretaceous Period by Helby *et al.* (1987) and the development of a provisional zonation for central Australia (Macphail 1996c, 1997a).

3.1.2 *Tertiary*

The key Australian schema is the *Esso-BHP* zonation, developed to date and correlate sequences in the Gippsland Basin by Stover and Evans (1973) and Stover and Partridge (1973). This schema and subsequent revisions (Partridge 1976, 1999) have been extrapolated to other continental margin and epicontinental basins in southern and central Australia, including the Bass, Eucla, Hale, Murray-Darling and Ti-tree Basins (Stover and Partridge, 1982, Milne, 1988; Macphail and Truswell 1989, 1993; Macphail 1997a, 1997b, 1999). No formal zonation exists for Late Cretaceous and Tertiary sequences in northeastern or northwestern Australia, with the predictable result that zones defined for the Gippsland Basin are in widespread use as *de facto* Stages names for these regions.

3.2 Independent age control

Pillans (1998) and Duller (2000) have reviewed the geological contexts and time ranges in which it is appropriate to use the various geochronometric techniques, such as optically stimulated luminescence (OSL), cosmogenic isotopes (^{10}Be, ^{36}Cl, ^{26}Al), oxygen isotopes and the uranium series isotopes. Calibrated and correlated age methods include fission track dating, amino-acid racemisation and palaeomagnetism. Grocke (1998) has discussed the use of carbon isotopes as a 'chemostratigraphic' tool.

Where possible, the age of zone boundaries cited in this study have been independently dated against the currently accepted International Time Scale using ammonites, planktonic foraminifera, dinocysts, nannofossils and sequence stratigraphy (Helby *et al.* 1987, Young and Laurie 1996, Shafik 1998). Because of provincialism, many of the biostratigraphic tie-points with the standard European stages remain uncertain and therefore are subject to ongoing revision.

An illustration of this is the proposal (H. Brinkhuis pers. comm.) that the first occurrence of high relative abundances of the marine dinoflagellate genus *Apectodinium* in the Northern Hemisphere was part of a globally synchronous event, which can be precisely correlated with the Paleocene-Eocene Thermal Maximum (PETM). However, in the Gippsland Basin, at least three species of *Apectodinium* are recorded in the Paleocene-Eocene transition as defined by spore-pollen. These are (1) a morphotype of *Apectodinium homomorphum* characterised by short processes, which is abundant near the top of the Late Paleocene/Upper *Lygistepollenites balmei* Zone, (2) *Apectodinium hyperacantha*, which reaches its maximum abundance in the lower part of the early Early Eocene/Lower *Malvacipollis diversus* Zone, and (3) a second morphotype of *Apectodinium homomorphum* characterised by long processes, which occurs throughout the Early Eocene/*M. diversus* Zone. If the first 'spike' in the relative abundance *Apectodinium homomorphum* species occurred at the Paleocene-Eocene boundary, then one corollary is that spore-pollen species, whose first occurrence now defines the Upper *Lygistepollenites balmei*/Lower *Malvacipollis diversus* Zone boundary in the Gippsland Basin, first appeared <u>within</u> the Early Eocene. This in turn implies the temperature-forced replacement of Austral Conifer Forest by tropical rainforest types took place over some tens to hundreds of millennia after the PETM.

The *Esso-BHP* zonation for the Gippsland Basin is under constant review (Partridge 1999) and absolute ages assigned to the zone boundaries also are subject to on-going revision. Some radiometric ages used to calibrate Cretaceous palynological zones are considered to be unreliable (Dettmann *et al.* 1992). Conversely, the few Potassium-Argon (K/Ar)-dated microfloras in southeastern Australia fall within the age range proposed for the associated

palynological zone (cf. Stover and Partridge 1973, Macphail and Hill 1994, Macphail *et al.* 1994).

Several competing International Time Scales are available. Two of the more widely used are Haq *et al*. (1987) and Harland *et al*. (1990). The ages proposed for many Cretaceous and Tertiary Epochs and Stages differ slightly from ages proposed by Chaproniere *et al*. (1996) in the recently published *AGSO Timescale* (Young and Laurie 1996). The latter are adopted in this study simply since they are based on Australian evidence.

SECTION 4 (GEOGRAPHIC BOUNDARIES AND TIME SLICES)

4.1   Geographic regions

Few Australian basins that preserve Cretaceous and/or Tertiary fossil floras fall neatly within existing geographic or political boundaries. For example, the Surat Basin extends from south-central Queensland into central northern New South Wales and was flooded by the same mid Cretaceous seas as the Eromanga Basin, which extends across much of southwestern Queensland and south-east of the Northern Territory into northern South Australia. Over the last 140 million years, Tasmania has moved from a land-locked position within East Gondwana during the Cretaceous to a small mountainous island situated in middle latitudes of the Southern Ocean during the Late Cenozoic.

The geographic regions used in this study have been selected to minimise overlap between the major sedimentary basins whilst broadly conforming to changes brought about by rotation of the continent relative to the geographic South Pole. These are;

1.   *North-West Australia*, encompassing northwestern Australia north of the Pilbara region (and the northern Carnarvon Basin), and regions eastwards to the Gulf of Carpentaria.

2.   *North-East Australia*, encompassing the Gulf of Carpentaria, Queensland and northern New South Wales.

3.   *Central Australia*, encompassing the southern half of the Northern Territory and the northern half of South Australia.

4.   *South-West Australia*, encompassing the Pilbara region (and the southern Carnarvon Basin), and southwestern Western Australia.

5.   *Central southern Australia*, encompassing the eastern Eucla Basin and southwestern South Australia.

6.   *South-East Australia*, encompassing central and southern New South Wales, Victoria and southeastern South Australia.

7.   *Tasmania.*

Larger basins and structural highs within each geographic region are listed in Table 4.

Table 4:   Geographic regions

Major Regions	Basins		Blocks and Uplands
	coastal/offshore	inland	
North-West	Browse, Bonaparte, Canning, Money Shoals	Canning	Kimberley
South-West	Bremer, Carnarvon, Eucla, Perth	Officer	Pilbara, Yilgarn
Central	-	(Alice Springs), Eromanga, Surat	Arunta
central-southern	Duntroon, Polda, St. Vincent	Eyre, Torrens	Gawler
North-East	Carpentaria/ Karumba, Maryborough	Casuarina, Duaringa, Styx, Yaamba	N.E. Highlands
South-East	Gippsland, Otway (including Torquay)	Murray-Darling	S.E. Highlands
Tasmania	Bass, Sorell + onshore extensions	(Midlands)	Central Plateau

4.2   Time Slices

Few palynostratigraphic zones fall neatly within a Period (Cretaceous) or Stage/Series (Tertiary) and the confidence with which the various fossil assemblages can be assigned to a given period of geological time varies markedly across the continent. The eleven Time Slices used in this study (Table 5) represent a compromise between subdividing the palynostratigraphic data into intervals defined by global climatic change and the mostly broad intervals of geologic time that can be recognised in all geographic regions.

Table 5:   Time Slices

Slice	Period	Age *	Palynostratigraphic Zones #
K-1	Berriasian to Barremian	141-115 Ma	*Cicatricosisporites australiensis–Foraminisporis wonthaggiensis*
K-2	Aptian to Albian	115-97.5 Ma	*Cyclosporites hughesii–Phimopollenites pannosus*
K-3	Cenomanian	97.5-91 Ma	*Appendicisporites distocarinatus*
K-4	Turonian to Santonian	91-83 Ma	*Phyllocladidites mawsonii–Tricolporites apoxyexinus*
K-5	Early Campanian	83-70 Ma	*Nothofagidites senectus*
K-6	Late Campanian to Maastrichtian	70-65 Ma	*Tricolporites lilliei–Forcipites longus*
T-1	Paleocene	65-54.8 Ma	*Lygistepollenites balmei*
T-2	Early Eocene	54.8-49 Ma	*Malvacipollis diversus–Proteacidites asperopolus*
T-3	Middle-Late Eocene	49-33.7 Ma	Lower to Middle *Nothofagidites asperus*
T-4	Oligocene to Middle Miocene	33.7-11.2 Ma	Upper *Nothofagidites asperus–Canthiumidites bellus*
T-5	Late Miocene to Late Pliocene	11.2-1.78 Ma	*Monotocidites galeatus–Tubulifloridites pleistocenicus*

* After Young and Laurie (1996)

\# After Stover and Partridge (1973), Helby *et al*. (1987), Macphail and Truswell (1993b)

SECTION 5 (EARLY CRETACEOUS CLIMATES)

5.1   Global backdrop

Phenomena shaping Early Cretaceous climate and vegetation on the global scale include: (1) changes in the area and relative position of the continents, which in turn altered oceanic circulation patterns (Frakes *et al.* 1987, Tarling 1997); (2) subdued orography, which may or may not have modified atmospheric circulation patterns; and (3) changes in relative sea level (isostatic and changes driven by variations in sea floor spreading rates). Cretaceous floral provinces have been reviewed by Herngreen and Chlonova (1981) and Srivastava (1994).

One not surprising consequence of the complex changes in palaeogeography is the continual challenging of existing climatic reconstructions. For example, calcareous nannofossils from high latitudes in the Northern Hemisphere indicate global 'ice house' conditions existed during the Early Valanginian, contrary to the widely held view that there were warm equable conditions in polar regions (Mutterlose and Kessels 2000). Ocean-wide anoxic events in the Late Barremian to Early Aptian (Bralower *et al.* 1994) almost certainly had terrestrial ramifications since high rates of carbon burial in marine sediments will have lead to drawdown of atmospheric carbon dioxide and reduced oxygen concentrations in bottom water. The global increase in the production of oceanic crust during the mid Cretaceous coincided with abundant volcanism in the Pacific Basin (Larson and Kincaid 1996).

In order to simulate observed temperature patterns in the mid Cretaceous, GCMs require atmospheric ρCO_2 to be four times the present-day value (Berner 1990, Moore *et al.* 1992, Barron *et al.* 1995). Volcanism provides a convenient mechanism for this increase but the explanation is under challenge (Sellwood *et al.* 1994, Heller *et al.* 1996, Cowling 1999, Sadler and Grattan 1999, Kump 2000). For example, high CO_2 concentrations could be due to a change in deepwater circulation, which in turn altered the flux of warm, saline water from low to high latitudes (MacLeod and Huber 1996). Climatic sensitivity experiments (references in Barron and Peterson 1991, Barron *et al.* 1995) predict that even small increases in poleward ocean heat transport will lead to a significant increase in temperatures at the poles and a decrease in temperatures at the equator.

Whichever explanation(s) prove to be correct, the point remains that Cretaceous Earth was very different from the present. Notable differences are: (1) a broad zone of largely non-seasonal climates stretching from palaeolatitudes 32^0N to 32^0S (Creber and Chaloner 1985) and (2) plant productivity reached its maximum in middle to high latitudes, a region encompassing Australia, which was located at palaeolatitudes of 65^0-78^0 during the Late Jurassic to mid Cretaceous (Veevers *et al.* 1991). Frakes and Francis (1988) note evidence of ice rafting on many continents at mid-high palaeolatitude, including Australia. In contrast, landmasses in the palaeotropics experienced arid conditions (Hallam 1984, 1985, Horrell 1991).

5.2   Australian backdrop

For much of the last 140-200 million years, Australia has been part of much larger continental landmasses, first as part of the Super Continent Pangaea, then part of East Gondwana. Thin coals confirm that rainfall and temperatures were adequate to support mire communities at palaeolatitudes >70^0S in southeastern Australia. Petrified tree trunks provide evidence for relatively mild climates in polar latitudes in West Antarctica, then part of West Gondwana (Jefferson 1992, del Valle *et al.* 1997).

5.2.1 *Late Jurassic*

During the Late Jurassic and earliest Cretaceous, the continent lay between palaeolatitudes of ~45-85^{0}S, with the South Coast of New South Wales being the part of the continent that was closest to the geographic South Pole. Much of the palaeo-northern Australia was at a palaeolatitude of 60^{0}S or lower (Veevers *et al.* 1991). Climates are likely to have been 'continental' although most reconstructions are in fact predictions based on GCMs, e.g. Moore *et al.* (1992). This model, which assumes topographic relief of up to 2 km elevation along the palaeo-eastern margin, predicts annual temperature ranges of –22^{0}C to +10^{0}C at palaeolatitude 70^{0}S (Hobart) and –10^{0}C to +20^{0}C at palaeolatitude 45^{0}S (Darwin). Annual precipitation is estimated to have been in excess of 1000 mm. The model also predicts that the palaeo-northwestern margin (palaeolatitude 40^{0}S), which fronted onto the Neo-Tethys Sea, was affected by storms.

5.2.2 *Early Cretaceous*

Patterns of climatic change during the Berriasian to Aptian [141-112 Ma] are complicated by the fragmentation of East Gondwana, which allowed seaways to develop around the palaeo-northern and western margins of the continent, and movement of Australia as a whole into increasingly high palaeolatitudes, which will have increased the area subject to low photoperiods during winter. For example, the region stretching from southern Queensland to northeastern Tasmania lay south of 80^{0}S during the Valanginian to Aptian [141-123.5 Ma] and therefore will have been subject to three or more months of winter darkness. Conversely, plants growing along the Western Australian coastline, then part of the palaeo-northern margin at ~45^{0}S, will have been unaffected by low photoperiods.

Marine flooding is likely to have provided new sources of moisture, tempering the continental climatic regimes and the third major influence on Early Cretaceous climates was a series of punctuated marine transgressions into the Perth and Carnarvon Basins (palaeo-northern margin) and Carpentaria, Laura, Eromanga and Surat Basins in the palaeo-centre and south-east of the continent). These transgressions began in the Valanginian and culminated in the Late Aptian [119-114 Ma] when approximately one quarter of the continent was occupied by epicontinental seas (cf. Immenhauser and Scott 1999). Any carbonate platforms developed along the palaeo-northern margin facing the Neo-Tethys Ocean will have been drowned during this prolonged 'high stand' (cf. Gotsch *et al.* 1993).

The epicontinental seaways in Australia were subject to winter freezing during the Valanginian to Albian [112-99 Ma]. Geological evidence for sub-zero temperatures in the Eromanga/Carpentaria Basin are supported by the GCM results, which predict a mean annual temperature range of –18^{0}C to +27^{0}C in these basins and averages close to 0°C over much of the continent (references in Frakes and Francis 1988, Frakes 1999). Sedimentary evidence indicates storms were frequent (cf. Barron and Washington 1982). Frakes (1999) proposes that the Cretaceous Period also included more temperate intervals, which were accentuated by the effective northward movement of the continent. For example, by the end of the Albian [112-97 Ma], Western Australia was located at palaeolatitudes of between 50-60^{0}S and oxygen isotope data indicate SSTs in the Carnarvon Basin had risen to between 7-11^{0}C (Stevens and Clayton 1971): Average SSTs in the Eromanga-Surat Seaway were ~12^{0}C, reaching up to 16^{0}C where marine circulation was more restricted (Pirrie *et al*. 1995). Conversely, water temperatures averaged 0°C (range from –5^0 to +5^{0}C) in the Otway Basin at a palaeolatitude of ~85^{0}S within the developing Australo-Antarctic Rift System (Gregory *et al*. 1989).

Regression during the late Middle to early Late Albian led to anoxic conditions within central areas of the Eromanga-Carpentaria Seaway. Haig and Lynch (1993) note that changes in relative sea level in northeastern Australia during the Albian are out-of-phase with eustatic

events on other continents and suggest this was due to increasing regional tectonism along the eastern margin of Australia. Frakes (1999) suggests that much of Australia may have been subject to dry polar easterly winds blowing from what are now the east and south-east quadrants.

5.3   Palaeobotanic evidence for Early Cretaceous climates

Early Cretaceous climates in Australia reflect global to regional tectonic and eustatic events superimposed on relatively flat equator to pole temperature gradients.

Much of the palaeobotanical evidence comes from exploration wells and boreholes drilled in southern Queensland, central Australia, Western Australia and Victoria. The most closely sampled regions are the Eromanga and Surat Basins. Other sites preserving continuous palynosequences occur in offshore basins on the western margin (Perth, Carnarvon and Canning Basins), the North West Shelf (Bonaparte and Money Shoals Basins), northeastern Queensland (Carpentaria and Laura Basins), the mid Queensland coast (Maryborough and Styx Basins), and the Australo-Antarctic Rift System (Bight, Otway and Gippsland Basins). Infrabasins of Early Cretaceous age underlie the Murray-Darling Basin.

Many of the sedimentary sequences are marine and can be independently dated using dinoflagellates (Morgan 1980, Helby *et al.* 1987). The richest macrofloral sequence however is preserved in freshwater facies in the Gippsland Basin – the Koonwarra Flora (Dettmann 1986a, Drinnan and Chambers 1986, Douglas 1990, 1994).

Numerous unpublished reports providing information on Early Cretaceous palynofloras are on open-file in the Geological Surveys of Queensland (GSQ), New South Wales (GSNSW), Victoria (DME), South Australia (PIRSA) and Western Australia (GSWA). Early Cretaceous palynofloras have not been recorded onshore in Tasmania. Publications dealing with Early Cretaceous palynosequences include taxonomic monographs. Examples are Dettmann (1963, 1973) and Douglas (1969, 1973a, 1973b) for the Otway Basin, Burger (1968, 1973, 1976, 1980, 1988, 1990, 1993) for the Eromanga and Surat Basins, Kemp (1976a) for the Officer Basin, Morgan (1980) for the Eromanga Basin, and Backhouse (1988) for the Perth Basin. Recent overviews of the Early Cretaceous flora and vegetation are Dettmann (1994), Douglas (1994), McLoughlin (1996 and in press), McLoughlin and Hill (1996), Hill *et al.* (1999) and Pole and Douglas (1999).

Plants growing at high to polar latitudes during the Late Mesozoic experienced up to 3-6 months of winter darkness. Nevertheless macrofossil evidence shows that woody species displayed the growth characteristics of trees that now grow in mid latitude/temperate regions with relatively long growing seasons. For example, tree-trunks preserved on Alexander Island, West Antarctica (Jefferson 1992), provide direct evidence of communities dominated by gymnosperms that were at least 7 m tall and spaced between 3-5 m apart. Thick coal measures accumulated between palaeolatitudes of 70-80^{0}S (Mount Morgan-Stanwell district and Laura Basin). Accordingly, interpretation of Cretaceous climates in southern Australia involves explaining how rapid plant growth could be sustained in the face of short growing seasons (cf. Axelrod 1984, Barron *et al.* 1995).

5.3.1   *Evolution and migration*

Most Early Cretaceous genera and species which were found in Australia are extinct, as are some lower order taxa, e.g. the pteridosperms (a group of plants that combined the characteristics of modern cycads and conifers) and brachyphyll araucarians. Extant taxa families such as Araucariaceae, Podocarpaceae and Schizaeaceae had much wider distributions than now. For example, during the Early Cretaceous, schizaeaceous ferns

producing cicatrose to canaliculate trilete spores (*Cicatricosisporites*, *Contignisporites*, *Ruffordiaspora*) had a cosmopolitan distribution that extended into very high latitudes whilst their NLRs (*Anemia*, *Mohria*, *Ruffordia*) are confined to tropical America, Africa and southern India (Dettmann and Clifford 1991, 1992). The same is true for the Araucariaceae, which are mostly confined to seasonally wet and warm to hot (mesotherm-megatherm) climates. Nevertheless, most of the plants that first appear during the Early Cretaceous survived into latest Cretaceous or early Palaeogene time. Consequently presence/absence data give the misleading impression that the Early Cretaceous vegetation was homogeneous across the continent.

Contributing to this impression of apparent uniformity is the mixing of palynofloras within the larger basins, most of which received water-transported miospores via rivers draining vast tracts of the continent. Examples are the Canning-Officer and Carpentaria-Eromanga Seaways and the Australo-Antarctic Rift System. In contrast, microfloras derived from coals or lignites mostly represent local mire communities. Climatically-forced provincialism of the flora had developed as early as the Valanginian [135 Ma]. For example, one clade of brachyphyll araucarians (*Balmeiopsis*) is restricted to the drier, palaeo-northern side of the continent (present-day northwestern to southwestern Australia) whilst the liverwort (*Foraminisporis wonthaggiensis*) was restricted to the wetter, palaeo-southern side of the continent (present-day northeastern to southeastern Australia).

Pollen data from northern and central Australia show that the primitive angiosperms (angiospermids *sensu* Vasanthy *et al.* 1990) expanded over the continent during the mid Cretaceous. Examples in the Eromanga Basin (times of first appearance in parentheses) are: *Clavatipollenites hughesii* (Barremian/Early Aptian), *Asteropollis asteroides* (basal Albian), *Phimopollenites* and *Tricolpites* (mid Albian) and tricolporate pollen types (Late Albian). Angiospermid pollen first occur in significant numbers in the Surat Basin at the Aptian/Albian boundary and show a marked increase in relative abundance during the Albian. Since the highest relative abundance values follow regressive movements of the palaeoshoreline, the earliest angiosperm communities are likely to have been riparian and/or colonisers of newly exposed seafloor sediments.

5.3.2 *Gymnosperms and cryptogams*

Mesozoic forests and woodlands growing at polar latitudes in Australia were dominated by gymnosperms and cryptogams. This woody biome has no living counterpart in the Southern Hemisphere but a general resemblance to the boreal conifer forests and taiga of the Northern Hemisphere is likely for bioclimatic and ecophysiological reasons. The name *Austral Conifer Forest* is coined here to emphasise the presumed eco-physiognomic relationship. Some Cretaceous plants were deciduous, e.g. the pteridosperm/pentoxylalean genus *Taeniopteris*, but it is unlikely that the deciduous habit *per se* was advantageous at polar latitudes in the Southern Hemisphere (cf. Wolfe 1987, Hill *et al.* 1999). Empirical evidence for this includes the prominence of evergreen gymnosperms in coastal palaeo-southern Australia and their relative rarity in coastal palaeo-northern Australia during the Late Cretaceous.

Creber and Chaloner (1985) note that the amount of light energy available at polar latitudes during summer months is not dissimilar to that received annually in the middle latitudes. Hence the light available within polar communities of widely spaced trees with tall conical crowns may not have been substantially less than light availability within more dense plant communities growing at lower latitudes. Similarly, a study of the response of selected Southern Hemisphere tree species to prolonged darkness (Read and Francis 1992) suggests that survival rates are higher under colder ($>4^0$C) than under warmer temperature regimes. Some species were able to survive 10 weeks of continuous darkness and Bond *et al.* (1999) have shown that the foliage of one Northern Hemisphere pine (*Tsuga*) can survive under less than 1% of full sun light in humid temperate climates.

If these considerations apply to the Early Cretaceous vegetation, then inland (continental) habitats may have been more suitable for tall gymnosperms than the milder climates found nearer the coast, and communities growing close to the coast or along shorelines are more likely to have been dominated by shrub and heath species of cryptogams. For the same reason, relatively open canopy communities found at higher latitudes may have been replaced by relatively closed canopy forests in lower latitude regions where sun angles are higher.

5.3.2 *Angiosperms*

The earliest unequivocal evidence of angiosperms are pollen grains of magnoliid dicotyledons and monocotyledons found in Hauterivian deposits in Israel and southern England (references in McLoughlin *et al*. 1995a). Macro and microfossil data show a major diversification of angiosperms in the Northern Hemisphere during the mid Cretaceous, with angiosperms first becoming abundant at lower latitudes and only subsequently becoming dominant at middle and high palaeolatitudes during the early Late Cretaceous. The same trend is apparent in the Southern Hemisphere (Drinnan and Crane, 1990). For example, angiospermid pollen, which first occurs in the Surat Basin in the Early Albian, becomes relatively common and widespread across the continent by Late Albian time (Burger 1980).

5.5.3 *Climatic indicator taxa*

Few Cretaceous species have NLRs with narrow ecological ranges. However, by comparing regional differences in the relative abundance of their macrofossils or miospores against palaeolatitude, it is possible to 'second-guess' the ecological preferences of some major plant groups. For example, observations by Dettmann *et al*. (1992), Dettmann (1994) and Pole and Douglas (1999) indicate that Podocarpaceae were more prominent in the Eromanga Basin, than in the south-east during Albian to Cenomanian time – suggesting podocarps were tolerant of strong seasonal contrasts in temperature as well as prolonged winter darkness. Ferns such as Gleicheniaceae and Schizaeaceae display the same bias but in this case, a not unreasonable explanation is that the diminished marine influence in the Albian allowed extensive fern heath to develop over emergent seafloor. The same studies indicate that *Gingko*, cycads and tree-ferns were characteristic of lower (warmer) palaeolatitudes and the same is probably true for most fern allies except for Lycopodiaceae-dominated communities, which were better developed at higher (colder) palaeolatitudes.
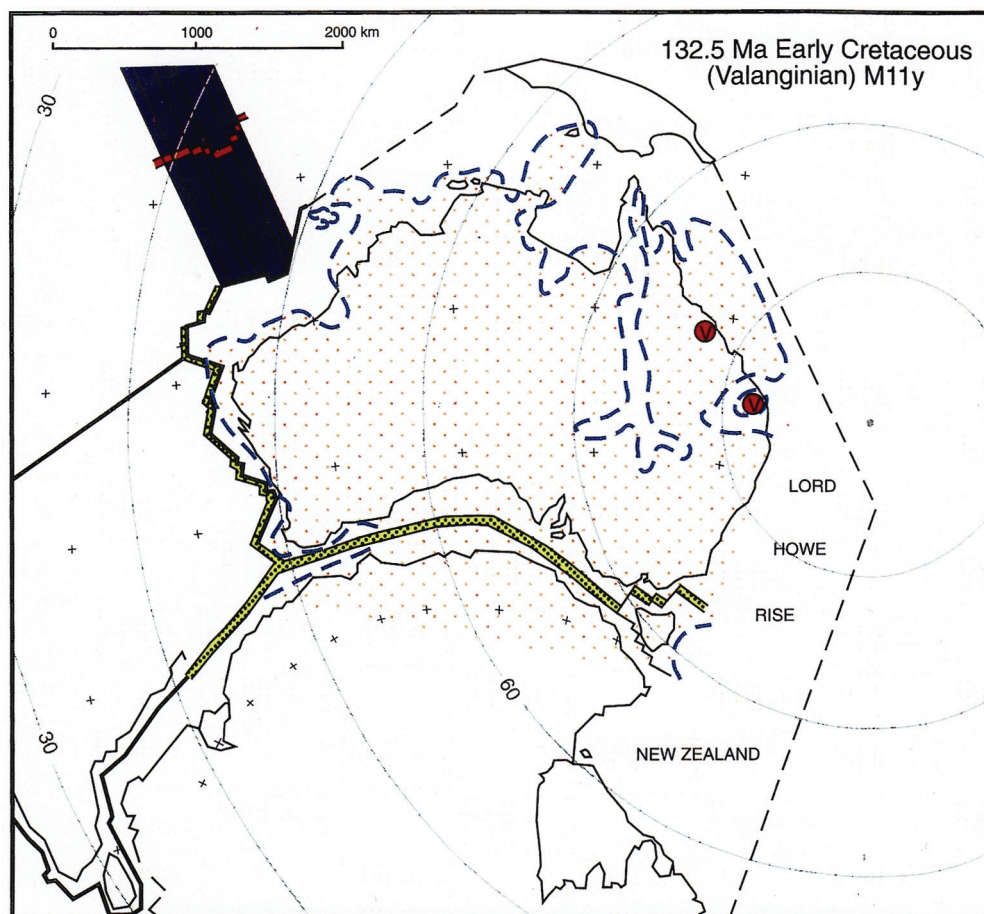
The fossil data may provide moderately reliable evidence for humidity but palaeotemperature preferences remain little more than speculations based on palaeogeography. For example, the literature consensus is that cheirolepidiacean woodland occupied (relatively cooler and possibly drier) upland areas rather than (relatively warmer and possibly wetter) coastal habitats despite Cheirolepidiaceae pollen (*Corollinia*) being most abundant in near shore marine sediments. Conversely, Backhouse (1988) has suggested an association with well-drained soils and warm (possibly seasonally arid) conditions. The relative abundance of *Sphagnum* spores (*Stereisporites* spp.) is amongst the more reliable palaeobotanical indicators of past climates in that *Sphagnum* (peat moss) bogs can only extend beyond the confines of topographic depressions under cool-cold and possibly uniformly wet conditions.

Other forcing factors may have included herbivory by dinosaurs (cf. Wing and Tiffney 1987, Archibald 1996), volcanism (Kerr 2000) and wildfires ignited by lightning strikes (Jones 1993). Evidence for palaeo-wildfires include a statistically significant correlation between the relative abundance of one pteridosperm clade (Bennettitales) and charcoal in the Eromanga Basin (Pole and Douglas 1999), implying that bennettitaleans were fire-tolerant or pioneers on burnt sites. Microfossils preserved in a charcoal conglomerate in the Murray Basin record the replacement of a gymnosperm-dominated community by ferns and fern allies (Macphail and Truswell 1989). In Argentina, volcanic ash-fall is suggested to have forced changes in the growth and distribution of Early Cretaceous gymnosperm-fern communities (Archangelsky *et al*. 1995).

5.4 Time Slice K-1. Berriasian-Barremian [141-115 Ma]

5.4.1 *Palaeogeography*

Figure 4: **Valanginian (133 Ma) palaeogeography (from Veevers *et al*. 1991)**

The early Early Cretaceous palaeogeography of Australia is summarised in Struckmeyer and Totterdell (1990), Veevers *et al*. (1991) and Taylor (1994). Seafloor spreading had commenced on the palaeo-northwestern margin and progressed clockwise around the continent (Figure 4) although at the beginning of the Berriasian, Australia was still attached to: Antarctica to the south; New Zealand, the Lord Howe Rise-Campbell Plateau and the Queensland Plateau to the east; and parts of Greater India to the west. One arm of the Neo-Tethys Ocean extended along the palaeo-northern margin past the Exmouth Plateau to a point southeast of Perth and another arm extended to the palaeo north-east. The Carnarvon region of Western Australia formed the palaeo-northern margin, and northeastern New South Wales the palaeo-southern margin, of the continent. By the end of the Barremian, the East Coast of New South Wales was at a palaeolatitudes of about 80^0S due to rotation of the continent about the geographic South Pole whilst the Carnarvon Basin remained part of the palaeo-northern margin of continent at a latitude of about 53^0S.

Rifting of the Indian sub-continent from Australia was marked by subsidence in the Perth and Carnarvon Basins and uplift of adjacent coastal regions. A large lake (Lake Murta) developed in the Eromanga Basin as the result of this internal drainage. Cratonic blocks such as the Yilgarn-Pilbara, Kimberley and Arunta Blocks, which had been prominent landscape elements for much of the Phanerozoic, became important sediment sources for the

surrounding basins. Thick sands eroded from these uplands began to accumulate along the palaeo-western and southern margins. A Chilean-type volcanic cordillera located in northeastern Queensland shed detritus westwards into the interior of the continent. A major rise in relative sea level during the Hauterivian to Barremian resulted in the formation of a seaway, which extended from the Gulf of Carpentaria southward into the Eromanga Basin. Sediments deposited at this time covered (and helped preserve) much of the pre-existing landsurface (Twidale and Campbell 1991). Gosses Bluff records one of a number of multiple meteorite impacts in central Australia during Early Cretaceous time (Plummer 1998).

5.4.2 *Palaeobotany*

Like the Late Jurassic, the Early Berriasian-Barremian floras were dominated by Araucariaceae, Podocarpaceae, Bennettitales and diverse cryptogams. Several archaic taxa had become extinct by the end of the Barremian whilst some angiospermids had migrated into the Australian region from West Gondwana by the Aptian (Douglas 1994).

5.4.3 *Palaeoclimates*

Floristic differences between regions are likely to reflect differences in palaeolatitude and proximity to the ocean and other large water bodies as well as climatic change *per se*.

Palaeo-northern Australia ($\sim$45-60^{0}S)

Climates in present-day southwestern and northwestern Western Australia probably were humid, and it is unlikely that plant growth was limited by low light intensities during winter because of the relatively low palaeolatitude. Some fossil woods possess prominent growth rings, implying strong seasonal variation in temperature and/or rainfall. Mean annual temperatures are presumed to have been 'warm' rather than 'cool' (lower mesotherm). The hypothesis that temperatures warmed from west (present-day south-west Western Australia) to east (present-day North West Shelf) along the palaeo-northern margin (Dettmann *et al*. 1992) cannot be tested by the current evidence.

Palaeo-central Australia ($\sim$60-70^{0}S)

Climates were wet (humid-perhumid) and average temperatures were adequate to support tree-growth during summer months despite the relatively high palaeolatitude. Palaeogeographic constraints imply mean temperatures are likely to have been seasonally cold (microtherm range) and probably frost-prone. Glendonites in the Eromanga, Surat and Carpentaria Basins provide the only direct evidence that winter temperatures fell below freezing point: plant growth will have been limited by low light intensities as well as low temperatures during winter.
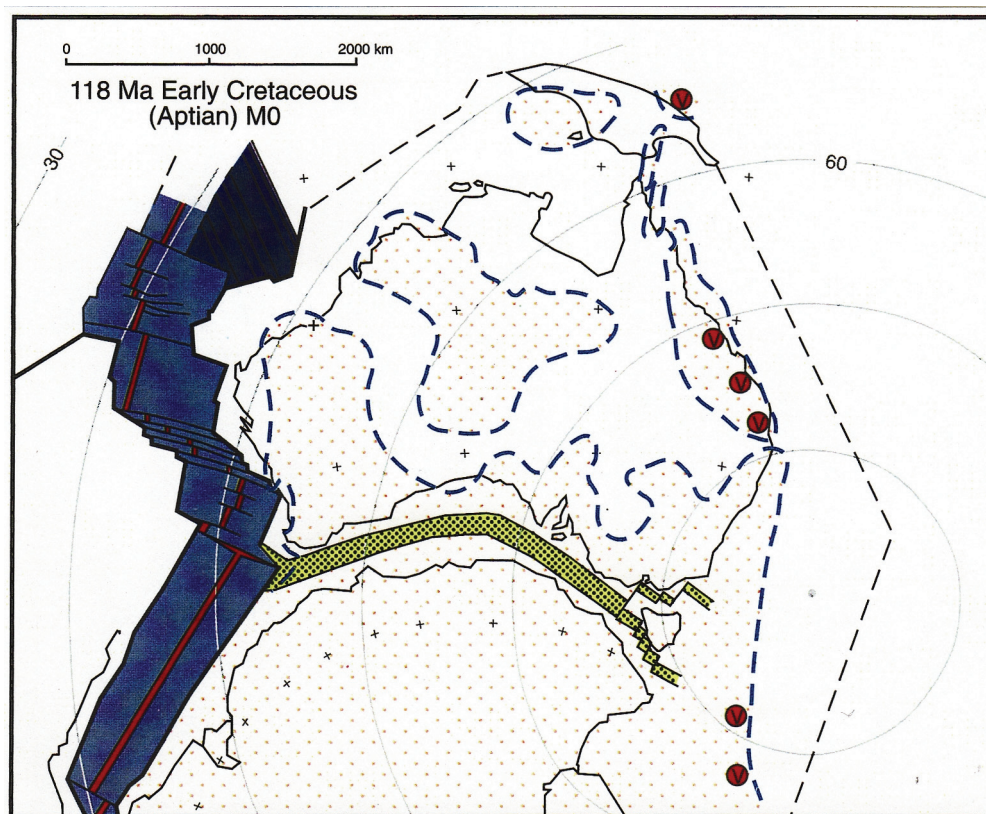
Palaeo-southern Australia ($\sim$70-85^{0}S)

Climates in present-day southeastern to northeastern Australia almost certainly were wetter (humid-perhumid) than in palaeo-northern Australia and it is reasonable to assume that mean temperatures varied from cold (lower microtherm) during winter months to cool (upper microtherm to lower mesotherm) in summer months. Plant growth in northeastern New South Wales and southern Queensland will have been strongly seasonal due to short summers, and freezing temperatures and prolonged darkness during winter. Evidence from palaeo-central Australia implies temperatures in palaeo-southern Australia also fell below freezing in winter. There is weak evidence that conditions within the (then) north-south orientated Australo-Antarctic Rift System were more temperate and supported denser vegetation than in the interior of the continent, possibly due to a marine influence.

5.5   Time Slice K-2. Aptian-Albian [115- 97.5 Ma]

5.5.1   *Palaeogeography*

Figure 5:   **Aptian (118 Ma) palaeogeography (from Veevers *et al.* 1991)**

By basal Aptian time, Australia had begun to move away from Antarctica (Figure 5). This involved stretching of the continental lithosphere beneath the Australo-Antarctic Rift System, which extended to and around Tasmania by the end of the Albian [~97 Ma].

Valleys at the Western Australian end of the rift system were flooded by the ocean to form a narrow seaway (Australo-Antarctic Seaway) whilst extensive brackish and freshwater swamps occupied tectonic depressions to the south-east. Fluvio-lacustrine sediments accumulating in one freshwater swamp in the Gippsland Basin (Koonwarra Fossil Beds) preserve the remains of a bird, fish and insects and angiosperm flowers (Taylor and Hickey 1990). Incipient rift valleys began forming in the Coral Sea region (palaeo-northeastern margin) and a volcanic arc (Eastern Cordillera) extended southwards down the Queensland and New South Wales coasts (palaeo-eastern margin). Igneous activity affected much of eastern Tasmania, then part of the palaeo-southern margin. Relative sea levels continued to rise, resulting in the continent being subdivided into four large islands (Yilgarn-Pilbara Block, Arunta-Kimberley Blocks, north-east Queensland, south-east Australia-Tasmania) separated by shallow epicontinental seaways during the Aptian. These seaways extended from the Gulf of Carpentaria (palaeo-northwestern margin) to near the Bight (palaeo-western margin) and eastwards onto the palaeo-southern margin (present-day New South Wales and southeastern Queensland).

Anoxic conditions developed in the central parts of the Carpentaria and Eromanga Basins during late Middle Aptian to Early Albian time. The Toolebuc Formation is an example of the distinctive condensed black shale sequences accumulating in many oceans at this time (cf.

Haig and Lynch 1993, Erbacher *et al*. 1999). By the end of the Albian [97 Ma], the sea had retreated from the southern Eromanga Basin. This allowed extensive freshwater swamps to form around the margins of the basin although a shallow sea bordered by large deltas and brackish estuaries remained present in its centre and also in the Gulf of Carpentaria (Carpentaria Basin) where maximum flooding occurred in the Early Albian (Haig and Lynch 1993, Henderson 1998). Much of the western half of the continent was subaerially exposed by this time, including part of the continental shelf seaward of the present-day coastline. This landscape rejuvenation, which is reflected in the marine sedimentary record (Henderson 1998), was broadly contemporary with renewed uplift in eastern and southern Australia. Nott and Purvis (1995) have recorded a ~100 Ma (Early Albian) basalt outcropping near sea level in southern New South Wales but its implications for uplift of the Southeastern Highlands remain controversial (Orr 1996).

5.5.2 *Palaeobotany*

The mid Cretaceous period was marked by the ecological re-assortment of gymnosperm and cryptogam communities making up Austral Conifer Forest, and the immigration and expansion of angiosperms, chiefly at the expense of ferns and fern allies.

Burger (1990) has proposed that, beginning in the Late Barremian/Early Aptian, successive waves of angiosperms entered palaeo-northeastern Australia (present-day Northern Territory) from (tropical) East Asia via Indonesia, and, less certain, from Africa via India. The diversity of angiosperm taxa increased markedly during the Albian. Nevertheless, in palaeo-southern Australia (present-day New South Wales and Victoria), gymnosperms continued to dominate the canopy strata into Late Cretaceous-Early Tertiary times. Floristic contrasts between palaeo-southern and palaeo-northern margins appear to have sharpened and the same may be true for the Perth and Eromanga Basins. The observations strengthen the case that Austral Conifer Forest was better developed (more diverse) at higher elevations and palaeolatitudes, including on the uplands bordering the Eromanga-Surat Seaway, whilst ferns dominated the coastal lowlands and analogous shoreline habitats.

5.5.3 *Palaeoclimates*

The relative impact on plant community evolution of marine transgression-regression, and low light intensities/low temperatures during winter months, are difficult to unravel. Rainfall may have been unequally distributed throughout the year in many regions but is unlikely to have limited plant growth during the Aptian-Albian.

Palaeo-northern Australia (~45-60^{0}S)

Climates in palaeo-northern Australia (present-day south-west to north-west Western Australia) were humid, possibly due to the movement of warm water eastwards into the Neo-Tethys Seaway. Temperatures are presumed to be warm (mesotherm range) and seasonal contrasts less marked than in inland and southern regions. NLR analysis is unhelpful since few of the fossil taxa have living relatives, and those that have, provide contradictory results, e.g. *Ruffordiaspora* (*Anemia*).

Palaeo-central Australia (~60-70^{0}S)

Regional climates were strongly influenced by marine transgression and regression events. Effective precipitation was sufficiently high (humid-perhumid) to support *Sphagnum* bogs in the southern Eromanga Basin, although this may have been as much due to low (microtherm range) temperatures reducing evapo-transpiration losses as to uniformly wet (humid-perhumid) climates. Mineralogical and sedimentary evidence confirm that water and therefore air temperatures fell below freezing during winter months, allowing ice to accumulate on uplands surrounding the Eromanga Basin. In spite of the strong seasonal contrasts in temperature and photoperiod, summers were sufficiently warm (upper microtherm) to support woody plant growth.

Palaeo-southern Australia (~70-80^{0}S)

Palaeobotanical evidence for Aptian-Albian climates in palaeo-southern Australia (present day south-east to north-east Australia) is distorted by the location of many sites in the then north-west to south-east orientated Australo-Antarctic Rift System. Other complicating factors include repeated tectonic disturbance and the ameliorating effect of marine flooding of the rift system as far 'east' as the Otway Basin. There is weak evidence that wet to very wet (humid-perhumid) conditions extended along the palaeo-southern margin, from the Otway Basin to the Maryborough Basin in southern Queensland. Temperatures were strongly seasonal (microtherm range) and probably below freezing during winter months.

SECTION 6 (LATE CRETACEOUS CLIMATES)

6.1 Global backdrop

Equator to pole temperature gradients remained relatively low during the Cenomanian to Maastrichtian but the poleward transport of heat via warm, saline water was far from uniform. For example, differences in surface water temperature between low and high latitudes are estimated to have been about $1\text{-}4^0$C during the Coniacian-Santonian and up to 14^0C during the Late Albian and Late Maastrichtian.

Most palaeotemperature estimates are based on stable isotope (δ^{18}O, δ^{13}C) analyses of Albian-Maastrichtian foraminifera recovered from deep-sea drilling (DSDP/ODP) sites. An exception is Horrell (1991) who has used a combination of geological and biological evidence to reconstruct global climatic zones for the Maastrichtian. Leaf margin analysis of floras preserved near the North Pole show mean annual air temperatures of $10 \pm 3^{0°}$C during the Cenomanian (Herman and Spicer 1997) whilst temperatures during the Coniacian and Campanian-Maastrichtian were $2\text{-}3^0$C and $2\text{-}8^0$C higher, respectively (Parrish and Spicer 1988). δ^{18}O data from the Naturaliste Plateau (palaeolatitude 58^0S) in the southern Indian Ocean, the Falkland Plateau (palaeolatitude $58^0\text{-}62^0$S) in the South-west Atlantic Ocean, and Weddell Sea (palaeolatitude 65^0S) indicate similar warming at middle to high palaeolatitudes in the Southern Hemisphere during the Cenomanian. Clarke and Jenkyns (1999) propose that global SSTs peaked sometime between the Cenomanian-Turonian boundary and the Middle Turonian, a period when global relative sea levels were higher than at any other time during the Mesozoic (Haq *et al*. 1987). The timing has been challenged by Kuypers *et al*. (1999), based on δ^{13}C evidence for a large drawdown in atmospheric CO_2 at the Cenomanian/Turonian boundary, which implies major climatic cooling during the Early Turonian.

SSTs remained relatively warm into the early Early Campanian but began to cool during the late Early Campanian (Huber *et al*. 1995). This cooling, which continued throughout the Maastrichtian, has been linked to the regression of epicontinental seaways from North America, Europe, Asia, South America and Africa (Frank and Arthur 1999). The same authors propose that a major reorganisation of ocean circulation patterns occurred at the mid-late Maastrichtian boundary, resulting in the development of a thermohaline circulation system similar to that of the modern oceans. Miller *et al*. (1999) interpret a very rapid drop of 30-40 m in relative sea level, which occurred at about the same time, as evidence for the development of moderate-sized ice sheets on high latitude landmasses.

Evidence is mounting that Late Cretaceous cooling was terminated by a short-lived warming event during the last 0.5 million years of Maastrichtian time although SSTs in the equatorial Pacific were only as warm ($\sim27\text{-}29^0$C) as now (Wilson and Opdyke 1996). Conversely, Li and Keller (1998) report rapid cooling occurred within 100,000 years of the Cretaceous/Tertiary (K/T) boundary at one mid latitude site in the South Atlantic. Johnson *et al*. (1989) report increased megafloral turnover below the K/T boundary in North Dakota but the change is smaller than turnover at the K/T boundary. Jeffery (1997) proposes climates became increasingly seasonal and unstable over a broad latitudinal range across the K/T boundary. The hypothesis that the K/T boundary reflects the impact of a large (~10 km) bolide onto the Yucatan Peninsula, Mexico is almost universally accepted (Norris *et al*. 1999).

6.2   Australian backdrop

Late Cretaceous sediments are preserved in most of the continental margin basins in southern, western and northern Australia. However the palaeobotanical record in northern Australia is usually discontinuous, due to limited sampling, sediment starvation and/or poor preservation of miospores in bioclastic carbonates. Consequently much of the detailed information on flora and vegetation comes from southeastern Australia where quasi-continuous pollen and spore sequences are preserved in the Gippsland and Otway Basin (cf. Dettmann 1994, Douglas 1994).

Elsewhere, fossil evidence is preserved in thin (and fortuitously preserved) carbonaceous deposits. For example, an unusually diverse macroflora is preserved in the Cenomanian Winton Formation in the Eromanga Basin. Turonian to Maastrichtian sediments in this basin usually preserve the cuticular remains of conifers and angiosperms but as yet these have not been systematically studied. The majority of Late Cretaceous microfloras represent coastal or floodplain communities or shoreline vegetation around deep freshwater lakes at the palaeo-southern (polar) end of the Australo-Antarctic Rift System, such as in the Gippsland and Bass Basins.

6.3   Late Cretaceous floras

6.3.1   *Evolution and migration*

Late Cretaceous microfloral provinces, including those encompassing Australia and neighbouring landmasses have been reviewed by Herngreen and Chlonova (1981). Coastal areas and rift valley systems at high latitudes may have been important in the adaptive radiation of species that subsequently migrated into lower latitudes (references in Lewin 1983, Hill and Scriven 1995). Rift valleys are likely to have been pathways for the migration of taxa adapted to disturbed environments as well as forming geographic barriers between formerly widespread populations (Hill *et al.* 1999).

Most of the plant genera that evolved or migrated into the Australian region during the late Early and Late Cretaceous were angiosperms but several modern gymnosperms and ferns also appear at this time.   Examples (fossil genera in parentheses) include *Lagarostrobos* (*Phyllocladidites mawsonii*) in the Turonian, and *Dacrydium* (*Lygistepollenites florinii*) and *Nothofagus* (*Nothofagidites*) in the Campanian.   Fossil spores preserved on the South Shetland Islands confirm that the migration of ground-ferns such as *Ruffordia* (*Appendicisporites*) and *Lophosoria* (*Cyatheacidites*) from western into eastern regions of Gondwana was time-transgressive (Dettmann 1986b, Helby *et al.* 1987, Dettmann *et al.* 1992, Hathaway *et al.* 1999).

Many of the taxa which first appear on the palaeo-northern margin (North West Shelf) during the Late Cretaceous are not recorded in central or southern basins until the Late Paleocene or Early Eocene, e.g. *Anacolosa* (*Anacolosidites acutullus*). This diachronism is likely to reflect differences in vagility as well as climatic forcing. Many of the angiosperms that became extinct at the Cretaceous/Tertiary boundary are likely to have been insect-pollinated (Macphail 1994a).

6.3.2   *Plant competition*

The adaptive radiation of the angiosperms during the late Early and Late Cretaceous initiated the wholesale reorganisation of most terrestrial ecosystems. Their competitive success reflects their superior reproductive strategies relative to gymnosperms and cryptogams, irrespective of climatic or edaphic forcing (Stewart 1983, Lupia *et al.* 1999). Bawa (1995)

has highlighted the roles played by animals in pollination and seed dispersal in the diversification of the angiosperms.

6.3.3 *Climatic indicator taxa*

Many Late Cretaceous genera can be assigned to extant families and, occasionally, extant genera or species in the case of monotypic genera (Dettmann 1994, Chambers *et al.* 1998, Hill and Brodribb 1999). Examples are (NLRs in parentheses): *Phyllocladidites mawsonii* (*Lagarostrobos franklinii*) which first appears in the Turonian, *Lygistepollenites florinii* (*Dacrydium*) which first appears in the Santonian, and *Dacrycarpites australiensis* (*Dacrycarpus*) and *Nothofagidites* (ancestral *Nothofagus*) which first appear in the Campanian.

All retain a preference for cool-cold (microtherm range) and wet-very wet (perhumid) conditions (Table 6) but only in a few cases do the geological and palaeo-distribution data show that the ecology of the ancestral taxon was similar to their nearest living relatives (NLR). An example is the microfossil species *Australopollis obscurus* which almost certainly was a freshwater aquatic herb like its NLR *Callitriche* (Callitrichaceae). Ancestral *Nothofagus* spp., which almost certainly evolved under microtherm conditions, appear to have given rise to at least one subgenus (*Brassospora*) that was adapted to warmer (lower mesotherm) conditions during the Late Cretaceous or earliest Tertiary.
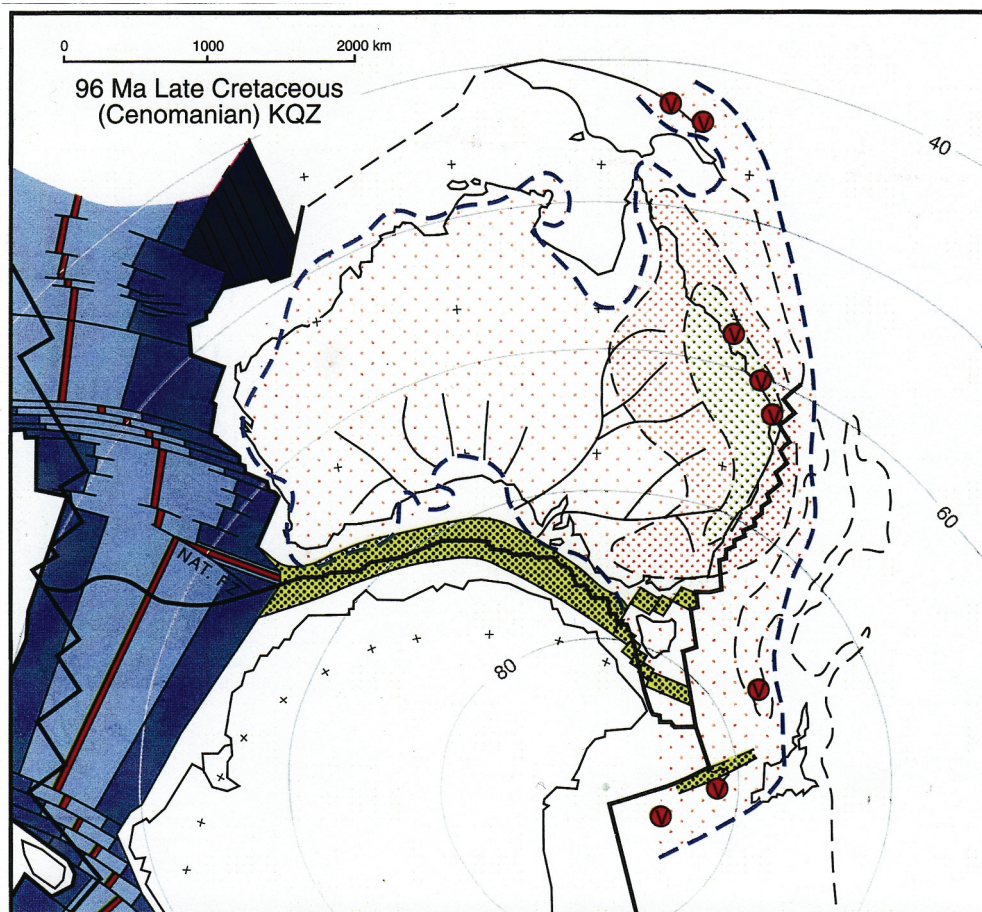
Table 6: Inferred ecological preferences

TAXON		GEOGRAPHIC BIAS			TOTAL RANGE	INFERRED CLIMATIC PREFERENCE
		Palaeolatitude		Coast		
Fossil	NLR	N	S	-		
Gymnosperms						
Araucariacites	*Araucaria*	●	●	●	pancontinental	warmer/drier
Dacrycarpites	*Dacrycarpus*		●	●	± southern	cooler/wetter
Dilwynites	*Agathis/Wollemia*		●	●	± southern	cooler/wetter
Lygistepollenites	*Dacrydium*		●	●	± southern	cooler/wetter
Podocarpidites	*Podocarpus*		●	●	pancontinental	cooler/wetter
Phyllocladidites	*Lagarostrobos*		●	●	± southern	cooler/wetter
Angiosperms						
Australopollis obscurus	Callitrichaceae		●	●	pancontinental	freshwater
Forcipites	extinct		●	●	southern	cooler/wetter
Ilexpollenites	*Ilex*	●		●	pancontinental	warmer
Longapertites	Palmae	●		●	±northern	±hot
Nothofagidites	*Nothofagus*		●	●	±southern	cooler/wetter
Proteacidites	Proteaceae	●	●	●	pancontinental	drier?
Tricolpites lilliei complex	*Neoscortechinia*?	●		●	pancontinental	warm/freshwater
Ferns and fern allies						
Camarozonosporites	Lycopodiales	●		●	pancontinental	drier?
Cicatricosisporites	Schizaeaceae	●			pancontinental	warmer/wetter
Cyatheacidites	*Lophosoria*		●		pancontinental	cooler/wetter
Cyathidites	Cyatheaceae	●	●	●	pancontinental	cooler/wetter
Gleicheniidites	Gleicheniaceae	●	●	●	pancontinental	riparian
Retitriletes	Lycopodiaceae		●	●	pancontinental	cooler/wetter
Stereisporites	*Sphagnum*		●	●	pancontinental	cooler/wetter

6.4   Time Slice K-3. Cenomanian [97.5-91 Ma]

Zones: *Appendicisporites distocarinatus* Zone
             Xenascus asperatus to *Palaeohystrichophora infusorioides* Zone

Figure 6:   **Cenomanian (96 Ma) palaeogeography (from Veevers *et al*. 1991)**

6.4.1   *Palaeogeography*

During the latest Albian [99 Ma], Chilean-type subduction of the Pacific Plate beneath East Gondwana changed to Mariana-type (sinistral oblique) subduction, due to the onset of sea-floor spreading between Australia and Antarctica, and back-arc spreading in the South-west Pacific (Veevers 1991a, 1991b, 1999). Tectono-stratigraphic changes associated with this 'swerve' led to uplift of the Eastern Highlands and forced the (asymmetric) drainage of much of the continent into what is now the Bight region (Figure 6). During the Early Cenomanian, marine regression left freshwater lakes and swamps in the Eromanga Basin although a shallow sea remained present in the Gulf of Carpentaria. Alluvial sequences accumulated in the Eromanga Basin include the Winton Formation (Dettmann *et al.* 1992). Continued subsidence along the palaeo-northwestern and western margins resulted in local marine transgression of the Carnarvon and Perth Basins. The Indian Ocean was sufficiently wide to have developed oceanic circulation, leading to carbonate deposition on the North West Shelf.

6.4.2   Palaeobotany

Cenomanian floras represent the early stages in the transition from gymnosperm- to angiosperm-dominated terrestrial ecosystems.   For example, Austral Conifer Forest communities lacked sphenopsids and some of the gingkophyte species found in the understorey of Early Cretaceous forests and woodlands.   Since most, if not all, early angiosperms were subcanopy shrubs or herbs or grew in low or open vegetation types such as heath, it is unlikely that angiosperms greatly altered the physiognomy of the forests, or indicate any fundamental shift in canopy-climate relationships. Niche disruption at ground level and altered conditions at the forest margins, however, may have enhanced rates of ecological speciation (cf. Brown 1999).

The palaeobotanical record for the Cenomanian is strongly biased towards coastal and riparian taxa whose miospores were transported by wind or water into offshore sediments. Two distinct types of vegetation are represented: (1) coastal heath communities dominated by ferns and increasing numbers of angiosperms, and (2) Austral Conifer Forest dominated by pteridosperms, araucarians and/or podocarps. The latter communities are presumed to have formed the regional/upland/hinterland vegetation.

6.4.3   *Palaeoclimates*

The composition and structure of the vegetation in palaeo-southern (Tasmania to southeastern New South Wales) and palaeo-central Australia are likely to reflect winter darkness as well as strong seasonal contrast in temperature and possibly precipitation. Low photoperiods are less likely to have influenced plant growth in palaeo-northern Australia (North West Shelf).

Palaeo-northern Australia

Norvick and Burger (1975) have proposed that climates along the palaeo-northern margin (including present-day north-west Australia) were warm and possibly dry.   The latter is inconsistent with the high diversity of cryptogams, including schizaeaceous ferns, although very warm (upper mesotherm) temperatures are supported by the microfossil data.   For example, araucarians were prominent in Austral Conifer Forest. Re-examination of Norvick and Burger's (1975) data indicates humidity was overall high (perhumid) although it is unclear whether there was a pronounced dry season. The presence of palms (and virtual absence of *Sphagnum*) hint that mean annual temperatures were in the upper mesotherm range in present-day north-west Australia.

Palaeo-central Australia

Gymnosperm and cryptogam communities occupying central areas of the Eromanga Basin appear to be floristically impoverished compared to communities in eastern areas of this basin or on the palaeo-northern margin: Austral Conifer Forest continued to dominate elevated regions in the hinterland. Conditions appear to have been humid-perhumid and cool-cold (microtherm range) and seasonal contrasts were higher than in regions closer to the coast.

Palaeo-southern Australia

In spite of the considerable difference in latitude ($\sim20^0$), plant communities on the palaeo-southwestern margin of the continent are similar to those found on the palaeo-northern margin, except that palms are not recorded. Climates appear to have been as humid but cooler (upper microtherm to possibly lower mesotherm), apart from present-day south-west Western Australia where subhumid conditions may have prevailed.

6.5 Time Slice K-4. Turonian-Santonian [91-83 Ma]

Zones: *Phyllocladidites mawsonii* to *Tricolporites apoxyexinus* Zone
Palaeohystrichophora infusorioides to lower *Nelsoniella aceras* Zone

6.5.1 *Palaeogeography*

Much of the continent remained subject to deep weathering. Australia and Antarctica were linked via Tasmania and the South Tasman Rise. In the Bass Strait region, depressions, which may represent part of a failed triple junction, became deep fresh to brackish water lakes (Marshall 1989, Baillie and Pickering 1991). Eruption of basalts in eastern Victoria and New South Wales are associated with opening of the Tasman Sea between Australia and the Lord Howe Rise-Campbell Plateau.

6.5.2 *Palaeobotany*

Almost all of the palaeobotanical evidence comes from basins on the palaeo-northern and southeastern margins. Many common microfossil species can be assigned to modern genera rather than families and taxa that had dominated the Early Cretaceous Austral Conifer Forest. For example, cheirolepidiacean conifers and brachyphyll araucarians, were mostly replaced by 'modern' gymnosperms such as *Dilwynites* (*Agathis*/*Wollemia*), *Dacrydium*, and *Lagarostrobos*. It is possible that some angiosperms were canopy trees, e.g. *Macadamia* (Proteaceae). The apparent rapidity with which the Proteaceae and other angiosperm clades continued to diversify, is consistent with high levels of tectonic disturbance within the Australo-Antarctic Rift System (Dettmann and Jarzen 1990, Dettmann *et al*. 1992). One fern (*Lophosoria*), which is first recorded on the palaeo-northern margin during the Albian appears to have migrated south onto the palaeo-southern margin during the latest Cenomanian or Early Turonian (see Figure 33 in Helby *et al*. 1987).

6.5.3 *Palaeoclimates*

Climatic gradients appear to have strengthened north to south and west to east (southern margin) on the continent. For example, angiosperms represented by unidentified tricolpate and tricolporate pollen are relatively common on the palaeo-northern margin whereas araucarians are prominent only on the palaeo-southern margin: *Lagarostrobos* swamp forests are best developed in palaeo-southeastern Australia and northern Tasmania. Austral Conifer Forest and fern heath remained the dominant vegetation types in coastal regions.

Palaeo-northern Australia

Communities included podocarp-dominated Austral Conifer Forest in the uplands and fern heath on the coast. Conditions on the coast appear to have been seasonally wet (humid-perhumid). A probable palm (*Dicolpopollis*) implies seasonally warm (upper mesotherm) temperatures in the present-day Arnhem Land.

Palaeo-central Australia

Fossil evidence is lacking but it is reasonable to presume the regional vegetation was a form of Austral Conifer Forest growing under relatively cool (possibly mesotherm range) and humid conditions.
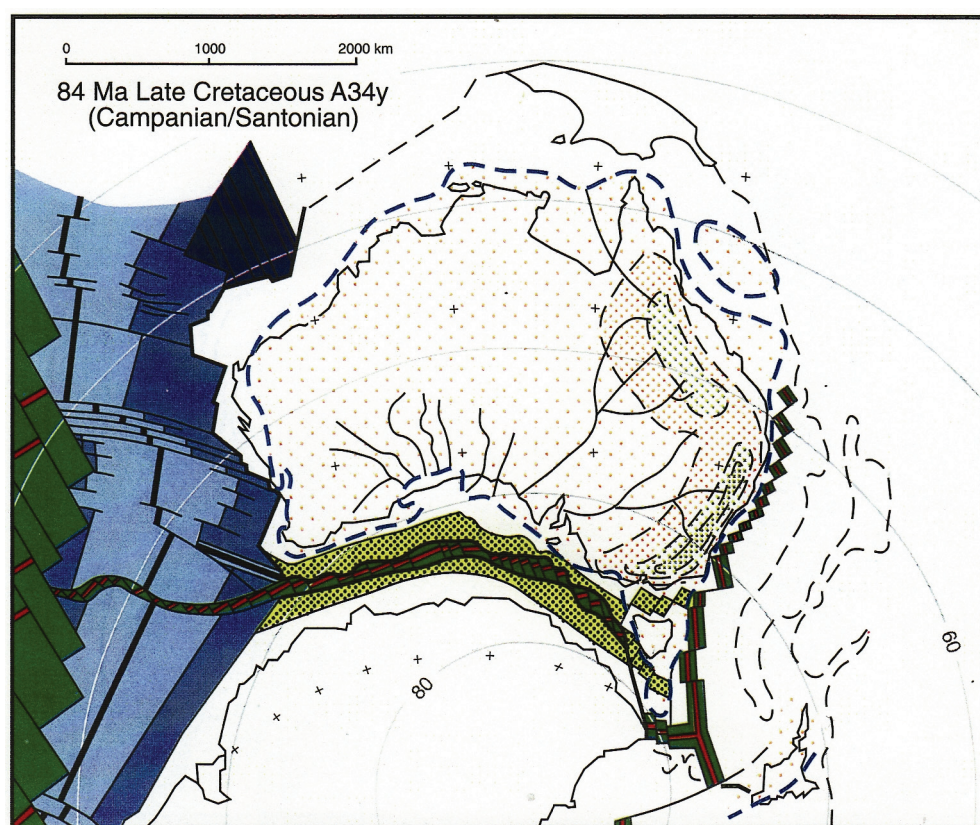
Dryland communities included Austral Conifer Forest, which was dominated by araucarians, podocarps and possibly pteridosperms. Conditions appear to have been effectively wetter (humid-perhumid) than on the palaeo-northern margin. Owing to the very high palaeolatitude (~80^0S), the extensive development of conifer swamp forests in present-day southeastern Australia and Tasmania may reflect reduced evapo-transpiration during summer rather than a higher annual rainfall. Mean annual temperatures were cool-cold (microtherm range) and almost certainly fell below freezing during the dark winters. One anomalous record in Turonian-Santonian sediments in the Torquay Sub-basin is *Spinizonocolpites*, a type that resembles pollen produced by the tropical mangrove palm *Nypa* (M.K. Macphail unpubl. data).

6.6   Time Slice K-5. Early Campanian [83- ~70 Ma]

Zones: Lower *Nothofagidites senectus* Zone
            Upper *Nelsoniella aceras* to *Xenikoon australis* Zones

Figure 7:   **Campanian (84 Ma) palaeogeography (from Veevers *et al.* 1991)**

6.6.1   *Palaeogeography*

By the Campanian (Figure 7), the orientation of the Australian continent relative to the geographic South Pole was similar to the present. The Australo-Antarctic Seaway between Antarctica and Australia was some hundreds of kilometres wide at its western end and extended eastwards along the present-day southern margin as far west as the west coast of Tasmania (Veevers *et al.* 1991, Langford *et al.* 1995). Thin Campanian sediments in the Eyre and Duntroon Basins suggest low sediment influx and/or strong marine circulation within this seaway. Fluvial and lacustrine sediments continued to accumulate within fault-bounded

troughs in the Bass and Gippsland Basins. Onset of seafloor spreading in the Tasman Sea at about 80 Ma led to the separation of New Zealand and a number of other continental fragments from the palaeo-eastern margin of Australia. Associated events included igneous activity in southeastern Queensland and eastern New South Wales. An extensive river system drained into the Indian Ocean via the Officer and Canning Basins. Elsewhere deep weathering continued over much the continent.

6.6.2   *Palaeobotany*

Forests and woodlands remained dominated by gymnosperms although the diversity and relative abundance of angiosperms continued to increase. Whether these angiosperms were shrubs or trees is uncertain. In palynostratigraphic terms, the most prominent clade to migrate into Australia at this time (at the Santonian/Campanian boundary) were ancestral species of *Nothofagus*, represented by the fossil pollen species *Nothofagidites endurus* and *N. senectus* (Dettmann *et al.* 1990). Fossil pollen representing the four extant subgenera of *Nothofagus* (Hill and Read 1991) are not recorded earlier than the Late Campanian. Other newly arrived taxa include horsetails (*Ephedra*), palms (*Longapertites*) and a fossil member of the Didymelaceae, which now is confined to angiosperm rainforest in Madagascar (*Schizocolpus marlinensis*).

6.6.3   *Palaeoclimates*

Assuming that ancestral *Nothofagus* has similar preferences to modern *Nothofagus,* differences in relative abundance of *Nothofagidites* indicates strong contrasts in rainfall and mean annual temperatures between the palaeo-northern and southern margins. The presence of palms (Palmae) is assumed to indicate very warm to hot conditions.

Palaeo-northern Australia

Podocarp-dominated Austral Conifer Forest and fern heath remained the dominant vegetation types in coastal regions throughout the Early Campanian. Conditions are likely to have been wet to very wet (humid-perhumid) and very warm (upper mesotherm) based on the presence of palms. Rare taxa in the offshore sequences include two probable temperate rainforest taxa, *Lophosoria* and *Nothofagus* (*Nothofagidites* sp. cf. *N. senectus*), which may imply conditions away from the coast were cooler with more uniform rainfall than in the Turonian-Santonian.

Palaeo-central Australia

No fossil evidence is available and it is uncertain whether temperate rainforest angiosperms such as *Nothofagus* were present in central Australia at this time.

Palaeo-southern Australia

Austral Conifer Forest and fern heath remained the dominant vegetation types in the southern margin basins although araucarians are less common than during the Turonian-Santonian, possibly because of different depositional contexts (reduced Neves Effect), and ancestral species of *Nothofagus* (*Nothofagidites endurus*, *N. senectus*) became frequent to common at many sites in the late Early Campanian. The latter is consistent with increasingly wet (perhumid) and/or more uniform conditions, although mean annual temperatures are likely to have remained within the microtherm range due to the high palaeolatitude (~70^0S).

6.7 Time Slice K-6. Late Campanian-Maastrichtian [~70-65 Ma]

Zones: *Tricolporites lilliei* to *Forcipites longus* Zones
Isabelidinium korojonense to *Manumiella druggii* Zones

6.7.1 *Palaeogeography*

By the end of the Late Cretaceous, Australia had become the 'island continent', separated from Antarctica by a shallow seaway across the South Tasman Rise, and possessing most of the major topographic features found today (Veevers *et al.* 1991, Langford *et al.* 1995). For example, fully oceanic conditions existed along the western and northwestern margins. The Eastern Highlands, which extended from Tasmania to northeastern Queensland, had been uplifted sufficiently to be a major source of sediment for the flanking basins. Fossil land surfaces preserved beneath Paleocene basalts indicate the Southeastern Highlands of New South Wales had reached an elevation of ca. 800 m during the Late Cretaceous. Precursors of the modern large inland river systems were established on both sides of the continent by the same time. Conversely, land-bridges connecting the mainland with Tasmania and New Guinea were not yet submerged and continent margin basins such as the Gippsland Basin continued to be foci for fluvio-lacustrine deposition, albeit subject to occasional marine flooding.

6.7.2 *Palaeobotany*

In contrast to the Early Campanian, many Late Campanian and Maastrichtian angiosperm pollen types are large and sometimes highly ornamented, with morphologically complex apertures. The trend is most evident in the Proteaceae but is also seen in clades producing tricolpate and tricolporate pollen. The phenomenon is presumed to represent adaptive radiation associated with tectonic or volcanic activity and, on the broader geographic scale, opening and enlargement of the southern oceans (Dettmann 1992, 1994, Wing *et al.* 1993). Relatively few of the types first appearing during the Late Cenomanian and Maastrichtian have been formally defined as fossil species; fewer still can be linked to extant plants in any ecologically meaningful way since most became extinct at the end of the Maastrichtian. One possible exception is *Tricolporites lilliei*, which may related to the tropical freshwater swamp genus *Neoscortechinia* (Euphorbiaceae).

A number of immigrant taxa appear to have reached Australia by long distance dispersal from landmasses to the north-west. The clearest example is the Lactoridaceae (*Lactoripollis*), which is recorded in South-west Africa during the Turonian and in northern Australia (and India) during the Campanian (Macphail *et al.* 1999, A.D. Partridge pers. comm.). Other examples are possible members of the important Northern Hemisphere Normapolles (*Myrtaceoipollenites*) and Triprojectites (*Integricorpus*) clades, which may have reached northern Australia as early as the Late Campanian (cf. Jarzen & Dettmann 1992, A.D. Partridge and M.K. Macphail, unpubl. results). More generally, the floras show strong provincialism along north to south and east to west gradients. For example, *Gambierina* spp., which are common to abundant in Late Maastrichtian microfloras in the south-east, are rare to absent in central and northern Australia. The same is true for *Dacrycarpus* and *Dacrydium* (including the extinct *Lygistepollenites balmei* clade). Small (mostly undescribed) tricolpate and tricolporate grains are more common in sites on the northern margin and these microfloras also include taxa that are not recorded in southeastern Australia until the Palaeogene, such as palms and *Anacolosa*.

6.7.3 *Palaeoclimates*

In global terms, the Late Campanian-Maastrichtian, like the Early Albian, is viewed as a relatively cool stage within the Cretaceous (Jenkyns and Wilson 1999). Cooling may have

had little impact in palaeo-southern and central Australia since the floras were already adapted to seasonally cool-cold temperatures and low light intensities.

Palaeo-northern Australia

Late Cenomanian and Maastrichtian microfloras appear to represent two distinct vegetation types, which are presumed to have occupied different niches. These are complex communities of ferns and angiosperms occupying the coastal plain, and araucarian-dominated Austral Conifer Forest. The latter is presumed to have occupied drier, upland sites since Araucariaceae pollen are most abundant in sites away from the coast. Conversely, some of the fossil species growing along the coast have NLRs that are now confined to low latitude wet forest types and, by the upper Maastrichtian, the flora is reminiscent of modern tropical palm forests. Conditions are likely to have been seasonally humid to perhumid (possibly monsoonal) and very warm (upper mesotherm) on the coast. The absence of palms in the Kimberley region and a minor increase in the relative abundance of *Dacrydium* in the Bonaparte Basin is weak evidence for cooler/more uniformly wet climates in the hinterland. The data are inadequate to show whether the presence of palms and other thermophilous rainforest taxa is due to local factors, such as warm water currents flowing along the northern coast, or whether the impact of global cooling during the Maastrichtian was reduced in the palaeo-middle latitudes.

Palaeo-central Australia

The presence of podocarp-dominated Austral Conifer Forest is evidence for seasonally wet (humid-perhumid) conditions. Palaeotemperatures are more difficult to reconstruct since palms (implying mesotherm temperatures) were growing in the Ayers Rock Basin at broadly the same time as *Sphagnum* bogs (implying microtherm temperatures) were widespread in the nearby Huckitta Basin (Macphail 1997a). The Ayers Rock microflora includes a halophytic dinoflagellate. One explanation for the presence of thermophilous taxa is that possibly warm, saline groundwater was being discharged into some basins.

Palaeo-southern Australia

Plant communities growing in present-day south-west Western Australia are floristically impoverished versions of communities found on the palaeo-northwestern margin. The absence of palms and the good development of *Sphagnum* bog imply climates in the Pilbara region were cool (upper microtherm) and wet (humid) but drought-prone, assuming groundwater discharge was not involved. The reconstruction of climates in central southern and southeastern Australia is complicated by the uncertain nature of environmental factors leading to the widespread replacement of *Nothofagus* communities by floristically complex associations of *Forcipites*, *Gambierina* and Proteaceae during the Maastrichtian. Given the high palaeolatitude of southeastern Australia, the preferred explanation is that conditions remained seasonally cool-cold (upper microtherm) but had become seasonally drier or more drought-prone relative to the Early Campanian. Cooling of ocean currents flowing along the southern and eastern margins provides a possible link between the regional demise of *Nothofagus* and global cooling.

SECTION 7 (TERTIARY CLIMATES)

7.1.   Global backdrop

During the Tertiary, the earth as a whole underwent progressive warming, then cooling/drying episodes (Frakes 1999). Although no single factor is likely to be paramount in any region, patterns of Tertiary climatic change are increasingly being linked to changes in deep ocean circulation associated with continental drift (Zachos *et al*. 1994).

As in the Cretaceous, global trends were interrupted or sharpened by a number of short-term climatic excursions whose impact was variable. For example, there is increasing evidence that the earth suffered a number of major impacts from extraterrestrial bolides during the Tertiary although the climatic consequences continue to be debated. Farley *et al*. (1998) cite geochemical evidence for a comet shower extending over a 2.5 million year period in the Late Eocene. Two impacts produced major craters – off the East Coast of America (Chesapeake Bay Crater) and in Siberia (Popigai Crater). The more important of these geologically short-term climatic excursions are: the Cretaceous-Tertiary boundary event at about 65 Ma; the Paleocene-Eocene Thermal Maximum at about 55 Ma; and four events linked to changes in ocean circulation, being the Eocene-Oligocene transition linked to the opening of the Tasmanian Gateway between Australia and Antarctica at about 33 Ma, the mid Miocene climatic transition between 21-27 Ma, mid Pliocene warming at about 3 Ma and Plio-Pleistocene bipolar glaciation after 2.5 Ma.

7.1.1   *Cretaceous-Tertiary boundary* (K/T) event [~65 Ma]

A number of events, which began during the late Late Cretaceous, culminated near to, but before, the Cretaceous-Tertiary (K/T) boundary. These range from abnormally high levels of volcanism (Sutherland 1994) and increased terrestrial erosion (Robert and Chamley 1990) to a decline in dinosaur diversity (Sereno 1999) and major changes in climate and ocean chemistry (Barrera 1994).

A common explanation is marine regression during the latest Maastrichtian, e.g. Barrera *et al*. (1997) and Eaton *et al*. (1997). Nevertheless, unlike earlier geological boundaries, the evidence is compelling that the Cenozoic era was initiated by the impact of a ~10 km diameter bolide moving at ~20 km sec^{-1} at Chicxulub in the Gulf of Mexico (Hildebrand *et al*. 1995, Melosh 1995, Kerr 1997, Kroon *et al*. 1998). Shocked quartz has been recorded as far north as the Gosau Basin in Austria (Preisinger *et al*. 1986). More immediate effects include the deposition of impact breccias up to 900 m thick at a distance of 100 km from the crater, the collapse of the shelf margin and emplacement of tsunami (megawave) deposits on the continental shelves in Texas and northern Mexico (references in Keller *et al*. 1997, Bralower *et al*. 1998).

Observed or predicted global-scale phenomena include abrupt mortality in pelagic organisms (Paul and Mitchell 1994, Kaiho *et al*. 1999), collapse of deepwater benthic foraminiferal communities (Coccioni and Galeotti 1994), massive reduction in marine productivity (Barrera and Keller 1994), a world-encompassing dust cloud (Covey *et al*. 1994), cooling due to sulphur released into the atmosphere (Ward 1995), acid-rain (D'Hondt *et al*. 1994), the possible collapse of the hydrological cycle (cf. Covey *et al*. 1994, Vonhof and Smit 1997), the geologically instantaneous combustion of ~18-24% of the terrestrial above-ground biomass (Ivany and Salawitch 1993, Arinobu *et al*. 1999), lava outpouring in India (*Geotimes* 1995), and the release and ignition of huge amounts of methane trapped in seafloor sediments (Day 1999).

In the Northern Hemisphere, the K/T event has been linked to the natural selection and diversification of deciduous plants (Wolfe 1987). An estimated 88% of land-dwelling vertebrates became extinct in eastern Montana (Sheenan and Fastovsky 1992) even though molecular evidence suggests at least 100 terrestrial vertebrate clades, including birds and mammals, survived the culling (Gibbons 1997). In the Southern Hemisphere, probable fragments of the K/T bolide have been recovered from abyssal sediments in the Pacific Ocean (Hecht 1996, Kyte 1998), and the K/T boundary is clearly defined in ODP Leg 189 cores drilled on the East Tasman Plateau east of Tasmania (ODP Leg 198 Initial Reports May, 2000): A single iridium anomaly correlated with the K/T boundary has been recorded on Seymour Island, Antarctica Peninsula (Elliot et al. 1994).

Although clastic deposition appears to have been continuous across the K/T boundary on Seymour Island, there is no evidence of any mass extinction event in the macrofossil record. The same is true in Australia where evidence from the Gippsland Basin indicates plant extinctions were largely confined to taxa producing highly ornamented pollen, e.g. Proteaceae (Macphail 1994a). Similar changes are recorded in New Zealand (Raine 1994). In both instances, the preferred explanation is that the microfloral changes were forced by the extinction or reduction in faunal pollinators, in particular insects. Because the flora was adapted to prolonged winter darkness, generalist angiosperm clades, and wind-pollinated gymnosperms were relatively unaffected. Nevertheless, the point remains that, in palynological terms at least, conifer-dominated plant communities in southeastern Australia during the Early Danian were distinctly impoverished relative to their Late Cretaceous predecessors.

7.1.2 *Paleocene-Eocene Thermal Maximum* [~55 Ma]

The Paleocene is considered to be a period of overall global warming, although drop stones found in the mid Paleocene Whangai Formation, North Island of New Zealand may indicate one or more cooling events if the source is confirmed to be glaciers in Antarctica (Leckie et al. 1995). The more commonly accepted date for glaciers reaching sea level in Antarctica is the Middle-Late Eocene (Mackensen and Ehrmann 1992). Conversely, the Paleocene-Eocene transition was marked by a major reorganisation of terrestrial and oceanic ecosystems, linked to a short-lived pulse of global warming – the Paleocene-Eocene Thermal Maximum event (PETM).

This major temperature excursion (see Figure A in Preamble) is arguably one of the most abrupt (~20 ka) warming events in recent geological time (Zachos et al. 1993, Corfield 1994, Steineck and Thomas 1996, Kroon et al. 1998). Effects included a dramatic turnover in mid bathyal ostracodes and planktonic and deep-sea benthic foraminifera in the Southern Ocean (Lu and Keller 1993, Steinbeck and Thomas 1996), the rapid diversification of planktonic foraminifera in the tropical Pacific (Kelly et al. 1996), a globally synchronous expansion of the dinoflagellate genus *Apectodinium* (H. Brinkhuis pers. comm.) and an equally dramatic increase in the diversity of mammalian fauna in the holoartic region (Clyde and Gingerich 1998). Peterson (1998) estimates that SSTs at high latitudes and temperatures in the deep ocean increased by 6-8^{0}C for a period of 10^5 years at about 55 Ma. Hallam and Wignall (1999) have concluded that the benthic extinction event is linked to deep-water oxygen deficiency via the dramatic switch in the source area for deep water, from high southern latitudes to subtropical Tethyan waters. Aeolian-transported particles in deep-sea sediments accumulating at palaeolatitude ~48^{0}S show a marked reduction in size for about 0.45 Ma across the Paleocene/Eocene boundary (Hovan and Rea 1992). In this instance, the phenomenon is explained in terms of a significant reduction of the strength of zonal winds in the Southern Hemisphere, which in turn reflect decreased latitudinal thermal gradients resulting from more effective poleward heat transport.

Explanations for the PETM are centred upon a transient increase in greenhouse gases in the atmosphere (Barron 1985, Rhea *et al.* 1990) although suggestions as to the trigger vary. Recent proposals include (1) the exhumation and oxidation of organic carbon during the collision of India and Asia (Beck *et al.* 1995) and (2) catastrophic dissociation of gas (methane) hydrates in the deep ocean (Sloan *et al.* 1992, Dickens *et al.* 1995, Bralower *et al.* 1997, Kerr 1997, Kroon *et al.* 1998, Yulsman 1999a, 1999b, Blunier 2000). An analogous but earlier (Early Cretaceous) 'methane hydrate' event is suggested to reflect oceanic turnover arising from major Caribbean volcanism and opening of the North-East Atlantic (Norris and Rohl 1999).

Whilst the marine signatures of the PETM coincide with the Paleocene-Eocene boundary, warmer temperatures continue to be recorded for the next 7 Ma. Globally averaged temperatures are estimated to have been 2-4^{0}C higher than at present throughout the Early Eocene. As the warmest interval of the Cenozoic, the climate system of the Early Eocene continues to be studied intensively, including by modelling experiments (Sloan 1994, Sloan and Merrill 1998). These experiments predict that the warming of very large lakes had a significant effect on Early Eocene climates in the continental interior of North America (Sloan 1994) and the same may be true of the larger lake basins in central Australia. Biological responses to Early Eocene warmth include the migration of the tropical mangrove palm *Nypa* southwards to a palaeolatitude of ~66^{0}S on the West Coast of Tasmania (Pole and Macphail 1996) and increased levels of insect damage on fossil leaves preserved in Wyoming (Wilf and Labandiera 1999). Whether rainfall became more or less seasonal is unclear. For example, Robert and Chamley (1990) propose that variation in clay mineral associations in oceanic sediments imply global warmth was associated with alternating wet and dry seasons in continents bordering the palaeo-Atlantic Ocean, and the same may be true for central Australia.

7.1.3   *Mid Eocene climatic transition* [~48 Ma]

The Middle-Late Eocene boundary marks the latest transition between the two opposing climatic modes experienced by the Earth during Phanerozoic time – the greenhouse (largely non-glacial) and icehouse (largely glacial) states. For example, high latitude climates remained warm and equable relative to the present (cf. Greenwood and Wing 1995, Jordan 1996, Wing and Greenwood 1996) and the fossil remains of a basking shark, now unknown in Subantarctic or Antarctic waters, occurs in Middle Eocene sediments on Seymour Island on the Antarctic Peninsula (Cione and Reguero 1998). Summer SSTs during the early Middle Eocene were similar to the present-day United States Gulf Coast whilst winters were 7-8^{0}C warmer due to strong oceanic heat transport (Andreasson and Schmitz 2000). Nevertheless, for the first time since the Palaeozoic, changes in global ice-volume provide a convincing explanation for rapid eustatic events (Browning *et al.* 1996).

Oxygen isotope data show that during the Middle to Late Eocene, global climate cooled in at least two stages, which were separated by significant warming (Frederiksen 1991, Mackensen and Ehrmann 1992, Graham 1994). This long-term cooling trend is recorded by climatic proxies as diverse as clay mineral associations in the Southern Ocean (Robert and Chamley 1990) and megafloral associations in southern California and the Yukon (Frederiksen 1991, Ridgway *et al.* 1995). Current explanations invoke plate tectonic movements (with a subsequent reorganisation of ocean currents) and decreasing concentrations of greenhouse gases, especially carbon dioxide, due to diminished hydrothermal, tectonic and volcanic activity. On present indications, atmospheric concentrations of carbon dioxide (ρCO_2) were similar to, or only slightly higher than, present values, based on a pH profile of the Middle Eocene tropical Pacific Ocean (Pearson and Palmer 1999).

7.1.4 *Eocene-Oligocene climatic transition* [~33 Ma]

The Eocene-Oligocene transition has emerged as one of the more critical intervals in recent geological history. Reasons include major changes in world ocean circulation, e.g. the development of the Circumantarctic Current, continental-scale glaciation of Antarctica and increased volcanism in the South Pacific. Opening of the second gateway allowing deep water circulation around Antarctica – the Drake Passage Gateway between western Antarctica and South America – is insecurely dated but circulation of surface and intermediate water was occurring in the Late Eocene (Diester-Haass and Zahn 1996). Co-eval events include the re-organisation of the Indo-Australian and Pacific Plate boundaries, significant stepwise floral and faunal turnover in both marine and terrestrial realms spanning >10 Ma of the Eocene (Zachos *et al.* 1993, Ridgway *et al.* 1995), and several closely spaced bolide impacts in the Northern Hemisphere (Kennett 1977, Kennett *et al.* 1985, Stoffler and Claeys 1997, Vonhof *et al.* 2000). Radiometric ages imply that two of the large impacts were contemporaneous (35.7 ± 0.2 Ma) in central Siberia and off the East Coast of North America (Poag *et al.* 1992, Clymer *et al.* 1996, Bottomley *et al.* 1997). Interestingly, this date coincides with the Eocene-Oligocene boundary as defined by Harland *et al.* (1990) but is ~2 million years older than the currently adopted date of 33.7 Ma in Australia (Young and Laurie 1996). Vonhof *et al.* (2000) propose that these impacts accelerated global cooling during the Late Eocene whilst Ivany *et al.* (2000) see cooler winters (cause unspecified) as a possible explanation for observed mass extinctions at the Eocene-Oligocene boundary.

Recent δ^{18}O and magnesium/calcium ratio data indicate that the first major accumulation of ice on East Antarctica occurred very rapidly during the earliest Oligocene (cf. Zachos *et al.* 1992, Lear *et al.* 2000). Associated events include diminished equatorial circulation (Kennett 1977, Barron and Peterson 1991), an abrupt drop of >3^{0}C in SSTs in the Southern Ocean (Wei 1991) and the earliest known Tertiary glacial event on any landmass outside of Antarctica – the transient development of a valley glacier in northwestern Tasmania (Macphail *et al.* 1993, Macphail and Hill 1994).

Abrupt cooling at about the Eocene-Oligocene boundary was temporarily reversed during the Early Oligocene, and warming SSTs recorded in the Great Australian Bight (Kamp *et al.* 1990) and around Antarctica (Mackensen and Ehrmann 1992) during the Early Oligocene match global trends elsewhere (Feary *et al.* 1991). Nevertheless, Shackleton (1986) has inferred that intense glacial events occurred in East Antarctica at about 31 Mar (Event E) and 24 Mar (Event F). Event E precedes a dramatic (>140 m) lowering of global sea level during the Early-mid Oligocene (cf. Haq *et al.* 1987, Pekar and Millar 1996), and cooling in the equatorial Pacific (Keigwin and Keller 1984). Event F coincides with the first and largest (Mi-1 Event of Zachos *et al.* 1997) of several brief glacial episodes marking the Oligocene-Miocene transition (23.8 Ma).

Brief cooling episodes at high latitudes, which are linked to longer term (100 ka, 400 ka) Milankovitch cycles, are recorded between ~27-21 Ma (Zachos *et al.* 1997). Otherwise the Late Oligocene-Early Miocene is usually considered to have been a time of relative global warmth in the sense that ocean temperatures were slowly increasing and continental ice volumes were decreasing from mid-Late Oligocene levels (cf. Miller *et al.* 1991).

7.1.5 *Middle Miocene climatic transition* [~13-16 Ma]

On current indications, Oligo-Miocene warming climaxed in the late Early Miocene [~16 Ma] and was followed by sustained global cooling. Flower and Kennett (1994) propose that the early [~16-15 Ma] stage of this transition was marked by major short-term instability in climate and relative sea-level, linked to changes in deep-sea circulation and the volume of ice making up the East Antarctica Ice Sheet. The late [~15-13 Ma] stage was marked by large fluctuations in relative sea level followed by a global sea level fall, major ice sheet growth in

East Antarctica and strengthening of the meridional surface temperature gradients. This 'strengthening' almost certainly was a major factor behind aridification of mid-latitude regions in Africa, Australia, and North and South America during the Middle-Late Miocene. Again, a primary driver is likely to be changes in deep-ocean circulation. For example, polar cooling during the early Middle Miocene is seen to have been curtailed by the production of warm, saline deep water in the eastern Paratethys/northern Indian Ocean and accelerated cooling in the Antarctic region is linked to a reduction in the flow of deep water to the Southern Ocean at about 14.8 Ma.

The roles of marine regression and orogeny in reinforcing global cooling and drying during the Middle-Late Miocene are more equivocal (Molnar and England 1990). For example, GCM modelling (Ramstein *et al.* 1997) links increasingly continental climates in central Asia and increasingly monsoonal climates across India and Indo-China to the retreat of the (epicontinental) Paratethys Sea during the Late Oligocene and Miocene; Burbank *et al.* (1993) and Filippelli (1997) propose that uplift of the Tibetan Plateau had intensified the Asian monsoon by about the same time (7-8 Ma). The consequences of renewed cooling and drying during the Late Miocene include a world-wide increase in the biomass of plants such as grasses that utilise C_4 photosynthesis. This in turn is linked to major faunal changes (Cerling *et al.* 1997, Cerling and Harris 1998). Modelling by Dutton and Barron (1997) predicts that this trend, to shrub- and herb-dominated vegetation types, is likely to have aggravated the cooling trend in the Northern Hemisphere. Dickens and Owen (1999) report that primary productivity increased simultaneously at upwelling zones in the Indian and Pacific Oceans during the latest Miocene and Early Pliocene. Whilst the consequences (if any) to terrestrial ecosystems remains elusive, the data are evidence for an important change in the global nutrient cycle (an increase in supply of organic carbon) during the Late Miocene.

Hodell and Kennett (1986) conclude that the latest Miocene (6.5-5 Ma) was characterised by pulses of ice sheet expansion and contraction, with the most intense events occurring during the latest Miocene at 5.5-5.1 Ma. The effects of mid and high-latitude cooling included an increase in the volume of ice forming the East Antarctic Ice Sheet, the formation of ice shelves in the Ross and Wedell Seas, the deposition of ice-rafted debris on the Falkland Plateau in the subantarctic Atlantic Ocean, and repeated extension of glaciers beyond the mountain-front in southern South America (Clapperton 1979, 1986, Hodell and Kennett 1986). The combined glacial events are estimated to have lowered global sea levels by 30-60 m, contributing to the isolation (and subsequent desiccation) of the Mediterranean Sea from the Atlantic Ocean between 6-5 Ma (Aharon *et al.* 1993). The magnitude of this event (Messinian salinity crisis) can be judged from the estimate that ~6% of the global oceanic salt budget was deposited as evaporites in the Mediterranean Basin (McKenzie 1999). The catastrophic reconnection of the basin to the world ocean at about 5 Ma defines the Miocene-Pliocene boundary.

7.1.6 *'Mid' Pliocene warming* [~3 Ma]

Consensus exists that the Early Pliocene [~5-3 Ma] was the most recent interval of sustained global warmth (King 1996, Billups *et al.* 1998, Kohler *et al.* 1998). For example, Raymo *et al.* (1996) conclude that the global mean temperatures at ~3 Ma may have been as much as $3.5^{\circ}C$ warmer than at present. High-resolution biostratigraphies from the Southern Ocean point to peak warming occurring at ~4.3 Ma, with other brief warming events recorded at ~4.5 Ma, ~4.2 Ma and ~3.6 Ma (Bohaty and Harwood 1998). SSTs at high latitudes in the North and South Atlantic are estimated to have been up to $8^{\circ}C$ and $2\text{-}3^{\circ}C$ respectively higher than today although little or no warming is recorded in the tropics (Dowsett *et al.* 1996). However, there is no agreement whether high latitude warming led to partial decay or growth of the Antarctic ice sheet (cf. Hodell and Warnke 1991, Wilson 1995, Burkle *et al.* 1996, Harwood *et al.* 2000). Significant cooling episodes are recorded at 4.5 Ma and between ~3.5-3.2 Ma (Hodell and Warnke 1991, Burkle *et al.* 1996).

Other events occurring during the Early Pliocene are the closure of the Isthmus of Panama between 4.4-3.2 Ma (Coates *et al*. 1992), constriction of the Indonesian Seaway to warm water transport between the Pacific and Indian Oceans (Srinivasan and Sinha 1998), sea levels up to 25-35 m above present (Cronin and Dowsett 1993), and growth of forest species at 82^0N in Greenland, some 2500 km north of the modern Arctic treeline (Funder *et al*. 1985). Diatom evidence indicates that between 3.1-2.9 Ma, the Antarctic Polar Front lay some 6^0S south of its present position – implying SSTs between 55-60^{0}S were up to 3-4^{0}C warmer than at present (Barron 1996). These events almost certainly were linked, directly or indirectly. For example, mechanisms proposed to account for the poleward transport of heat (and enhanced moisture supply) needed to allow forest species to grow at 82^0N include intensification of the Gulf Stream following closure of the Isthmus of Panama (Willard *et al*. 1993), and altered intermediate and deep water circulation (Kwiek and Ravelo 1999): Raymo *et al*. (1996) and Billups *et al*. (1998) suggest a combination of increased atmospheric CO_2 and enhanced thermohaline circulation. As yet, the relative contribution of these and tectonic and palaeogeographic factors is unclear (Crowley 1996).

7.1.7 *Plio-Pleistocene bipolar glaciation* [<2.5 Ma]

Global cooling, which began in the Middle Eocene, culminated in the continental scale glaciation of Eurasia, Greenland and North America during the Late Pliocene, some 31 million years after the earliest indications of ice sheet development in Antarctica. Key evidence includes δ^{18}O enrichment in benthic foraminifera between 3.1-2.5 Ma and the widespread appearance of ice-rafted debris in northern high-latitude oceans after ~2.7 Ma (references in Macphail 1997b). Large ice sheets first developed in the Northern Hemisphere at about 2.54 Ma during the Late Pliocene (Driscoll and Haug 1998) and have remained a global feature for approximately 90% of Quaternary time. The build up of ice was cyclical and apparently paced by orbitally driven oscillations in incoming solar radiation (Milankovitch cycles) although changes in terrestrial vegetation during the Late Pliocene also display periodicity on a longer (124 ka) time scale, e.g. Willis *et al*. (1999).

Driscoll and Haig (1998) have proposed that closure of the Isthmus of Panama enhanced not only the poleward transport of heat but also the delivery of freshwater from Siberian rivers, thus facilitating the formation of sea ice across the North Pole. If correct, intensification of glaciation in the Northern Hemisphere is due to 'short-circuiting' of thermohaline circulation. Augmenting factors include a progressive increase in the orbital factor (obliquity) that control the seasonal distribution of insolation at high latitudes at 3.1 to 2.25 Ma and, more speculatively, the impact of a 1-4 km diameter asteroid in the Southern Ocean at ~2.15 Ma. The latter precedes a period of intensified global cooling (Gersonde *et al.*, 1997) and a corollary is that ejecta landing on the Transantarctic Mountains may have been a source of the marine diatoms used to 'date' the contested partial deglaciation of Antarctica during the mid Pliocene warm period (cf. Francis and Hill 1996, Harwood *et al*., 2000).

The discrepancy in the scale of ice sheet development around the two poles during the Plio-Pleistocene can be explained by the absence of land across the geographic North Pole but a number of fundamental questions remain unanswered (Driscoll and Haug 1998). Examples are: Why did global climate systems fail to generate and maintain major ice sheets in the Northern Hemisphere until Late Pliocene time despite evidence of minor ice-rafting in the Arctic and North Atlantic since ~11 Ma? What are the mechanisms which nearly synchronise Plio-Pleistocene climates of the Northern and Southern Hemispheres at orbital (10^4-10^5 years) time scales despite asynchronous insolation forcing (Clark *et al*. 1999)? Why did variation in global ice volumes change from dominant 41 ka insolation cycles to dominant 100 ka cycles during the Middle Pleistocene (Clark *et al*. 1999)? What is certain is that once in place, the continental ice sheets actively interacted with the rest of the ocean-climate system by

amplifying, pacing and potentially driving global climatic change over orbital time scales throughout the Quaternary (Broecker and Denton 1989, Clark *et al.* 1999).

7.2   Australian backdrop

Tertiary climates in Australia reflect global and regional tectonic and eustatic events, which were superimposed on strengthening equator-to-pole temperature gradients and decreasing atmospheric carbon dioxide concentrations. Of particular significance has been the continents rapid drift into middle-low latitudes. This provided background warming when the earth as a whole underwent progressive cooling and drying during the Late Palaeogene and Neogene (Frakes 1999). Although no single factor is likely to be paramount in a given region within Australia, patterns of Tertiary climatic change are increasingly being linked to changes in deep-ocean circulation. Long-term warming and cooling trends have been interrupted or sharpened by a number of short-term excursions in global climate, whose impacts will have varied across the larger basins and in mountainous terrain.

7.3   Palaeobotanical database

As for the Cretaceous, the bulk of the palaeobotanical evidence for Tertiary climatic change is palynostratigraphic, and comes from exploration wells and boreholes drilled in southern and central Australia. The key basins are the Gippsland, Bass, Otway and Murray Basins where relatively continuous deposition has preserved macro and microfossil records of the Paleocene-Eocene and/or Oligocene-Middle Miocene vegetation. The coverage, however, is highly variable, ranging from over 700 wells in eastern Bass Strait, to less than 17 wells in the Great Australian Bight.

Other regions, which preserve discontinuous Tertiary sequences are offshore basins along the northwestern margin (Bonaparte and Carnarvon Basins) the southwestern margin (Eucla and Duntroon Basins), northwestern Tasmania (Sorell Basin), central Australia (Lake Eyre Basin and small basins near Alice Springs) and northeastern margin (e.g. Yaamba Basin). Apart from central Australia and the Eastern Highlands and Tasmania (where basalt flows have buried fluvio-lacustrine deposits) the microfloras mostly represent coastal plain communities. The richest and most informative macrofossil assemblages are those recovered from thick brown coal measures in Victoria and South Australia, and analogous but much thinner lignites in Tasmania.

Palynosequences in the offshore Gippsland, Otway and North West Shelf can be tied to the International Time Scale using marine microfossils, in particular dinoflagellates, e.g. Partridge (1976, 1999) and Harris (1985). The *Esso-BHP* zonation developed for the Gippsland Basin by A.D. Partridge and *Esso/Exxon* colleagues is widely used to date and correlate Tertiary and Late Cretaceous sediments elsewhere in Australia. Potassium-argon dating of basalts has confirmed that the age ranges assigned to Gippsland zones are applicable to Tasmania (Macphail *et al.* 1994).

Numerous unpublished reports that include information on Tertiary microfloras are on open-file in the Geological Surveys of New South Wales, South Australia, Tasmania and Western Australia, and Geoscience Australia (formerly Bureau of Mineral Resources and the Australian Geological Survey Organisation). Studies of Tertiary macrofloras have tended to focus on specific taxa but the evolutionary histories of the Araucariaceae, Cupressaceae, Podocarpaceae, Proteaceae and *Nothofagus* are sufficiently well known to use morphological trends as evidence of climatic change, e.g. Hill (1983a, 1992a, 1994a, 1995), Hill and Jordan (1993), Carpenter (1994), Scriven and Hill (1996), Hill and Brodribb (1999). Recent overviews of Palaeogene flora and vegetation have been published by Truswell (1993), Macphail *et al.* (1994), Martin (1994) and Hill *et al.* (1999). 'Structural' limitations that

constrain the use of palaeobotanical data as evidence for climate or climatic change in the Tertiary have been reviewed by Hill (1994a), Macphail *et al.* (1994) and Jordan (1997b).

7.3.1 *Constraints*

Many of the larger, morphologically distinctive and/or short-ranging taxa have been formally described over the past fifty years, e.g. by Cookson and colleagues (references in Harris 1965a, 1972, Stover and Partridge 1973, 1982). In contrast, morphologically simple tricolpate and tricolporate angiosperm fossil pollen types usually have been ignored, even though some of these morphotypes dominate particular assemblages. Similarly, industry techniques designed to 'concentrate' rare but biostratigraphically useful taxa has meant that the majority of small (<10-20 μm) fossil pollen are often eliminated from the acid-insoluble extracts during processing (Macphail 1991). Taxa in the lost category include Burseraceae, Cunoniaceae, Elaeocarpaceae, Eucryphiaceae and smaller Myrtaceae. Much of the pre 1990s industry data consists of species lists with a subjective estimate of relative abundance: in other instances, the relative abundance data are based on statistically unreliable (<100) counts. More recent analyses usually include statistically reliable (>250) estimates of relative abundance.

7.3.2 *Life forms*

Most biostratigraphically useful (and therefore systematically recorded) Tertiary species represent woody taxa, which in turn could represent either tree-sized, canopy-forming species or understorey shrubs. Examples (NLRs in parentheses) are *Myrtaceidites* (Myrtaceae), *Nothofagidites* (*Nothofagus*), *Proteacidites* (Proteaceae), many gymnosperms including *Araucariacites* (*Araucaria*) and *Podocarpidites* (*Podocarpus-Prumnopitys*) and tree-ferns, e.g. *Cyathidites* (Cyatheaceae) and *Ischyosporites* (Dicksoniaceae). Aquatic and semi-aquatic herbs such as *Australopollis obscurus* (Callitrichaceae), *Milfordia* (Restionaceae) and *Sparganiaceaepollenites* (Sparganiaceae) are locally common in northwestern and central Australia during the Paleocene-Early Eocene but other wetland (and most dryland) herbs are rarely recorded before the Late Eocene-Oligocene in the southeastern basins.

7.3.3 *Evolution and migration*

Macrofossil assemblages unusually comprise taxa that are unique to one or a small number of sites. The observation demonstrates that ecological speciation has been an ongoing process throughout the Tertiary. Conversely, the majority of Tertiary microfloras are dominated by the same small group of well-represented/long-ranging taxa and differences between regions are mostly due to the presence and/or absence of rare taxa whose NLRs may not be identified.

Because access to palaeobotanical data from South-East Asia is difficult (Morley, 1998), it is unclear whether many taxa that first appear in Australia during the Palaeogene evolved locally or have migrated onto the continent from neighbouring landmasses to the north. Geological evidence indicates that continental fragments in the South-west Pacific and islands on the South Tasman Rise and East Tasman Plateau, between Tasmania and East Antarctica, could have provided stepping stones for migration of plants with low vagility. Nonetheless other palynostratigraphic evidence, e.g. from Ninetyeast Ridge, the Kergulen Plateau and New Zealand, demonstrate most gymnosperms and many angiosperms were able to disperse across wide ocean gaps in the Indian and Pacific Oceans (references in Macphail *et al*. 1994, Macphail 1997c), although the role played by transportation mechanisms such as wind, birds, and volcanic ash- and peat-rafts remain unclear.

A comparison of microfloras from the Bonaparte, Carnarvon, Murray and Gippsland Basins confirms that times of first appearance and extinction may be time-transgressive north-west to south-east across the continent. In most instances, the shared species appear later in

southeastern Australia than elsewhere in Australia (M.K. Macphail and A.D. Partridge unpubl. data). Exceptions are mainly taxa whose NLRs are confined to cool temperate rainforest, e.g. *Dacrydium* and *Nothofagus*, and one now widespread family of herbs (Stylidiaceae), which first occurs in Tasmania during the Eocene-Oligocene transition (Macphail and Hill 1994). Whether the north-west bias implies that northern Australia was a main point of entry, or the region was a centre of speciation during the Late Cretaceous and Tertiary is uncertain. More generally, times of first occurrence are likely to reflect the vagility of the parent plants as well as climatic forcing.

7.3.4 *Plant competition and climatic change*

Factors contributing to the competitive success of the major plant taxa inhabiting the continent included climatic change, the impact of deep leaching on soil fertility, disturbance due to tectonism and volcanism, and (Late Tertiary) herbivory. Because of northward drift of the continent, low light intensities during winter are unlikely to have been a significant limiting factor except possibly in Tasmania during the Danian, whilst the amount and seasonal distribution of rainfall replaced temperature as the major environmental forcing factor during the Late Palaeogene and Neogene except at high elevations.

During the Palaeogene, angiosperms largely replaced gymnosperms as the canopy dominants in rainforest over much of the continent. Only the Podocarpaceae with functionally broad leaves were able to compete successfully with angiosperms in the low-light environment within the forest canopy (Brodribb and Hill 1997, Hill and Brodribb 1999). Araucariaceae and Cupressaceae, which lack flattened foliage, remained fairly common only in less shaded habitats. Hill (1990a, 1998a, 1998b) has proposed that sclerophyll species evolved originally in response to low fertility soils in rainforest environments during the Palaeogene, and the morphological expressions of sclerophylly subsequently pre-adapted these plants to reduced or increasingly seasonal rainfall. As aridity became more severe during the Neogene, sclerophyllous plants evolved xeromorphic adaptations to prevent water loss; predominantly-mesic biomes such as rainforest gave way to more xeric/open biomes such as sclerophyll forests, woodlands and savannah. The same xeromorphic adaptations may have adapted sclerophyllous plants to withstand the cool-cold (microtherm) conditions that began to develop at high elevations during the Late Oligocene or Early Miocene, and also may have contributed to the probable increased incidence of wildfires at lower elevations during the Late Neogene.

7.3.5 *Climatic indicators*

The Tertiary differs from the Cretaceous in that a significant number of macrofossil and microfossil species can be assigned to extant genera with a moderate to high degree of confidence. As for the Late Cretaceous, key climatic indicator taxa are araucarians, podocarps, palms (Palmae), *Nothofagus*, *Anacolosa* and other mesotherm-megatherm taxa although it is recognised that the ecological preferences and tolerances of these and most taxa will have changed (possibly narrowed) to a lesser or greater degree during the Tertiary. For example, *Nothofagus* (*Brassospora*)-dominated microfloras are more likely to represent rainforest growing under warm (lower mesotherm) conditions than the cool (microtherm) conditions preferred by most living *Nothofagus* spp. Typically megathermal taxa such as palms are able to survive under mean annual temperatures as low as 14°C (lower mesotherm) as long as the annual temperature *range* is very low (Wolfe 1987). Accordingly, where other data indicate a more extreme temperature range, fossil palm pollen such as *Dicolpopollis*, *Longapertites* and *Spinizonocolpites* is reliable evidence for very warm to hot (upper mesotherm-megatherm) conditions.

Palaeo-distribution data can allow the ecological preferences of a number of commonly occurring to rare taxa to be deduced with some confidence in qualitative terms (Table 7). However, there are compelling reasons why it is premature to use the same data to reconstruct past climates in quantitative terms (cf. Taylor *et al.* 1990, Sluiter 1991, Greenwood and Wing 1995, Jordan 1997a, Macphail 1997b): (1) The present-day distribution of many plants reflects anthropogenic effects or conditions that are unique to the Late Quaternary. For example, several endemic gymnosperms and ferns in Tasmania have failed to recapture habitats vacated during the Last Glaciation (Macphail 1986, 1997c). (2) Plant successions can be initiated or shaped by non-climatic factors. One example is volcanism whose impacts often mimic those of aridity (Harris and Van Couvering 1995) and the same may be true of frequent wildfires, decreasing soil fertility, forest pathogens and herbivory (references in Van der Putten 2000). (3) Many Tertiary taxa co-occur in associations or communities that have no modern analogue, or which included extinct ecotypes. An example of the latter is the alpine shrub conifer *Microcachrys tetragona*, now the sole surviving species of a clade that was very widely distributed during the Mesozoic (Dettmann 1994) and Tertiary (Macphail *et al.* 1993, Jordan 1994, 1997a).
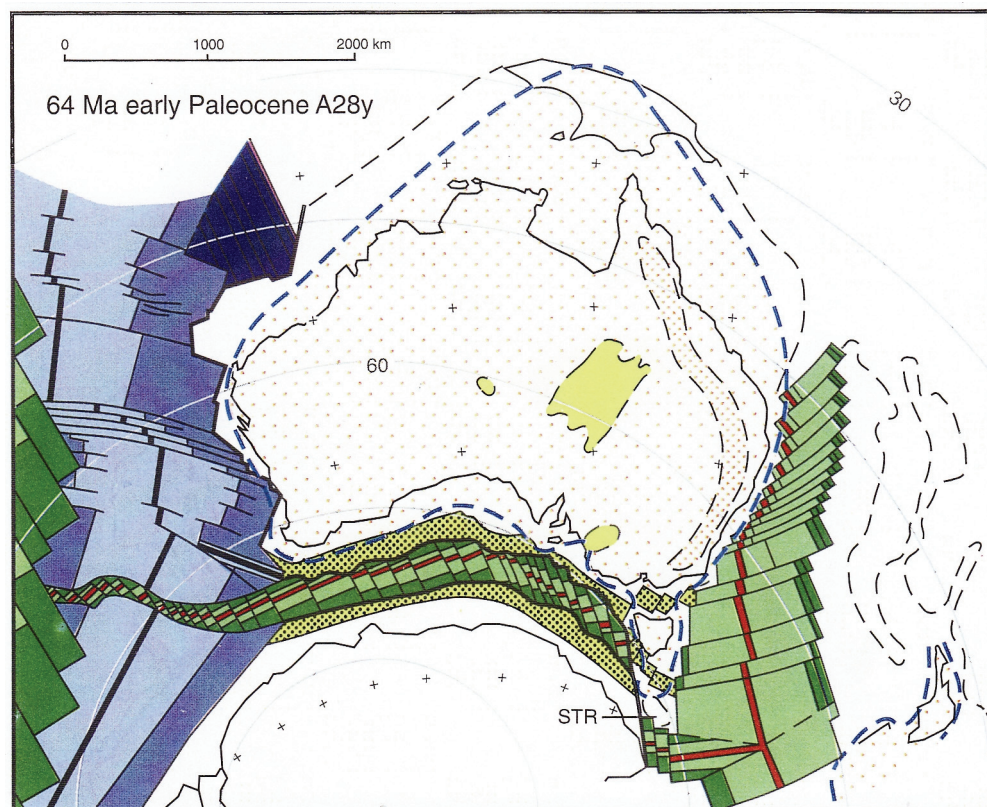
Table 7:   Inferred climatic preferences of selected Tertiary taxa.

FOSSIL TAXON	MODERN EQUIVALENT	INFERRED CLIMATIC RANGE
Mosses, ferns and fern allies		
Cyatheacidites annulatus	*Lophosoria*	upper microtherm to lower mesotherm
Matonisporites ornamentalis	*Dicksonia antarctica*	upper microtherm to lower mesotherm
Polypodiaceoisporites sp.	*Pteris*	upper mesotherm to megatherm
Stereisporites spp.	*Sphagnum*	±microtherm
Trilites tuberculiformis	Dicksoniaceae, Matoniaceae	microtherm to ?megatherm
Gymnosperms		
Araucariacites australis	*Araucaria*	lower? to upper mesotherm
Dacrycarpites australiensis	*Dacrycarpus*	upper microtherm to lower mesotherm
Dilwynites spp.	*Agathis/Wollemia*	lower? to upper mesotherm
Lygistepollenites balmei	*Dacrydium* (extinct lineage)	upper microtherm to lower mesotherm
L. florinii	*Dacrydium*	upper microtherm to lower mesotherm
Microcachrydites antarcticus	*Microcachrys*	upper microtherm to lower mesotherm
Podocarpidites spp.	*Podocarpus-Prumnopitys*	microtherm to ?megatherm
Angiosperms		
Anacolosidites spp.	*Anacolosa*	upper mesotherm
Australopollis obscurus	*Callitriche*	upper microtherm to lower mesotherm
Bluffopollis scabratus	*Strasburgeria*	upper mesotherm
Canthiumidites bellus	*Randia* s.l.	±upper mesotherm
Cupanieidites sp.	*Cupanieae* (Sapindaceae)	lower to upper mesotherm
Gothanipollis spp.	Loranthaceae	lower to upper mesotherm
Granodiporites nebulosus	*Embothrium*	upper microtherm to lower mesotherm
Ilexpollenites spp.	*Ilex*	lower mesotherm to megatherm
Haloragacidites harrisii	*Gymnostoma*	lower mesotherm to megatherm
Intratriporopollenites notabilis	Tiliaceae incl. *Brownlowia*	upper mesotherm to megatherm
Longapertites spp.	Palmae	upper mesotherm? to megatherm
Malvacearumpollis spp.	Malvaceae	lower to upper mesotherm
Myrtaceidites parvus-mesonesus	non-eucalypt Myrtaceae	lower to upper mesotherm
Nothofagidites asperus,	*Nothofagus* (*Lophozonia*)	upper microtherm to lower mesotherm
N. brachyspinulosus	*Nothofagus* (*Fuscospora*)	upper microtherm to lower mesotherm
N. emarcidus-heterus, N. falcatus	*Nothofagus* (*Brassospora*)	upper microtherm to lower mesotherm
N. endurus, N. senectus	Ancestral *Nothofagus*	upper microtherm to lower mesotherm
N. flemingii	*Nothofagus* (*Nothofagus*)	upper microtherm to lower mesotherm
Nupharipollis spp.	Palmae	upper mesotherm to megatherm
Perisyncolporites pokornyi	Malpighiaceae	lower to upper mesotherm
Polyadopollenites cf. *granulosus*	*Archidendron*-type	lower to upper mesotherm
Santalumidites cainozoicus	Santalaceae	lower to upper mesotherm
Sapotaceoidaepollenites spp.	Sapotaceae	lower to upper mesotherm
Spinizonocolpites prominatus	*Nypa*	upper mesotherm to megatherm
Tricolpites thomasii	Loranthaceae	lower to upper mesotherm
Zonocostites ramus	Rhizophoraceae	upper mesotherm to megatherm

7.4 Time Slice T-1. Paleocene [65-54.8 Ma]

Zones: Lower to Upper *Lygistepollenites balmei* Zone
Trithyrodinium evittii to Lower *Apectodinium hyperacanthum* Zone

Figure 8: **Early Paleocene (64 Ma) palaeogeography (from Veevers *et al*. 1991)**

7.4.1 *Palaeogeography*

During the Paleocene, Australia was located between palaeolatitudes 45^0-70^0S (Figure 8). The continent remained linked to a largely ice-free Antarctica via the partially submerged South Tasman Rise (STR). In northern Australia, regression at the Cretaceous-Tertiary boundary was followed by widespread transgression in the Paleocene, with maximum flooding of the North West Shelf occurring during the Late Paleocene (Bradshaw *et al.* 1988). Carbonates accumulating on the North West Shelf contain less siliciclastic material than those deposited during the Late Cretaceous, possibly reflecting low relief and increasing aridity (Apthorpe 1988). During the same period, sea-floor spreading in the Tasman Sea had rotated the submerged Lord Howe Rise and a partially emergent Campbell Plateau away from Australia. Ranges on the eastern margin (Eastern Cordillera) had shrunk in width and height to form the present-day Eastern Highlands, although much of the area now occupied by the Great Barrier Reef remained dry land. Taylor *et al*. (1990) estimate regional relief on the Southeastern Highlands of New South Wales was at least 400 m and possibly greater than 800 m by ca. 58-60 Ma. Subsidence in northern South Australia produced a large, shallow basin (Lake Eyre Basin) in which fluvio-lacustrine sands, silts and clays (Eyre Formation) accumulated possibly during latest Paleocene to Middle Eocene time. Paleocene (*Lygistepollenites balmei* Zone) facies reach thicknesses of up to 950 m in the offshore Gippsland Basin (Partridge 1999). Elsewhere, deep weathering or erosion seems to have continued unabated across much of the continent (Bain and Draper 1997, Alley 1998, Alley *et al.* 1999).

7.4.2 *Palaeobotany*

A disproportionate number of the taxa that became extinct at the K/T boundary were angiosperms, especially Proteaceae characterised by large, highly ornamented pollen. Two consequences of this during the Danian in southern Australia are: (1) Gymnosperm populations expanded at the expense of angiosperms rather than cryptogams. (2) Austral Conifer Forest and fern heath communities were impoverished (floristically simple) relative to their Maastrichtian predecessors. On present indications, Paleocene forests and/or woodlands in northern and central Australia were co-dominated by angiosperms and gymnosperms although the most common canopy species were Cupressaceae and/or Taxodiaceae and Cunoniaceae, not Podocarpaceae as in southern Australia. Sparganiaceae (burr reed) swamps, which formed along the northwestern margin and in the centre during the Late Paleocene, appear to be the first extensive herb-dominated communities to develop in Australia.

7.4.3 *Palaeoclimates*

Floristic trends, especially the increased diversity and dominance of angiosperms during the late Danian and Thanetian, are consistent with increasing global temperatures and (southern Australia) photoperiods. For example, although ancestral *Nothofagus* spp. become sporadically dominant in the south-east, these quasi-temperate rainforest communities usually included angiosperms and cryptogams whose NLRs are found in subtropical and tropical rainforest. Whether north-south climatic gradients were less strong than during the Late Cretaceous is less clear because of the uncertain taxonomic affinity of some commonly represented taxa, e.g. Casuarinaceae (*Haloragacidites harrisii*).

Palaeo-northern Australia

Lithostratigraphic evidence (Apthorpe 1988) indicates that Late Paleocene climates in the Bonaparte and Browse Basins were very warm (upper mesotherm) as well as seasonally dry (subhumid-humid). More generally, the shift from entirely coarse clastic to predominantly carbonate sedimentation is seen as evidence that climates were relatively dry during the Early Paleocene. The only palaeobotanical evidence for Paleocene climates in northeastern Australia comes from a site on the Northern Tablelands of New South Wales. Here, conditions were sufficiently wet (humid-perhumid) and warm (mesotherm range) to support Austral Conifer Forest dominated by Araucariaceae and ferns. *Nothofagus* is absent despite the moderately high elevation. Wildfires were common although the cause may have been volcanism rather than a prolonged dry season. Indirect evidence for seasonally warm and wet conditions across much of western Queensland is provided by deep weathering of Cretaceous landsurfaces, although age control is poor.

Palaeo-central Australia

Reconstruction of Paleocene climates in central Australia is hindered by poorly constrained ages and the unusual composition of the terrestrial vegetation. *Nothofagus* is rare or absent and, assuming the source(s) of one dominant pollen type (Cunoniaceae) had similar climatic preferences to the NLRs, then conditions were seasonally wet (humid) and relatively warm (mesotherm range). The presence of Sparganiaceae swamps is consistent with sluggish flow regimes and, by extrapolation, a pronounced dry season. Dinoflagellates imply that some of the lakes or ponds were sub-saline although this could be due to an influx of saline groundwater rather than a prolonged dry season. Silcrete began forming in the Eyre Basin.

Unlike northern and central Australia, the palaeobotanical evidence from southeastern, central southern and the north of southwestern Australia provides a comprehensive record of geographic and temporal trends in the vegetation bordering the Australo-Antarctic Seaway to the west and Tasman Sea to the east.

Conditions in the southern Carnarvon Basin were sufficiently wet to allow Proteaceae-dominated coastal communities to be replaced by Casuarinaceae (*Gymnostoma* swamp forest) and freshwater Sparganiaceae swamps. Nevertheless the paucity of rainforest species and cryptogams such as Gleicheniaceae and *Sphagnum* is consistent with rainfall being either sub-optimal for mesophytes (subhumid-humid) or with a pronounced dry season in present-day northern southwestern Australia. The presence of *Nypa* implies mean annual temperatures were very warm (upper mesotherm). Further to the south-east, wetter (humid-perhumid) and cooler (lower mesotherm) conditions supported extensive Callitrichaceae swamps and araucarian-dominated Austral Conifer Forest. This forest type extended from the Duntroon Basin in south-west South Australia onto the Southeastern Highlands of New South Wales. Macrofossil data from the Southeastern Highlands imply strong seasonal contrasts in temperature and the same may true of southern Australia as a whole, although temperature *per se* is unlikely to have been a limiting factor on plant growth, except during the Early Danian.

Rising temperatures during the Late Paleocene were accompanied by the expansion of floristically complex, angiosperm-dominated rainforest types although climates remained too cool to support palms south of the Carnarvon Basin. In the central southern region, this trend is associated with the expansion of Myrtaceae and a marked decline in *Nothofagus* populations, implying that rainfall remained high (perhumid) but with a stronger seasonal bias. A more complex situation prevailed in the south-east where the first appearance of taxa with well-defined tropical affinities, e.g. *Anacolosa* and Tiliaceae, was followed by the re-expansion of *Nothofagus* towards the end of the Thanetian. Whether this (temporary) event was due to transient cooling (possibly cold ocean currents flowing along the eastern margin) or other factors, such as an increase in effective precipitation during summer months, is unknown. The combined data imply warming temperatures were associated with more reliable or increasingly uniform rainfall.

Strong parallelism between marine dinocyst successions in New Zealand and Europe make it unlikely that the Australian region was quarantined from the impact of the PETM. At present the strongest indications of abrupt warming at the Paleocene-Eocene boundary are the expansion of the warm water dinoflagellate genus *Apectodinium* (cf. Partridge 1976, H. Brinkhuis pers. comm.), the abrupt appearance of the tropical mangrove palm *Nypa* in continual margin basins in southeastern Australia, and the collapse of *Nothofagus* populations in the Gippsland Basin at the *Lygistepollenites balmei/Malvacipollis diversus* Zone boundary.

7.5   Time Slice T-2. Early Eocene [54.8-49 Ma]

> **Zones**: *Malvacipollis diversus* to *Proteacidites asperopolus* Zones
> Upper *Apectodinium hyperacanthum* to *Homotryblium tasmaniense* Zones

7.5.1   *Palaeogeography*

During the Early Eocene Australia lay between palaeolatitudes 30^0S to about 65^0S. Opening of the Coral Sea rotated the Papuan Peninsula into its present position, and completed the present-day shape of northern Australia. Deposition of marls and carbonates continued along the northwestern margin. The site of Perth was a shallow valley infilled with marine

mudstones (Kings Park Shale). Sporadic basaltic eruptions occurred in eastern Tasmania and along the length of the Eastern Highlands into Queensland, where a number of terranes lay off the northeastern margin. A series of fresh to brackish water lakes formed in fault troughs aligned along the present Queensland coastline. Carbonaceous sediments accumulated in these basins, and also in central Australia where the absence of piedmont deposits implies the topography was relatively subdued (Alley 1998). Restricted to open marine conditions existed along the southern margin where clastic sedimentation became episodic due to regional tectonic and eustatic forcing. Bass Strait remained a swampy alluvial plain surrounding large freshwater to saline lakes whilst the South Tasman Rise land-bridge had become partially submerged.

7.5.2 *Palaeobotany*

The progressive replacement of cryptogams and archaic gymnosperms by rainforest angiosperms appears to have been almost complete in the coastal vegetation in the Gippsland and Bass Basins by the earliest Early Eocene. Prominent families included Casuarinaceae (representing *Gymnostoma* rather than *Allocasuarina*/*Casuarina*), Euphorbiaceae and Proteaceae. The relative abundance of *Malvacipollis* and *Proteacidites* pollen in coastal plain and marginal marine sediments suggests Euphorbiaceae and Proteaceae were prominent in riparian communities and may have included salt-tolerant (mangrove) species. Fossil pollen data indicate that a number of angiosperm clades that reached their maximum diversity in Australia during the Early Eocene (Martin 1994, Jordan *et al*. 1998). However a significant number of rare taxa occurring in northern and central Australia during the Early Eocene are not found in southeastern Australia until the Middle-Late Eocene.

7.5.3 *Palaeoclimates*

The Paleocene-Eocene transition in southeastern Australia is marked by the first occurrence of fossil *Nypa* pollen (*Spinizonocolpites prominatus*). The presence of this pollen type and *Nypa* macrofossils (Pole and Macphail 1996) confirms that very warm to hot conditions persisted into late Early Eocene time *within* the Gippsland Basin (palaeolatitude 62^0S) and Macquarie Harbour in western Tasmania (palaeolatitude 66^0S). Conditions in the northern half of the continent during the early Early Eocene are less easily reconstructed due to the paucity of reliably dated fossil assemblages although, surprisingly, conditions may have been cooler in northeastern Australia than within the Australo-Antarctic Seaway to the south. For example, there is no definite pollen evidence for palms in coastal southern Queensland despite its relatively low (~50^0S) palaeolatitude.

Palaeo-northern Australia

Occurrences of palm (and paucity of gymnosperm) pollen in Casuarinaceae-dominated microfloras in the Bonaparte Basin are consistent with hot (megatherm range) and seasonally very wet (perhumid) conditions during the late Early Eocene. The presence of freshwater Sparganiaceae swamps along the coast complements sedimentary evidence for increased continental run-off into the northern Carnarvon Basin in the Early Eocene, although at some time during this period warm water faunas began to be replaced by cool water faunas (Apthorpe 1988). *Banksia* macrofossils indicate that conditions in the Kimberley region were either drier or soils has become strongly leached.

Conditions at similar palaeolatitudes in northeastern Australia appear to have been cooler (lower mesotherm) and probably wetter during summer months (humid-perhumid), based on macrofossils of *Agathis*, *Gymnostoma* and Lauraceae and microfloras, which include rainforest taxa with mesotherm (*Anacolosa*, Tiliaceae) and microtherm (*Dacrydium*, *Lagarostrobos*, *Microcachrys*) NLRs. The absence of palms is best explained by cold currents flowing northwards along the eastern margin.

Palaeo-central Australia

As for the Late Paleocene, the reconstruction of Early Eocene climates in central Australia is hindered by the uncertain age of many assemblages and the heterogeneous nature of the rainforest vegetation. For example, taxa that are now characteristic of warm temperate rainforest (Cunoniaceae, Elaeocarpaceae) co-occur with *Nothofagus* in the Lake Eyre Basin, whilst further to the north in the Alice Springs district, the rainforest vegetation, which is dominated by Casuarinaceae (*Gymnostoma*) and Proteaceae, includes palms but lacks *Nothofagus*. Nevertheless, the increasing dominance of microfloras by angiosperms other than *Nothofagus* is weak evidence for relatively warm (upper mesotherm) and seasonally wet to very wet (perhumid) conditions during the Early Eocene.
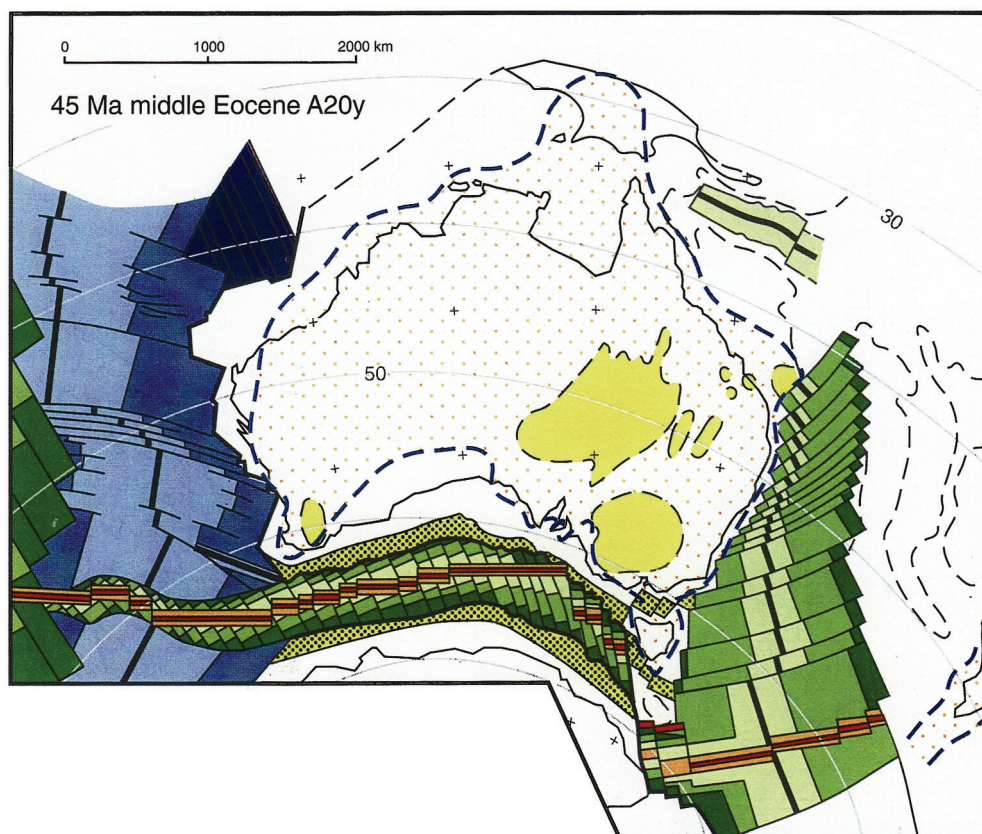
Palaeo-southern Australia

Palms such as *Nypa* were present in the southern Carnarvon and Perth Basins but the relatively high diversity of gymnosperms and persistent presence of *Nothofagus* suggests that Early Eocene climates were marginally cooler (mesotherm range) and wetter (humid-perhumid) or rainfall was more uniform in southwestern Australia than in northwestern Australia. Similar relatively mild conditions may have extended as far east as the Eyre Peninsula in South Australia due to the influence of warm water gyres within the Australo-Antarctic Seaway.

Conditions in the south-east of the continent were wetter (perhumid) and equally warm (upper mesotherm) although temperature regimes were more complex at the local scale. One contributing factor is likely to have been higher SSTs within enclosed embayments such as Macquarie Harbour than in embayments exposed to the open ocean. For example *Nothofagus* (*Brassospora*) spp. appears to have remained relatively common in southeastern Tasmania throughout the Early Eocene whilst differences in the relative abundance of *Nypa* pollen imply that SSTs in the Gippsland Basin were slightly cooler than in Macquarie Harbour during the late Early Eocene.

7.6   Time Slice T-3. Middle-Late Eocene [49-33.7 Ma]

Zones: Lower to Middle *Nothofagidites asperus* Zones
Rhombodinium waipawaense to *Gippslandica extensa* (*Corrudinium incompositum*) Zones

Figure 9:   **Middle Eocene (45 Ma) palaeogeography (from Veevers *et al*.1991**

7.6.1   *Palaeogeography*

During the Middle-Late Eocene Australia lay between palaeolatitudes of ~27^{0}S to ~63^{0}S (Figure 9). At about 43 Ma (late Middle Eocene), the Pacific Plate underwent a second swerve, increasing the velocity of northward drift from an average 70 mm yr^{-1} to 93 mm yr^{-1} (Veevers 1999). Co-eval events include the formation of monoclines, broad arches and domes in central Australia and grabens (some now filled with oil shale deposits) in coastal Queensland. Seismic and geological evidence indicate that the northern Bonaparte Basin suffered multiple meteor impacts during the same (Late Eocene) interval (Gorter 1999). Four cycles of eustatic are recognised in southern Australia (Harris 1985). The earliest evidence of the (southward flowing) Leeuwin Current in southwestern Western Australia is late Middle Eocene (McGowran *et al.* 1997). Palaeochannels incised into the southern edge of the Yilgarn Plateau were infilled with thin lignite measures (Clarke 2000). Further to the east, thick lignite sequences have accumulated in the Noarlunga and Willunga Embayments of the St. Vincent Basin (Fairburn 1998, 2000), at Anglesea in the Torquay Sub-basin and in the Gippsland Basin (Holdgate and Sluiter 1991, Holdgate *et al.* 2000).

7.6.2 *Palaeobotany*

The palaeobotanical database for the Middle-Late Eocene is more extensive in terms of geographic coverage than any other period within the Cenozoic. Reasons include margin sag (along the southern margin) and uplift and/or compression (in central Australia) creating the necessary accommodation space, and humid conditions allowing organic preservation in regions that are now sub-humid to arid. In contrast to previous epochs, however, climatic events in southern Australia tend to be obscured by the sheer volume of spot data and because geographic differences are concealed by broad fossil species definition. For example, Middle-Late Eocene species lists for coastal Queensland are virtually identical to those from the Murray Basin in south-east South Australia.

The key botanical event is the abrupt increase in the relative abundance of *Nothofagus* (*Brassospora*) spp. across southern Australia during the Early/Middle Eocene transition. By Middle/Late Eocene time *Nothofagus* (*Brassospora*) spp. had become locally common in gallery rainforest in central Australia and may have extended northwards into sheltered upland valleys in Pilbara Region by the Late Eocene or Early Oligocene. The Pilbara populations appear to represent the most northwestern extension of *Nothofagus* in Australia during the Tertiary. Islands on the South Tasman Rise may have facilitated floristic change with East Antarctica, where a depauperate *Nothofagus*-podocarp scrub formed the coastal vegetation during the Middle-Late Eocene (Macphail and Truswell 2000). It is unlikely that comparable successions occurred in northwestern Australia because of deep weathering (onshore) and sediment starvation (offshore).

7.6.3 *Palaeoclimates*

The presence or absence of palms remains the primary evidence for inferring palaeotemperatures in northern Australia. Elsewhere, reconstruction of Middle to Late Eocene climates depends on the inferred palaeoecology of the four extant subgenera of *Nothofagus* (Hill and Read 1991), in particular species within the subgenus *Brassospora* whose living representatives are largely confined to montane (uniformly wet, lower mesotherm to microtherm) habitats in New Guinea and New Caledonia. However, the presence of occasional stands along lowland rivers in New Caledonia (G.S. Hope pers. comm.) suggests a potentially wider distribution in the absence of humans and fires. *Nothofagus* (*Brassospora*) spp. tend to form extensive almost pure stands, and Tertiary and Quaternary distributions make it unlikely that drought-tolerant ecotypes have ever evolved within the subgenus. The same intolerance to prolonged water stress appears to be true for *Nothofagus* (*Lophozonia*), all species of which are confined to wet, microtherm climates. Conversely the distribution of NLRs in New Zealand and South America suggest that some Tertiary *Nothofagus* (*Fuscospora*) and *N*. (*Nothofagus*) spp. were tolerant of short-term moisture deficits. Apart from the Podocarpaceae, the NLRs of other fossil taxa that are likely to have formed the canopy stratum in Tertiary rainforests are confined to perhumid/mesotherm habitats where the annual rainfall distribution varies from uniform (ever-wet) to strongly seasonal (monsoonal).

Palaeo-northern Australia

Subtropical-tropical mangroves (Rhizophoraceae) and palms (*Longapertites, Nypa, Nupharipollis*) indicate very warm to hot (upper mesotherm-megatherm) conditions and strongly seasonal wet (possibly monsoonal) conditions existed in the Bonaparte Basin during Middle and possible Late Eocene time. SSTs warmed on the North West Shelf and lithostratigraphic data indicate a decrease in continental run-off into the Carnarvon Basin. Limited evidence from the Capricorn Basin indicates that rainfall in coastal northeastern Queensland was similar (perhumid) but more uniformly distributed. Temperatures vary from very warm (upper mesotherm) on the coast to cool (upper microtherm-lower mesotherm) on

the adjacent highlands. Seasonal contrasts may have been weaker than in northwestern Australia.

Palaeo-central Australia

The high degree of geographic variation in fossil floras is matched by disparities in climatic reconstructions. Nevertheless general agreement exists that conditions were much wetter than at present, and rainfall was adequate to support meandering river systems and permanent freshwater lakes.

Macrofossil evidence indicates that the regional vegetation was a mosaic of mesotherm rainforest and sclerophyll communities, consistent with very warm (upper mesotherm), moderately wet (humid) but strongly seasonal (possibly monsoonal) conditions. In contrast, microfossil data point to very wet (perhumid) and relatively cool (lower mesotherm) conditions with only a weak seasonal bias in rainfall. One not unreasonable explanation is that the two forms of palaeobotanical evidence represent different areas of vegetation, *viz*. sclerophyll communities growing on drier, infertile (interfluve) sites with gallery rainforest growing in wetter, more fertile (riverine) sites, and analogous moist habitats in the uplands. If correct, then the regional temperatures are likely to have been at the upper end of the lower mesotherm range whilst rainfall was geographically variable within the humid-perhumid range. Since climatic change directly or indirectly will have underpinned the expansion of *Nothofagus* in gallery rainforest in central Australia, the data are emphatic that conditions during the Middle-Late Eocene were cooler and (riparian environments) effectively wetter (more humid) than during the Early Eocene.

Palaeo-southern Australia

Assuming the microfloras are correctly dated, conditions at higher elevations in the Pilbara region appear to have been relatively cool, and summer rainfall (or groundwater discharge) was adequate to support *Nothofagus* (*Brassospora*) communities. Mean temperatures in the southern Carnarvon Basin had fallen below the minimum value to support palms. The same appears to have been the case elsewhere in southern Australia, except for the Polda and St. Vincent Basins. Conditions remained wet to very wet although summer rainfall appears to have been too low to support *Nothofagus* populations away from riverine habitats in south-west Western Australia. For the first time in the Tertiary, macrofossils and microfossils are preserved over a sufficiently wide region to allow reconstruction of climatic gradients within some southern margin basins.

1.   Palaeotemperature

Fossil *Nypa* pollen indicates that conditions in the eastern Bight Region (Polda and St. Vincent Basins) were warmer (upper mesotherm) than in coastal south-west Western Australia (southern Carnarvon and Eucla Basins) or southeastern Australia (Otway, Gippsland and Bass Basins). This is best explained in terms of locally warm SSTs at the heads of Spencer and St. Vincent Gulfs, analogous to the warm conditions that allow relict mangrove to survive near Port Augusta at present. Elsewhere in the Bight region, temperate indicators such as *Nothofagus* (*Brassospora*) spp. and podocarps such as *Lagarostrobos* are associated with numerous angiosperm taxa whose NLRs are confined to subtropical rainforest. This implies mean *maximum* temperatures were in the lower to low upper mesotherm range and, in contrast to southeastern Australia, pollen of the cool climate taxon *Nothofagus* (*Lophozonia*) are only sporadically recorded.

A more complicated pattern occurs to the east in the Gippsland and Murray Basins. Here Lower *Nothofagidites asperus* Zone microfloras imply that conditions had cooled markedly during earliest Middle Eocene time to lower mesotherm values, whilst Middle *N. asperus*

Zone microfloras imply temporary warming occurred during the Late Eocene, possibly into the upper mesotherm range. The latter is presumed to correlate with transient warming recorded elsewhere along the southern margin (McGowran *et al.* 2000) although it is unclear whether higher temperatures were sufficient to influence plant successions at higher latitudes or higher elevations in southeastern Australia. For example, one probable thermophilous Proteaceae species, *Triorites magnificus* is not recorded in southern Tasmania and it seems probable that mean temperatures here and in the Eastern Highlands remained within the upper microtherm to lower mesotherm range throughout the Middle and Late Eocene. *Ginkgo* and deciduous species of *Nothofagus* provide circumstantial evidence that mean *minimum* temperatures fell below freezing during winter in the southeastern Tasmania during the Middle-Late Eocene.

2. Rainfall

The abundance of *Nothofagus* (*Brassospora*) spp relative to gymnosperms appears to increase, and the diversity of uncommon angiosperms with subtropical NLRs decrease, quasi-systematically from west to east along the southern margin. Assuming this trend reflects differences in the seasonal distribution and reliability of rainfall, then summer rainfall was lowest (or least reliable) in the Eucla Basin and adjacent inland regions, and highest (or most reliable) in Tasmania, the Gippsland Basin and, possibly, the Eastern Highlands. Any increase in orographic cloudiness almost certainly will have reduced evapo-transpiration losses and increased effective annual precipitation in mountainous regions.

7.7 Time Slice T-4. Oligocene-Middle Miocene [33.7-11.2 Ma]

Zones: Upper *Nothofagidites asperus* to *Canthiumidites bellus* Zones
Phthanoperidinium comatum and informal *Oligospheridium* Zones

Figure 10: Earliest Oligocene (35 Ma) palaeogeography (from Veevers *et al.* 1991)
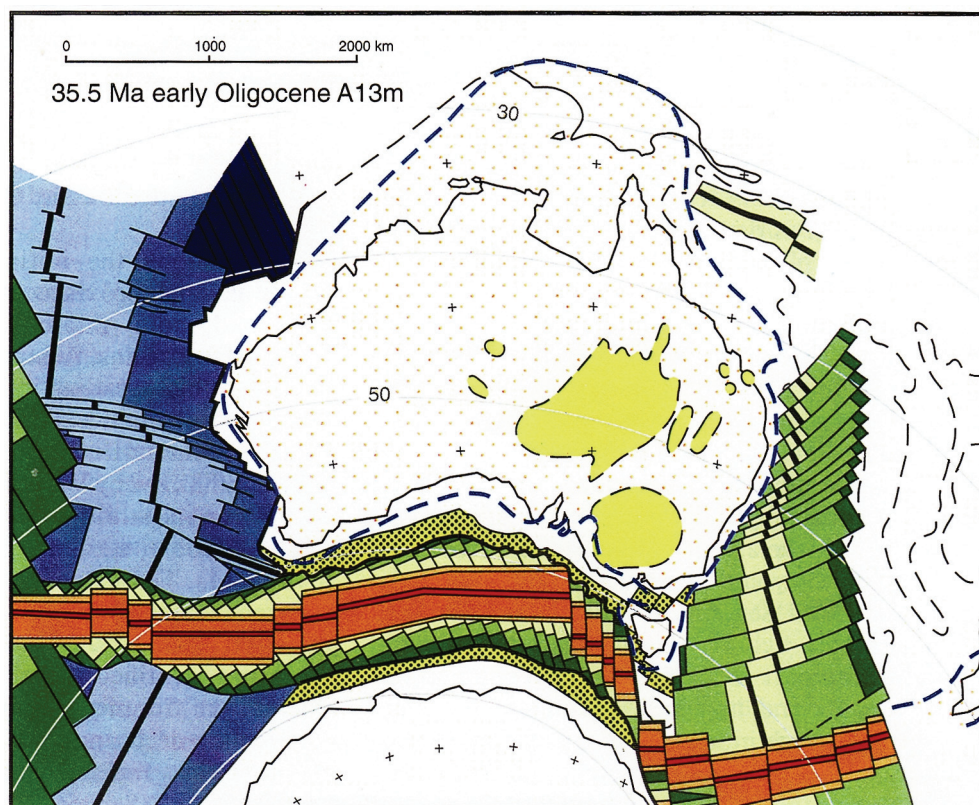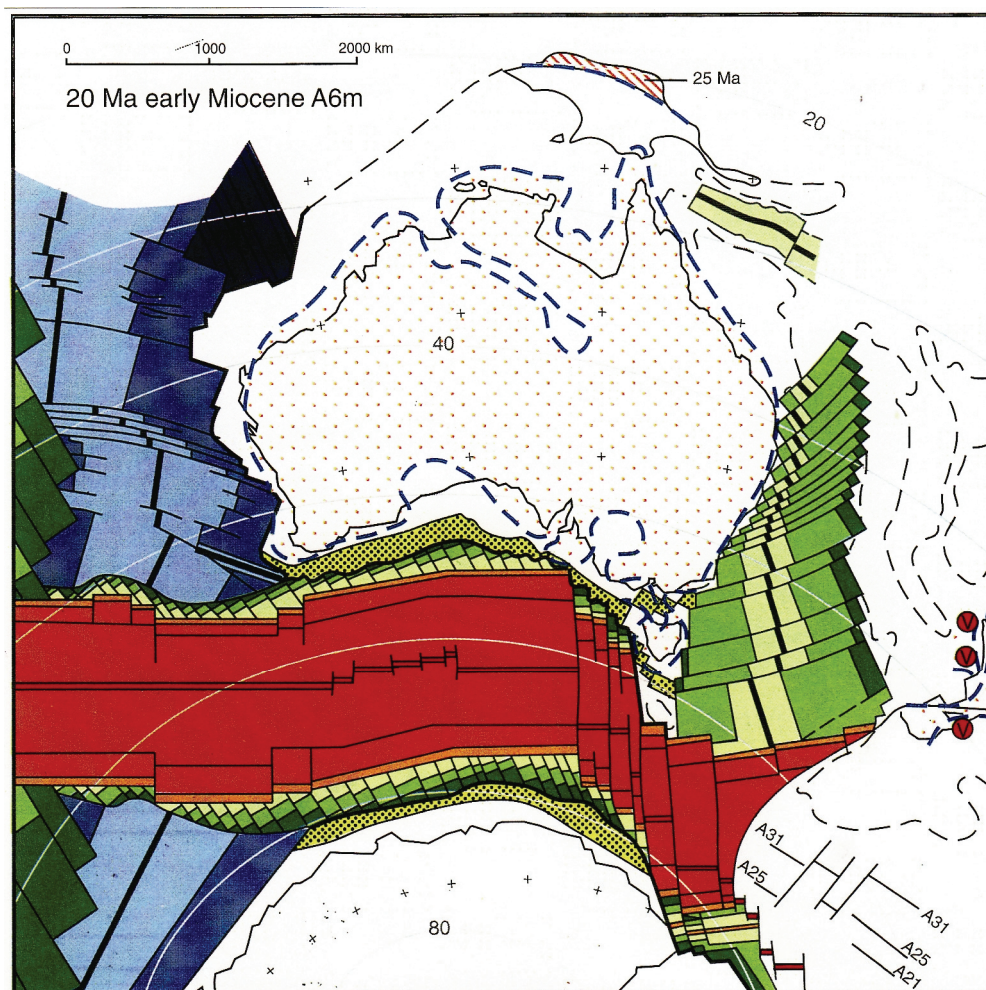
Figure 11:   Early Miocene (20 Ma) palaeogeography (from Veevers et al. 1991)

7.7.1   *Palaeogeography*

During Oligo-Miocene time, Australia drifted through some 20^0 of latitude (Figures 10-11). For example, between Early Oligocene and Late Miocene time, northern Tasmania moved from about palaeolatitude 60^0S to palaeolatitude 40^0S whilst Cape York moved from about palaeolatitude 32^0 to palaeolatitude 11^0S.

Opening of the Tasmanian Gateway to deepwater circulation at about 33 Ma (Eocene-Oligocene boundary) initiated continent scale glaciation of Antarctica and profoundly altered ocean current systems in the Australian region. For example, planktonic foraminifera indicate that currents that had flowed from Antarctica northward along the western Australian margin were diverted eastward to become part of the Circumantarctic Current. It is unclear how currents flowing along the eastern margin of Australia were affected. By this time Tasmania was separated from the Antarctic continent by $5\text{-}8^0$ latitude but remained connected to the mainland via the Flinders Island landbridge. A transient valley glacier formed (Lemonthyme Glaciation) on the >700 m high Central Plateau of Tasmania during the early part Early Oligocene (Macphail *et al.* 1993).

A major fall in global sea levels during the Early Oligocene caused the palaeocoastline to extend to near the continental shelf edge. Deposits of this age are rare or non-existent except in the tectonically active south-east where sedimentary sequences accumulated in actively subsiding basins. Examples are the upper Eastern View Group and Demons Bluff Formations

in the Bass Basin, the basal Seaspray Group in the Gippsland Basin, and the upper Buccleugh beds, Ettrick Formation and Renmark Group in the Murray Basin. No carbonaceous terrestrial sediments of confirmed Early Oligocene age have been recorded on the eastern margin. Conversely, marls of this age are preserved in distal areas of the North West Shelf (Quilty 1977, Apthorpe 1988) where rising sea levels allowed carbonate accumulation to recommence during the Late Oligocene.

Gorter and Bayford (2000) have proposed that a small multi-ringed structure (Puffin Structure) on the Ashmore Platform, North West Shelf was formed by the impact of a meteorite or small asteroid into unconsolidated shallow marine carbonates sometime during the Middle Miocene. By this time, the northern margin was at about palaeolatitude 20^0S and, during the mid-Miocene, began to collide with South-East Asia. One consequence was an episode of major mountain-building in New Guinea from ~30 Ma onwards (New Guinea Orogeny). Formation of the 3 km high island of Timor and the adjacent 3 km deep Timor Trough foredeep reflect the same event.

At about the same time, coral reefs began to develop in the area of the present northern Great Barrier Reef. To the south, the same major rise in relative sea-level caused Bass Strait to become a shallow seaway whilst a somewhat smaller seaway developed across the top of the Fleurieu Peninsula. Shallow epicontinental seas flooded the Eucla and western Murray Basins (Brown and Stephenson 1991). In the offshore Gippsland Basin, thick carbonate wedges developed over the paralic and other terrigenous sediments deposited during the Palaeogene. Onshore terrestrial sequences include deposition of a great thickness of peat (now brown coal measures) in the Latrobe Valley (Holdgate *et al.* 2000).

Gentle uplift split the Eyre Basin into two sub-basins, the Tirari Sub-basin to the west, and Callabonna Sub-basin to the east, of Coopers Creek. River systems here and in inland south-west Australia became very sluggish and began to break up into chains of lakes, whilst Paleocene-Eocene deposits such as the Eyre Formation became deeply weathered and capped by silcrete (Cordillo Surface). Sedimentation in the Lake Eyre Basin recommenced during the latest Oligocene and Miocene (Alley 1998), leading to the deposition of the Oligocene-Middle Miocene Etadunna Formation in the Tirari Sub-basin and the correlative Namba Formation in the Callabonna Sub-basin. Intraplate volcanism continued to occur in northwestern and eastern Tasmania and along the Eastern Highlands where some vents developed into shield volcanoes. An example is the Ebor Volcano at Dorrigo on the New England Plateau. This volcano was at least 45 km across and stood 800 m above basement during the Early Miocene (Ashley *et al*. 1995). Fluvial sediments blanketing coastal lowlands of southern New South Wales may date from the same period (Nott *et al*. 1991).

In northern Queensland, sequences of probable Oligocene-Middle Miocene age unconformably overlie Mesozoic sedimentary sequences (Smart *et al.* 1980, Bain and Draper 1997). One possible Late Oligocene-Early Miocene formation in the Karumba Basin (Bulimba Formation) is reported to include thin coals. Grimes (1980) suggests this formation (and correlatives) were deposited, then exposed as the Aurukum Surface in the earliest (Bulimba Cycle) of three cycles of erosion, deposition and weathering that shaped this basin during the Tertiary. More generally, Idnurm and Senior (1978) have proposed that western Queensland underwent extensive deep weathering during the Late Oligocene. Revisions to the Australian apparent polar wander path suggest a Miocene age for this weathering cycle (Idnurm 1985, 1986).

7.7.2 *Palaeobotany*

Palaeobotanical trends in southern and central regions reflect the immediate or delayed but ecologically opposed effects of background warming associated with the rapid northward drift of the continent, and global cooling and strengthening of equator-to-pole thermal gradients following the thermal isolation of Antarctica (Macphail *et al.* 1994). Whether the same is true for northern regions is unknown.

In southern Australia, a significant number of long-ranging, widely distributed taxa became extinct in the terminal Eocene. For example, a member of the peat moss family Sphagnaceae [*Stereisporites* (*Tripunctisporis*) sp.], which first appears in the Late Maastrichtian, is last recorded in the Upper *N. asperus* Zone in the Gippsland Basin. Here, and also in south-west Western Australia, central Australia and southern Queensland, palynological dominance became increasingly restricted to one or more of only four taxa: *Nothofagus* (*Brassospora*) spp., Casuarinaceae, Podocarpaceae and, less frequently, Araucariaceae. This floristic impoverishment is associated with the earliest consistent occurrence of pollen of sclerophyll trees, shrubs and herbs that are common to abundant in present-day subhumid to semi-arid vegetation.   Examples   include   the   daisy   (Asteraceae),   samphire   (Chenopodiaceae-Amarathaceae) and grass (Poaceae) families in the Oligocene, and wattles (*Acacia*) and bloodwood eucalypts (*Eucalyptus gummifera*-type) in the Early Miocene.

Oligocene-Middle Miocene pollen sequences give the impression of being characterised by fewer first appearances and extinctions than are Eocene pollen sequences although it is recognised the difference may be due to an industry focus on short-ranging or morphologically distinctive spore and pollen types. For example, many less distinctive types that may have first appeared or become extinct at this time, remain undescribed and/or their time distributions have never been systematically recorded. If correct, then Oligo-Miocene vegetation is likely to have been far more heterogeneous than is indicated by a simple comparison of correlative microfloras. A corollary is that comparisons of Oligo-Miocene microfloras may underestimate the strength of environmental gradients across the continent.

7.7.3 *Palaeoclimates*

Many Oligo-Miocene floras are difficult to date or evaluate in climatic terms for three reasons.

1.   The zone index fossil of the *Canthiumidites bellus* Zone (*Canthiumidites bellus*) has not been recorded in inland Tasmania, central Australia or Queensland and may have appeared earlier in northeastern Australia than in the Gippsland Basin. This makes it difficult to distinguish between Oligocene to late Early Miocene and late Early to Middle Miocene floras in the former regions.

2.   There is no reason to suppose that more than a moderate fraction of the Australian Oligo-Miocene flora has been preserved, except possibly in the Murray Basin and Tasmania. Moreover, if the Murray Basin record is typical of other inland regions, then community composition and presumably structure will have been shaped as much by local (edaphic) factors as by changes in regional climate.

3.   Macrofossil data from Tasmania indicate that cool climate species had begun to evolve within families that now are confined to warm temperate to tropical environments. This group includes several extinct species of *Araucaria* (Macphail *et al.* 1991). The same may be true for *Nothofagus* (*Brassospora*).

Similarly it is difficult to summarise bioclimates within most of the selected geographic regions due to strengthening temperature and rainfall gradients between coastal, inland and upland districts. Nonetheless changes in miospore dominance and the palaeodistribution of some cryptogams provide unequivocal evidence of the impact of cooling followed by temporary warming during the Oligocene-Early Miocene. Examples include the marked impoverishment of *Nothofagus* forest in the onshore Gippsland Basin during the Eocene-Oligocene transition (Upper *Nothofagidites asperus* Zone) and the re-establishment of *Lophosoria* in southeastern Australia during the Early Oligocene (Macphail *et al.* 1994). Fossil spores of *Lophosoria* (*Cyatheacidites annulatus*) indicate this large ground fern, which is now restricted to cool-cold climates in South America, reached Tasmania via trans-oceanic dispersal during or slightly before the Lemonthyme Glaciation (Macphail and Hill 1994). The fern then spread rapidly northwards throughout southeastern Australia during the Early Oligocene (*Proteacidites tuberculatus* Zone time) but is not recorded in southern Queensland until the Early Miocene (Dettmann, 1986b), due to relatively warm conditions at lower latitudes. Increasingly dry, seasonal climates explain the failure of *Lophosoria* to extend into central and north-west Australia.

Palaeo-northern Australia

Sparse pollen evidence from the Argo abyssal plain off Port Hedland hints that continental climates in north-west Western Australia were strongly seasonal (upper mesotherm-megatherm, semiarid-subhumid) although Oligocene to Early Miocene microclimates in the Pilbara region were sufficiently humid during summer months to allow *Nothofagus* (*Brassospora*) spp. and podocarps to survive along palaeochannels on the Hamersley Ranges (M.K. Macphail unpubl. data). Conditions in inland northeastern Australia appear to have been warm to hot (upper mesotherm) and seasonally very wet (perhumid) based on faunal remains and leaf impressions of subtropical-tropical rainforest species preserved in karst terrain at Riversleigh, northwestern Queensland (R.S. Hill pers. comm.).

Isotopic evidence from the Coral Sea indicates SSTs in the region increased from between 9.5-13.0^{0}C (microtherm range) in the earliest Early Oligocene to 14.5-19.5^{0}C (mesotherm range) in the Early Oligocene and reached a maximum of 20.5^{0}C (upper mesotherm) in the Middle Miocene (Feary *et al.* 1991). Floristically complex *Nothofagus* communities remained the dominant vegetation type on the western slopes of the Leichhardt Range inland of Mackay, into Early-Middle Miocene (*Canthiumidites bellus* Zone Equivalent) time (Beeston 1994). This rainforest included taxa with cool temperate NLRs, e.g. *Dacrydium*, *Lagarostrobos*, *Microcachrys* and *Nothofagus* (*Lophozonia*), as well as taxa with warm temperate to subtropical-tropical NLRs, e.g. *Anacolosa*, *Archidendron*-type, Cupanieae and *Ilex*. How representative this flora and vegetation were of areas to the west in central Queensland is unclear. Further to the south, uniformly wet and relatively cool (lower mesotherm) climates allowed *Nothofagus* (*Brassospora*) spp. to become prominent during the Late Oligocene in coastal southern Queensland. Conditions became increasingly warm (upper mesotherm) and/or seasonally dry, resulting in the replacement of *Nothofagus* communities by other rainforest types during the Early to Middle Miocene. The presence of *Nypa* in Foram Zones N5-N7 marine sediments but not in Foram Zones N8-N9 marine sediments in the Capricorn Basin implies maximum warmth in southern Queensland occurred during the Early Miocene.

The combined data demonstrate that precipitation gradients across northern Australia were parallel in direction but not as strong as those of the present-day. Because warm water flow through the Indonesian archipelago was not severely constricted until the Early Pliocene (Srinivasan and Sinha 1998), it is premature to explain these gradients in terms of modern ocean current patterns or monsoonal climates associated with uplift of the Tibetan Plateau (cf. Ramstein *et al.* 1997).

Palaeo-central Australia

Nothofagus (*Brassospora*) spp. and rainforest gymnosperms remained common only in sites where the local topography can be expected to have maintained cool, humid microclimates, such as sheltered valleys in the Macdonnell Ranges, or around permanent springs. This observation, allied to lithostratigraphic evidence for the fragmentation of river systems into stagnant ponds, indicates that summer rainfall had decreased significantly or become unreliable since the Late Eocene. Nonetheless, the remains of fish, reptiles, birds and mammals in the Oligocene-Middle Miocene Tirari and Namba Formations show that climates in northern South Australia were still substantially wetter than at present (cf. Martin 1998a). Paradoxically, pollen evidence from the upper reaches of the Darling River imply climates became *effectively* wetter and/or less seasonal during the Early-Middle Miocene, allowing evergreen rainforest species to survive (or extend) along river corridors as far west as Broken Hill. Floristic impoverishment of the flora remains the strongest evidence that mean palaeotemperatures also decreased (lower mesotherm) or the annual temperature range become more extreme in central Australia during the Oligo-Miocene.

Palaeo-southern Australia

During the Oligo-Miocene, temperate rainforest dominated by *Nothofagus* (*Brassospora*) and Podocarpaceae became increasingly restricted to Tasmania and southeastern Victoria although individual *Brassospora* species such as *Nothofagidites falcatus* and members of other subgenera, e.g. *Lophozonia* (*Nothofagidites asperus*), maintained a much wider distribution across southern and eastern Australia.

1.   South-west and central southern Australia:

Oligo-Miocene microfloras from the Norseman area in south-west Western Australia closely resemble those found in central Australia and it is reasonable to assume that microclimates within deeper valleys incised into the southern Yilgarn Craton were relatively cool (lower mesotherm) and possibly uniformly wet (perhumid). Conditions in the St. Vincent Basin were similar during the Oligocene but became warmer (upper mesotherm) during the Miocene. Seasonality appears to have increased from weak in the late Early Miocene to strong in the Middle Miocene, resulting in the near complete elimination of *Brassospora* spp. from the Adelaide coastal plain. Foraminifera and mollusc faunas indicate significant warming of surface waters within the Bight during the Early Oligocene and Miocene, with maximum warmth being reached in the early Middle Miocene (McGowran and Li 1997, Li and McGowran 1997). On present indications, SSTs in the Eucla and St. Vincent Basins were warmer than in the Otway, Murray, Gippsland and Bass Basins to the east.

2.   Otway Basin

Oxygen isotope stratigraphies from the Browns Creek-Castle sections in the Torquay Sub-basin, southwestern Victoria, show that SSTs decreased by up to 7^0C, reaching a minimum value of $\sim13^0$C during the Eocene-Oligocene transition (Kamp *et al.* 1990). This was followed by a rapid warming during the Early Oligocene as circulation within Bight was effectively decoupled from the developing Circumantarctic Current.

3.   Murray Basin

Microfloras from the Murray Basin provide highly detailed records of the flora and vegetation growing in eastern South Australia, northwestern Victoria and southwestern New South Wales, but the climatic inferences are constrained by sample quality, strong edaphic control of community composition, and the potentially enormous size of the pollen source area.

However, the data are emphatic that rainfall gradients across the basin were similar in direction but not in strength to those of the present-day.

Climates in the western Murray were suboptimal for the extensive development of *Nothofagus* (temperate) or *Araucaria* (subtropical) rainforest during the Oligocene although conditions remained seasonally wetter (humid) and warmer (mesotherm range) than at present. Trends in rare thermophilous taxa suggest mean air temperatures reached maximum values during the late Early to Middle Miocene, whilst diminishing *Araucaria* and *Lagarostrobos* values imply that climates became effectively drier about the same time. Marine flooding appears to have allowed grass communities to form around the margins of the basin at a time when grasses were uncommon or absent in drier, interfluve habitats. Conditions in the central Murray Basin initially were more equable in terms of rainfall (perhumid) and mean temperatures (upper mesotherm) but became more strongly seasonal during the Miocene. Helping maintain high humidity were the marine transgression of the basin during the Early Oligocene and Late Oligocene-Middle Miocene, and rivers draining the Southeastern Highlands. The replacement of *Nothofagus* (*Brassospora*) dominated rainforest (Oligocene) by communities successively dominated by Araucariaceae (~Early Miocene) then Casuarinaceae and Myrtaceae (~Middle Miocene) is reliable evidence that conditions became effectively drier and increasingly seasonal during a period when mean temperatures were increasing elsewhere in southern Australia.

The reconstruction of Oligo-Miocene climates in the eastern Murray Basin is complicated by the influx of miospores derived from plants growing on the south-west slopes of the Southeastern Highlands. For example *Lophosoria* and *Nothofagus* (*Lophozonia*) spp. are consistently recorded in Oligo-Miocene assemblages in this sector but are rare elsewhere in the basin. The data confirm that conditions were wet (perhumid) relative to the western Murray Basin and probably cooler (upper microtherm-lower mesotherm) than the central Murray Basin. Rainfall became effectively reduced (possibly more seasonal) during the Middle Miocene. Warm temperatures and high sea level are likely to have increased orographic cloudiness, and therefore increased humidity and lower mean temperatures, at higher elevations on the Southeastern Highlands (cf. Martin 1973, 1993).

3. Gippsland Basin

Upper *Nothofagidites asperus* Zone microfloras representing the Eocene-Oligocene transition lack many of the uncommon to rare taxa found in microfloras representing the Late Eocene and Early-Late Oligocene lowland vegetation. Although the role of climatic change is blurred by a major fall in global sea levels, very high relative abundances of *Nothofagus* (*Brassospora*) spp. confirm that conditions remained wet to very wet (perhumid) throughout the year. Accordingly, the most ecologically convincing explanation for the observed floristic impoverishment is that mean temperatures decreased catastrophically during the Eocene-Oligocene transition. If correct, then Upper *Nothofagidites asperus* Zone microfloras are contemporary with the Lemonthyme Glaciation of northwestern Tasmania and development of the Circumantarctic Current. Subsequent developments such as the re-appearance of species with warm temperate-subtropical NLRs in the onshore Gippsland Basin, point to gradual warming during the Early Oligocene-Early Miocene (*Proteacidites tuberculatus* Zone). Maximum temperatures (mesotherm range) occurred late in the Early Miocene (early *Canthiumidites bellus* Zone time). Conditions remained uniformly very wet (perhumid) but rainfall may have become more seasonal during the Middle Miocene, based on the decline in *Nothofagus* (*Brassospora*) spp. relative to sclerophyll taxa such as Myrtaceae and Proteaceae. Runoff remained adequate to support *Lagarostrobos* swamp forests and herb-dominated wetlands into Late Miocene time.

4.   Northern New South Wales

Microfloras from the Northern Tablelands and adjacent slopes indicate that mean annual rainfall was sub-optimal (humid) for *Nothofagus* except where orographic uplift of moist air from the Tasman Sea maintained uniformly wet (perhumid) conditions. The upslope increase in the relative abundance of *Nothofagus* (*Lophozonia*) spp. and other cool temperate rainforest taxa indicates mean annual temperatures decreased from lower mesotherm on the western slopes of the Northern Tablelands to upper microtherm in deeper valleys and on the summit plateaux. Conditions on the coastal plain near Taree to the south are likely to have been warmer (upper mesotherm) and more seasonal although summer rainfall was adequate to support palms in a form of araucarian (dry) rainforest.

5.   Southern New South Wales

Rainforest communities in sheltered areas at high elevations on the Southeastern Highlands were dominated by *Nothofagus* (*Brassospora*) spp. throughout the Oligo-Miocene despite a variable, but overall increasing sclerophyll component. Conditions here and at lower elevations on the southwestern flanks of the highlands and the coastal plain to the east remained wet to very wet (humid-perhumid) during the Oligocene-Early Miocene but became too dry to support extensive *Nothofagus* (*Brassospora*) stands in the Middle Miocene. Temperatures remained possibly within the lower mesotherm range but may have become less equable over the same period. A late Early to early Late Miocene (*Canthiumidites bellus* Zone) sequence at Little Bay near Sydney preserves a fossil leaf of a subtropical mangrove (*Brugiera*) as well as marine dinoflagellates and abundant *Nothofagus* pollen. If correctly interpreted (Pickett *et al*. 1997), the site provides compelling evidence that conditions on the central coast of New South Wales were warm (upper mesotherm) and uniformly wet (perhumid) during the Middle Miocene thermal maximum although it is recognised that this interpretation also requires that some *Brassospora* and *Lophozonia* ecotypes were able to tolerate atypically warm conditions.

6.   Northern Tasmania

Macrofossils and microfossils provide a discontinuous record of the flora and vegetation lining rivers flowing onto and across the Bassian Plain during the Oligo-Miocene. Only one site (Fossil Bluff) possesses independent age control (Early Miocene). Cryptogam and gymnosperm floras are diverse, but the *Nothofagus*-dominated angiosperm component is distinctly impoverished, and taxa with warm temperate to subtropical NLRs are rare, compared to correlative microfloras in mainland southeastern Australia. Common macrofossils include Cunoniaceae and Lauraceae leaves. The combined data indicates conditions were relatively cool (upper microtherm) and possibly uniformly wet (perhumid).

7.   Central Plateau of Tasmania

Microfloras preserved in palaeochannel deposits on and below the northwestern margin of the Central Plateau are unique in Tasmania in that their ages can be constrained by K/Ar dating of associated basalt flows. The oldest Oligo-Miocene flora found so far is associated with till deposited possibly during the earliest Oligocene Lemonthyme Glaciation. Despite the glacial context, the only palaeobotanical evidence for cold (lower microtherm) conditions is the high diversity of cryptogams and gymnosperms relative to angiosperms, and virtual absence of microfossil taxa with warm temperate to subtropical NLRs. Palynological dominance and foliar physiognomic analysis (Carpenter *et al*. 1994a) indicate mean annual temperatures at Cethana on northwestern margin of the Plateau were within the upper microtherm range (~12^{0}C) during the Oligocene. Conversely temperatures at Monpeelyata on the eastern

margin of plateau were cooler (~7^{0}C) during the Early Miocene. High-grade (V) fungal germlings imply local climates were uniform and very wet (perhumid).

7.8. Time Slice T-5. Late Miocene-Pliocene [11.2-1.78 Ma]

Zones: *Monotocidites galeatus/Cingulatisporites bifurcatus* to *Tubulifloridites pleistocenicus* Zone. Informal *Oligospheridium* Zones

Figure 12: **Late Miocene (10 Ma) palaeogeography (from Veevers *et al*. 1991)**

7.8.1 *Palaeogeography*

By Late Neogene time, Australia and New Zealand were separated by about 1000 km and the Australian continent was within 1-2° of latitude of its present position relative to South-East Asia (Figure 12). New Guinea had begun to dock with a number of formerly isolated terranes in the South-west Pacific. Ongoing collision of the Australian plate against the Banda Arc affected northern Australia (and regions to the north) in two ways: (1) Folding and downwarping occurred along the northwestern and northeastern margins during the Late Miocene (Bradshaw *et al*. 1988, Muller *et al*. 2000) and it is probable that intraplate tectonism in central Australia during the Pliocene reflects the same deformation event. (2) Partial closure of the Indonesian Seaway blocked the westerly flow (Pacific Equatorial Current) of warm water from the tropical Pacific Ocean into the north-east Indian Ocean. This event has had considerable climatic consequences for landmasses bordering the Pacific Basin during the

Plio-Pleistocene. For example, the pile up of equatorial water in the western Pacific resulted in the largest expanse of warm water on the globe (Western Warm Pool) and probable intensification of the warm East Australian Current flowing south along the eastern margin of Australia (Srinivasan and Sinha 1998, Wei 1998).

Otherwise the major palaeogeographic and geomorphic changes to the Australian continent were those forced by increasing aridity and, around the margins, marine regression and transgression associated with expansion and contraction of the East Antarctic Ice Sheet. For example, some silcretes in central and western regions of Australia have been assigned a Late Miocene age [11-5 Ma]. Retreat of the sea from the Eucla Basin created the broad limestone Nullarbor Plain at about the same time. During the Early Pliocene [5-2.5 Ma], marine flooding led to the emplacement of estuarine and beach deposits in the south-west of the Murray Basin and as far inland as Hamilton in southwestern Victoria. Many ancient river systems on the Yilgarn Block and in central Australia appear to have become rejuvenated, allowing sedimentation to recommence in central Australia (Eyre Basin). Tectonic damming of the Murray Basin in the mid Pliocene [~2.5 Ma] created a mega freshwater lake known as Lake Bungunnia. Volcanic activity became confined to western Victoria and northern Queensland. Faulting along the Eastern Highlands created small but deep graben basins such as at Lake George on the Southeastern Highlands of New South Wales. During the Pleistocene glacial maxima, large areas of continental shelf were subaerially exposed, including the North West Shelf, Bass and Torres Straits, and small ice sheets and mountain glaciers developed in central and southwestern Tasmania. Many of the larger coastal plains are the result of oscillations in sea level up to 100-120 m in amplitude.

As elsewhere, the Plio-Pleistocene was characterised by alternating cycles of cool-cold, dry climates (glacial arid conditions) and more temperate (interglacial) climates and fluctuating sea-levels (Hope 1994). The Barrier Reef and continental dune fields are products of this climatic forcing. Associated phenomena include a shift from leached/acidic soils to the formation of alkaline, saline soils, widespread hillslope instability, cycles of erosion and alluviation in upland areas, and intensified aeolian activity across much of the continent during Pleistocene 'glacial arid' intervals. Deglaciation began about ca. 17 ka and was essentially complete by the Pleistocene/Holocene boundary at 10 ka B.P. By 8 ka, mean temperatures may have been 1°C higher than today. By 6 ka, sea level had stabilised around its present day position, completing the isolation of New Guinea and Tasmania.

7.8.2 *Palaeobotany*

From the minimal evidence preserved off the North West Shelf and in palaeochannels of the Victoria River in the Northern Territory, it seems likely that the Late Neogene vegetation in northwestern Australia was not dissimilar to the present day mosaic of tropical evergreen rainforests, semi-deciduous (monsoonal) rainforests, sclerophyll woodlands, semi-arid shrublands and arid grasslands. This was not the case in southern or northeastern Australia where some tree genera that had been prominent in the Palaeogene-Early Neogene rainforests, survived in local refugia into Plio-Pleistocene time. Examples occur in southwestern Tasmania, Yallalie in south-west Western Australia, Daylesford in the Central Highlands of Victoria, the Southeastern Highlands of New South Wales, and the Atherton Tableland in northeastern Queensland.

Late Neogene palaeoenvironmental change appears to have selected for taxa able to tolerate high levels of disturbance (Markgraf *et al*. 1995) and modern sclerophyll taxa, many of which first appeared in the Early Neogene, became common to dominant during the Late Neogene. Nevertheless, ecological speciation continued to occur even in cool perhumid environments. For example, a microflora from western Tasmania demonstrates that by Late Pliocene time, some species within the *Nothofagus* (*Brassospora*) group were well adapted to microtherm conditions; Early Quaternary macrofossil assemblages from the same region indicate some

fossil taxa that are morphologically indistinguishable from extant species, almost certainly represent extinct ecotypes (Macphail *et al.* 1993, Jordan 1997a).

7.8.3 *Palaeoclimates*

Australian marine records for the Late Neogene are mostly confined to the north, mainly the Coral Sea (Feary *et al.* 1991) and North West Shelf (Quilty 1994). These imply that Pliocene climates were gradually cooling, although still warm and generally stable. Palaeobotanical evidence for Late Neogene climates in Australia are reviewed by Kershaw *et al.* (1994) and Macphail (1997b). As for earlier periods within the Tertiary, the age control is of variable quality, and reconstruction of Late Neogene palaeotemperatures depends heavily on the assumption that Late Neogene species of *Araucaria* and *Agathis* had much the same temperature requirements as their NLRs in Australia. On present indications, patterns of wind and oceanic circulation became comparable to those of the present-day during the late Neogene whilst geographic variation in the relative abundance and time of extinction of the 'Tertiary rainforest' component provides a reliable indication of the direction and changing strength of climatic gradients across the continent (Macphail 1997b). Some Late Neogene vegetation types have no surviving analogue in Australia, and the same may be true of the associated microclimates.

Palaeo-northern Australia

Sparse records from northwestern Australia (Macphail 1997b) indicate that mean annual rainfall decreased from 600-1500 mm to below 600 mm and became strongly seasonal (arid-semiarid) during the Late Miocene, and this drying trend was maintained throughout the Pleistocene. Lowland climates in coastal northeastern Australia were seasonally too dry and/or warm to support *Nothofagus* (*Brassospora*) spp. during the Late Miocene although cooler (lower mesotherm) conditions allowed small populations to survive at high elevations on the Atherton Tableland into Pliocene time. On the coast, summer rainfall and mean annual temperatures were adequate (upper mesotherm, perhumid) to support a mosaic of Araucariaceae dry rainforest and angiosperm-dominated sclerophyll communities during the Late Miocene, but an increasing representation of sclerophyll taxa and hints that rainfall became increasingly seasonal (possibly monsoonal) during the Pliocene. The combined data imply that a very strong west to east rainfall gradient – from <600 mm pa to >1300 mm pa – was in existence across northern Australia by the Late Pliocene.

Palaeo-central Australia

Deep weathering during the Neogene has destroyed all organic remains except in highly fortuitous contexts. The limited data available (including macrofaunas) point to the continuing existence of permanent or semi-permanent freshwater ponds. Although vegetation is likely to have been open sclerophyll woodland or shrubland, some evergreen rainforest species survived in gallery communities lining possibly ephemeral rivers draining into the Eyre Basin. The regional climate appears to have been humid to sub-humid (below 900-1000 mm pa) and strongly seasonal.

Palaeo-southern Australia

A comparison of microfloras from southwestern and southeastern Australia confirms that rainfall increased markedly along west to east gradients during the Late Neogene; the reliability and amount of rainfall received during summer months almost certainly increased along the same longitudinal gradient as well as upslope. Similarly, a comparison of sites in northern New South Wales and Tasmania confirms the decrease in mean annual temperature with increasing latitude. Similar gradients are recorded upslope in the Northern Tablelands and Southeastern Highlands of New South Wales and were presumably also present in

mountainous regions of Tasmania. Data from individual sites that preserve vegetation histories covering all or part of Late Miocene to Late Pliocene time flesh-out the palaeoclimatic inferences. A particularly detailed record of climatic change in south-west Western Australia during the mid Pliocene warm period is preserved in a probable meteor impact crater site at Yallalie north of Perth (Dodson and Ramrath in press, Dodson and Macphail in press).

1.   Rainfall

The survival of *Araucaria*, *Agathis*, *Dacrycarpus*, *Dacrydium* and *Nothofagus* (*Brassospora*) spp. in south-west Western Australia (Yallalie), southwestern New South Wales (Lachlan Valley), southwestern Victoria (Grange Burn), southeastern Victoria (Hapuku-1), and western Tasmania (Linda Valley) is compelling evidence that conditions during the mid Pliocene were *effectively* wetter than at present although at Yallalie and possibly Grange Burn groundwater discharge may have compensated for any moisture deficit during summer. Transient upsurges in the relative abundance of semiarid plants and halophytic diatoms at Yallalie demonstrate that warm (upper mesotherm) and seasonally wet conditions within and beyond the crater were interrupted by three distinct episodes of aridification at about 2.90 Ma, 2.59 Ma and 2.56 Ma. In contrast, if stands of Araucariaceae dry rainforest at Grange Burn were wholly supported by rainwater, then mean annual rainfall will have been between 1300-2000 mm *versus* 680 mm at present. Trends in relative pollen abundance in the Murray and Gippsland Basins imply that conditions in south-eastern Australia remained relatively wet (humid) during the Early Pliocene, and rainfall became weakly to strongly seasonal during the Late Pliocene. The apparent increase in the mean annual precipitation on the Southeastern Highlands of New South Wales (Lachlan Valley, Lake George) is likely to be local, due to orographic cloudiness reducing evapo-transpiration losses.

2.   Temperature

The survival or re-establishment of Araucariaceae at Grange Burn before 4.46 Ma and Yallalie between 2.5-3.6 Ma indicates that mean temperatures in south-west and central southern Australia during the Early to Middle Pliocene were within the upper mesotherm range. If the climatic envelope for the southern-most living species of *Agathis* (*A. bidwillii*) is used as a guide, then the mean minimum temperature of the coldest month will have been about 5-10^{0}C and mean maximum temperature of the hottest month will have been about 28-32^{0}C. Slightly lower mean values are obtained if the climatic data for living *Araucaria* are used.

Because of site-specific factors, palaeotemperatures in southeastern Australia are more difficult to estimate in absolute terms. However geographic and temporal changes in the relative abundance of Araucariaceae indicate: (1) Mean values (lower mesotherm) were lower than in southwestern and central southern Australia. Cool-cold (microtherm) conditions occurred at high elevations on the Southeastern Highland and Tasmania. (2) Mean temperatures during the Early Pliocene were generally warmer (mesotherm range) than in the Late Pliocene (microtherm range).

3.   Late Neogene climatic instability

Oxygen isotope data indicate that global climates became increasingly variable (unstable) during the Late Neogene. Two sites that appear to link the aridification of Australia with increasingly variable climates are diatomites preserved in Palaeolake Bunyan on the Southeastern Highlands of New South Wales, and Yallalie (*ibid*). Taylor *et al*. (1990) propose that cyclic bedding of the Bunyan diatomite is evidence for climatic cycles with a periodicity less than or equal to 8000 years during the Late Miocene in southeastern Australia. The arid vegetation response seen at Yallalie is similar to that seen in southeastern Australia

during Late Pleistocene glacial maxima and hints that alternating cycles of high humidity and aridity analogous to Late Pleistocene glacial-interglacial conditions, had developed in southern Australia as early as the mid Pliocene.

SECTION 8 (CONCLUSIONS)

Climatic inferences for each of the eleven Cretaceous and Tertiary time slices and seven geographic regions are summarised in Tables 8a and 8b, respectively. These inferences represent highly simplified versions of the data presented in Appendices 1-3 and summarised in Sections 3-8 and must be treated as working hypotheses for reasons given in the Introduction and re-iterated below:

- Each of the seven geographic regions almost certainly encompassed a wide range of bioclimates at any particular period within the Cretaceous and Tertiary.

- Each of the eleven time slices almost certainly encompassed a number of shorter-term climatic excursions imposed upon the longer term climatic trends.

- Many of the sedimentary sequences and spot samples represent very short intervals of geological time.

- The fossil floras are strongly biased towards species living in mesic (environmentally complacent) habitats, in particular plants living on coastal plains (fluvio-deltaic environments) and along the shorelines of lakes or riverbanks. Plants living in interfluve habitats are less likely to be represented in the fossil record. The relative representation of plants that produce and widely disperse miospores in very large numbers is exaggerated in large/deepwater lakes and analogous marine environments (Neves Effect).

- The distribution of living plants (NLRs) provides only a general guide to the ecology of fossil taxa, due to the climatically forced extinction of many genera, species and ecotypes (most gymnosperms, ferns and fern allies) or adaptive radiation into novel environments (many woody angiosperms and herbs). It is emphasised that none of the NLRs of plants forming the Cretaceous to Paleocene vegetation in high to polar latitudes are adapted to prolonged winter darkness under mild (upper microtherm-lower mesotherm) conditions. Accordingly it is reasonable to assume that the ecophysiological adaptations of these taxa to thermal and water stresses were different from the presumed living relatives.

- Shorter-term trends in community composition and structure almost certainly reflect forcing factors other than rainfall and temperature. The more important of these are low light intensities during the Cretaceous and strongly leached, infertile soils during the Tertiary. The role of volcanism and wildfires is less clear although both were part of the Cretaceous and Tertiary environments.

Irrespective of the mostly low taxonomic and ecological resolution, the palaeobotanical (and related) evidence is adequate to infer qualitative long-term trends in the Early Cretaceous, Late Cretaceous and/or Tertiary climate for many regions of Australia with moderate confidence.

8.1   Results in retrospect

8.1.1   Palaeoclimatic records

- Long-term trends correspond well with changes in global climate documented elsewhere. Anomalies such as the persistence of very warm to hot conditions at high

palaeolatitudes into the late Early Eocene, are sufficiently well grounded to challenge the value of GCM estimates (predictions) at the local or regional level.

- Plant fossils and/or coldwater minerals preserved in the Perth, Eromanga and Surat Basins provide a detailed record of Early Cretaceous climates. The Gippsland and Murray Basins provide a more or less continuous palaeobotanical record of Palaeogene and Neogene climatic change in southeastern Australia although these records are of limited use in inferring climatic trends in northern Australia. Lack of suitable deposits in northern Australia is compounded by the absence of regional palynostratigraphies to date and correlate the few known fossil floras.

- Two sites have the potential to provide exceptionally detailed (world class) information on climatic change during short periods of Late Tertiary time. These are the ~34 m thick, possibly earliest, Oligocene rhythmite sequence at Lemonthyme Creek in northwestern Tasmania, and the 110 m thick mid Pliocene lacustrine sequence at Yallalie in south-west Western Australia.

8.1.2 *Palaeoclimatic gradients and seasonality*

- At no time during the Cretaceous or Tertiary have homogeneous climates existed across the length or breadth of the Australian continent, although climatic gradients have strengthened during the Late Cretaceous and Tertiary (markedly so during the Late Tertiary). It is important to note that, due to rotation of the Australian Plate about the geographic South Pole, the orientation of latitudinal gradients in temperature and rainfall will appear to have altered during the Cretaceous.

- For the same reasons, conditions on the coast are an unreliable guide to environments occurring inland or at higher elevations. The lapse rate (mean decrease in mean temperature with increasing elevation) in southeastern Australia appears to have steepened during the Late Palaeogene and Neogene.

- Seasonality during the Cretaceous was most strongly expressed via temperature and (southern and central Australia) photoperiod, not precipitation. Comparisons of the Early Cretaceous data imply that seasonal variations in temperature increased away from the coast.

- Seasonality during the Tertiary was most strongly expressed via rainfall. Comparisons of the palaeobotanical data demonstrate that seasonal variation in the distribution and reliability of rainfall has increased markedly during the Late Palaeogene and Neogene.

8.1.3 *Photoperiod*

- Photoperiod was a major forcing factor on plant community composition and structure during the Cretaceous and (southern Australia) Early Tertiary and therefore may have had an indirect influence on weathering.

8.1.4 *Temperature*

- Oxygen isotope data, glendonites and dropstones demonstrate that temperatures were below freezing during winter months; and conceptualising Early Cretaceous climates as warm is misleading despite the undoubted presence of timber-sized trees at high to

- On present indications, Early Cretaceous (Berriasian-Albian) temperatures in palaeo-southern and palaeo-central Australia were cool-cold (microtherm range). Temperatures in palaeo-northern Australia almost certainly were warmer (mesotherm range).

- Climates in palaeo-southern Australia remained cool-cold (microtherm range-lower mesotherm) throughout the Late Cretaceous. Elsewhere warming is recorded, with temperatures in palaeo-central and palaeo-northern Australia becoming warm (lower mesotherm) and very warm to hot (upper mesotherm-megatherm), respectively.

- Warming during the Paleocene culminated in maximum Tertiary warmth during the Early Eocene when upper mesotherm to megatherm temperature regimes are recorded in northwestern, central, southwestern, central southern and southeastern mainland Australia. The Paleocene-Eocene thermal maximum event (PETM) is reflected in warmer sea surface temperatures within the Australo-Antarctic Seaway but is best represented by the abrupt appearance of a tropical mangrove palm (*Nypa*) in the Gippsland Basin (palaeolatitude 62^0S) and Macquarie Harbour (palaeolatitude 66^0S) during the Paleocene-Eocene transition.

  Locally high (mesotherm range) temperatures persisted into late Early Eocene time in Macquarie Harbour and the Gippsland Basin, and into Middle-Late Eocene time in the Polda Sub-basin in south-west South Australia. Temperatures in coastal northeastern Queensland appear to have remained cool (lower mesotherm) during the Early Eocene warm period, possibly because of cool ocean currents flowing northwards along the eastern margin.

- Very warm to hot (megatherm range) temperatures persisted in northwestern Australia throughout the Middle-Late Eocene and, despite a global cooling, regional temperatures remained high throughout the Late Tertiary due to the rapid northward drift of the continent. Very warm (upper mesotherm) conditions do not appear to have developed in coastal northeastern Australia until Oligo-Miocene time.

- Temperatures in central and southern Australia began decreasing to lower mesotherm-upper microtherm values during the Middle Eocene although there is weak evidence for temporary warming in southeastern Australia during the late Late Eocene. This was followed by abrupt cooling, associated with opening of the Tasmanian Gateway and Drake Passage allowing deepwater circulation around Antarctica. Outside of Antarctica, cooling was most severe in Tasmania, where the Eocene-Oligocene transition is marked by transient glaciation (Lemonthyme Glaciation), and in the Gippsland Basin, where the event is reflected in major impoverishment of the rainforest flora. Temperatures in central southern and southwestern Australia remained relatively warm, probably due to warm water gyres within the Great Australian Bight.

- Climates in southern Australia appear to have been milder during the Early Miocene than during the Oligocene or the Middle-Late Miocene (microtherm-mesotherm range), and appear to have warmed appreciably (mesotherm range) along the southern margin during the Early Pliocene before continuing to decline during the Late

Pliocene. The warm phase correlates with the 'mid' Pliocene warm event recorded elsewhere at middle-high latitudes in the Southern and Northern hemispheres.

8.1.5 *Rainfall*

- Unlike marine microfossils, terrestrial fossil floras provide *direct* information on one of the major factors (rainfall) promoting chemical weathering. Seaways developing across Australia helped to maintain high humidity in the interior of the continent during the mid Cretaceous. Orographic effects and groundwater discharge helped maintain humid-perhumid microclimates within drying environments during the Late Tertiary.

- Apart from the Berriasian-Barremian, when climates may have been subhumid in northwestern Australia, humid to perhumid climates extended across the continent throughout Early Cretaceous time. On present indications, conditions remained wet to very wet (humid-perhumid) in central southern and southeastern Australia during the early Late Cretaceous (Turonian to Early Campanian).

- Rainfall appears to have decreased in northwestern Australia from humid-perhumid in the Late Campanian-Maastrichtian to sub-humid-humid in the Paleocene. A similar but less marked decrease is recorded in southwestern Australia. Other regions appear to have become wetter (perhumid).

- The Early Eocene thermal maximum is associated with perhumid conditions across the continent, including northwestern and central Australia where rainfall may have been strongly seasonal (possibly monsoonal). Similar conditions persisted into Middle-Late Eocene, except that rainfall in central Australia became more variable (less reliable and more seasonal) and rainfall across basins along the southern margin became more uniformly distributed.

- By Oligo-Miocene time, subhumid conditions prevailed in north-west Western Australia although conditions at higher elevations within the Pilbara region remained sufficiently wet during summer months to support temperate rainforest species. There is weak evidence for a decrease in rainfall in central and south-west Australia. Rainfall remained in the perhumid range in the south-east mainland and Tasmania but may have become less reliable or weakly seasonal.

- By the Late Pliocene, essentially modern rainfall regimes were in existence across Australia. Conditions on the Southeastern Highlands of New South Wales were effectively wetter during the mid Pliocene than now. The Yallalie site provides unequivocal evidence for three periods of aridification, at 2.9 Ma, 2.59 Ma and 2.56 Ma, in south-west Western Australia during the same interval (Middle Pliocene warm period). The vegetation response is similar to that observed during Quaternary glacial-interglacial cycles and corresponds broadly with the development of continental ice sheets in the Northern Hemisphere.

TABLE 8a: **INFERRED CRETACEOUS PALAEOCLIMATES**

Meteorological parameter	INFERRED PALAEOCLIMATE						
	North-West	North-East	Centre	South-West	central southern	South-East	Tasmania
TIME SLICE K-1: BERRIASIAN to BARREMIAN 141-115 Ma							
temperature	lower mesotherm?	microtherm range	microtherm range	lower? mesotherm	lower mesotherm	microtherm range?	no record
rainfall	humid?	humid	humid-perhumid	humid	humid	humid-perhumid	
seasonality	strong (temperature)	strong (temperature)	strong (temperature)	strong? (temp.)	strong? (temp.)	strong (temperature)	
TIME SLICE K-2: APTIAN to ALBIAN 115-97.5 Ma							
temperature	mesotherm range	microtherm range	microtherm range	lower mesotherm	microtherm range	lower microtherm	no record
rainfall	humid	humid-perhumid	humid	humid	humid-perhumid	perhumid	
seasonality	weak?	strong (temperature)	strong (temperature)	weak?	strong? (temp.)	strong (temperature)	
TIME SLICE K-3: CENOMANIAN 97.5-91 Ma							
temperature	upper mesotherm	mesotherm range	upper microtherm	lower mesotherm?	micro-mesotherm	micro-mesotherm	no record
rainfall	perhumid	humid	humid	subhumid?	humid	humid	
seasonality	strong? (rainfall)	strong? (rainfall)	weak (temperature)	strong? (rainfall)	weak (temperature)	weak (temperature)	
TIME SLICE K-4: TURONIAN to SANTONIAN 91-83 Ma							
temperature	upper mesotherm?	no record	no record	no record	lower mesotherm?	upper microtherm	microtherm range
rainfall	humid-perhumid				humid-perhumid	humid-perhumid	humid-perhumid
seasonality	strong (rainfall)				±uniform (rainfall)	±uniform (rainfall)	strong (temperature)
TIME SLICE K-5: EARLY CAMPANIAN 83-70 Ma							
temperature	upper mesotherm	no record	no record	no record	micro-mesotherm	microtherm range	no record
rainfall	humid-perhumid				humid	perhumid	
seasonality	strong? (temp.)				weak? (rainfall)	±uniform (rainfall)	
TIME SLICE K-6: LATE CAMPANIAN to MAASTRICHTIAN 70-65 Ma							
temperature	meso-megatherm	no record	no record	no record	upper microtherm	upper microtherm	upper microtherm
rainfall	no record				humid	humid	humid
seasonality	strong (rainfall)		variable (rainfall)	strong (rainfall)	strong (rainfall)	strong (rainfall)	strong (rainfall)

TABLE 8b: **INFERRED TERTIARY PALAEOCLIMATES**

Meteorological parameter	INFERRED PALAEOCLIMATE						
	North-West	North-East	Centre	South-West	central southern	South-East	Tasmania
TIME SLICE T-1: PALEOCENE 65-54.8 Ma							
temperature	upper mesotherm	lower mesotherm	mesotherm range #	upper mesotherm *	lower mesotherm	lower mesotherm	upper microtherm
rainfall	subhumid-?humid	humid-perhumid	humid	subhumid-humid	humid-perhumid	humid-perhumid	perhumid
seasonality	strong (rainfall)	weak (rainfall)	weak (rainfall)	strong (rainfall)	weak (rainfall)	±uniform (rainfall)	±uniform (rainfall)
TIME SLICE T-2: EARLY EOCENE 54.8-49 Ma							
temperature	megatherm range *	mesotherm range	upper mesotherm	upper mesotherm *	upper mesotherm *	upper mesotherm *	mesotherm range *
rainfall	perhumid	humid-perhumid	perhumid	perhumid	humid-perhumid	humid-perhumid	perhumid
seasonality	strong (rainfall)	weak (rainfall)	weak (rainfall)	strong (rainfall)	weak (rainfall)?	weak (rainfall)	weak (temperature)
TIME SLICE T-3: MIDDLE to LATE EOCENE 49-33.7 Ma							
temperature	megatherm range *	mesotherm range *	mesotherm range	mesotherm range	mesotherm range *	mesotherm range	micro-mesotherm
rainfall	humid-perhumid	perhumid	humid-perhumid	humid-perhumid	perhumid	perhumid	perhumid
seasonality	strong (rainfall)	weak (rainfall)	variable (rainfall)	variable (rainfall)	weak (rainfall)	weak (rainfall)	±uniform (rainfall)
TIME SLICE T-4: OLIGOCENE to MIDDLE MIOCENE 33.7-11.2 Ma							
temperature	megatherm range	mesotherm range *	lower mesotherm	lower mesotherm	lower mesotherm	mesotherm range	microtherm range
rainfall	subhumid-semiarid	perhumid	humid	subhumid-humid	perhumid	humid-perhumid	perhumid
seasonality	strong (rainfall)	weak (rainfall)	variable (rainfall)	variable (rainfall)	weak (rainfall)	variable (rainfall)	±uniform (rainfall)
TIME SLICE T-5: LATE MIOCENE to PLIOCENE 11.2-1.78 Ma							
temperature	megatherm range	upper mesotherm	lower mesotherm	mesotherm range	mesotherm range	mesotherm range	microtherm range
rainfall	subhumid-semiarid	humid-perhumid	subhumid-humid	subhumid-humid	subhumid-semiarid	humid-perhumid	perhumid
seasonality	strong (rainfall)	strong (rainfall)	strong (rainfall)	strong (rainfall)	strong (rainfall)	weak (temperature)	strong (temperature)

possibly Early Eocene
* *Nypa* present

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8.2   Results in prospect (recommendations)

Plants and animals, and the communities within which they co-exist, are evolutionary responses to climate, not organic equivalents of the thermometer or rain-gauge, and this will have been true of their Cretaceous and Tertiary predecessors. Similarly, many of the *caveats* identified in this and an earlier review (Macphail *et al*. 1994) are unlikely to be resolved in the near future. Nevertheless the scale of this review does suggest ways in which palaeobotanical evidence can be better mined to meet CRC-LEME objectives.

8.2.1   *Samples*

The review of old exploration reports and borelog data held by the State geological surveys indicates that, contrary to expectation, thin carbonaceous units are preserved in subcrop in many sub-humid, semi-arid and arid regions of the continent. However in New South Wales, and presumably in other states, much of the conventional core that is archived in core libraries is Palaeozoic or older. This problem is exacerbated by deep-weathering of much of the Cretaceous and Tertiary regolith and, with few exceptions, outcrop samples submitted for palynostratigraphic dating by CRC-LEME have proved to be barren, even though potentially fossiliferous intervals occur below the weathering front in the same time-rock unit.

Unlike in the 1960s-1980s, the current emphasis on geophysical and remote sensing (GIS) techniques makes it increasingly unlikely that routine stratigraphic holes will be drilled to resolve geological problems. Nonetheless, this short-fall can be circumvented in at least four ways to extend the existing palaeobotanical database:

1.   Improved networking

Numerous boreholes continue to be drilled in many areas for infrastructure projects such as bridges, roads and groundwater, but organic sediments brought up to the surface almost always are discarded by the drillers because "no-one knew anyone would be interested in them" [comment to author, 1995].

Formal networking with geologists employed by the State authorities responsible for groundwater and rivers, mining, and private sector borehole drilling services arguably provides the best alternative means of recovering fossiliferous sediments in inland Australia (cf. Macphail 1997b). One example of the benefits of such networking occurred in the mid 1980s when an interested workman bulldozing roads on the Central Plateau for the Forestry Commission of Tasmania uncovered the world class Tertiary macrofossil deposit at Little Rapid River (R.S. Hill pers. comm.).

2.   Analysis of RAB cyclone samples

Analyses made in the course of this study have shown that well-preserved microfloras can be recovered from medium to dark grey dust samples collected from the cyclone during RAB drilling, arguably the cheapest and most commonly used form of drilling in hard-rock mineral exploration at present. Because the cover beds are often deeply weathered, the only contaminants found in these other types of ditch cuttings samples are easily recognised modern pollen types (Macphail 1999).

3.   Palaeontological collections

Blocks of sediment encasing Cretaceous and Tertiary macrofossils often preserve diverse plant microfloras. The State geological surveys, museums, and some former technological

colleges usually hold extensive collections dating back to the mid nineteenth century. In some instances, the institutional holdings may be the *only* fossiliferous material to survive, due to shaft collapse, or because weathering over the past century has destroyed the microfossil content of sediments exposed in the mine or quarry face. Examples of both occur in the deep lead gold fields in New South Wales and Victoria (M.K. Macphail pers. observ.).

4.   Early journals

Nineteenth and early twentieth journals published by the Royal Societies often include comment on fossil specimens 'tabled' by members. A search through nineteenth century issues of the *Papers and Proceedings of the Royal Society of Tasmania* has resulted in the re-discovery of important Tertiary macrofossil sites in Tasmania (G. Jordan pers. comm.).

8.2.2 *Improved taxonomy*

Unlike macrofossil taxonomy, which is thriving thanks to the work of R.S. Hill and colleagues at the Universities of Adelaide and Tasmania, the taxonomy of Cretaceous and Tertiary microfossils is living on over-draft from work undertaken on the southern margin basins in the 1960s to 1970s (C.B. Foster pers. comm.). At present, formally described microfossil species are complemented by a sizeable number of informal (manuscript) species that may or may not be in wide use, and the existence of many more undescribed species is documented only by photomicrographs held in private archives maintained by palynostratigraphic consultants, e.g. Mary Dettmann, Clinton Foster, Robin Helby, Mike Macphail, Helene Martin and Alan Partridge.

These private archives potentially allow bioclimatic and chronostratigraphic connections to be made between widely separated sites, or sites analysed many years apart. For example the undescribed spore of an extinct possibly aquatic fern, first recorded by E.M. Truswell in a Late Cretaceous microflora from central Australia in the early 1970s, was found in a probable correlative microflora from the Hamersley Ranges by M.K. Macphail in 1999.

Continuing *systematic* documentation of these and other undescribed taxa is essential to reconstructing geographic patterns in the Cretaceous and Tertiary flora, vegetation and climate in inland Australia; and developing local spore-pollen based palynostratigraphies for northeastern and northwestern Australia, which can be tied to the independently dated marine sequences.

8.2.3 *Improved processing*

Plant microfossil assemblages are usually biased by processing and therefore may give a false impression of past floras, vegetation and past climate. For example, the dominant pollen types in many Neogene assemblages (Cunoniaceae, Elaeocarpaceae and/or some Myrtaceae) are <15 μm in maximum diameter and therefore often lost by the two techniques routinely used to concentrate palynomorphs of higher biostratigraphic value (short-spinning, micro-sieving).

For this reason it is recommended that each sample of organic material submitted for microscope analysis is processed to provide: (1) unfiltered organic debris recovered from the sample by treatment with hydrofluoric acid (kerogen strew mount); (2) unoxidised organic debris that has been filtered through 5 μm and 10 μm sieve cloth (unoxidised, filtered strew mounts); and (3) oxidised organic debris that has been filtered through 5 μm and 10 μm sieve cloth (oxidised/filtered strew mounts).

The 10 μm sieved, oxidised extract minimises the time required to determine the age of the sample (using larger palynomorphs) whilst the other extracts provide the quantitative information required to make reliable estimates of the palaeovegetation and climate.

8.2.4 *Improved age control*

Only rarely can fossil assembles in inland Australia be directly dated using geochronometric techniques. At present, macrofloras and some local faunas are directly or indirectly dated via criteria established for basins hundreds to thousands of kilometres away.

This review indicates that fossil pollen and spores provide the only cheap, moderately reliable means of dating terrestrial fossil floras and faunas across the range of depositional environments found in Australia. The existing data make it highly likely that local palynostratigraphies can be synthesised from disparate short sequences and spot samples for the various regions in inland southern, central and northern Australia. An alternative is to use systematic changes in regional climate as a basis for developing *eco-stratigraphic* criteria to date continental fossil assemblages.

8.2.5 *Application of Quaternary quantitative (objective) analytical techniques*

Three of the objective (statistical) techniques used by to capture palaeoclimatic information for the Late Quaternary are likely to be applicable to Cretaceous and Tertiary microfloras. These are *Isopollen mapping*, *Principal components analysis* and *Biome analysis* respectively.

1.   Isopollen maps

Isopollen mapping was developed in North West Europe and North America as a way of visually tracking the climatically forced expansion of individual species and vegetation types during the Late Pleistocene and Holocene (Birks and Saarnisto 1975, Bernabo and Webb 1977, Birks and Birks 1980). The method is analogous to the preparation of weather maps in that lines linking sites with similar relative pollen values can be used to reconstruct patterns in past vegetation and climate. An example is the 1998 video clip (SiteSeer) showing the postglacial expansion of the major tree taxa across North America (http://www.ngdc.gov/paleo/siteseer.html).

Essential requirements are statistically reliable quantitative data based on a minimum of 200-250 counts, good site coverage across the region of interest; and reliable age control.

On present indications, these conditions are best met for the Early Cretaceous where sites preserving diverse microfloras can be found across much of the continent. For example, quantitative analysis of ~1000 microfloras (about 2 years work using processed material housed at the various State geological surveys) would allow isopollen maps to be prepared for all palynostratigraphic subdivisions of Berriasian to Albian time. By comparing isopollen maps of commonly occurring Cretaceous taxa against, for example, the changing position of Cretaceous shorelines, it should be possible to *objectively* infer palaeoecological relationships. These in turn provide a method for tracking climatic developments during the Early Cretaceous.

2.   Principal components analysis (PCA)

This technique is widely used in ecological and palaeoecological research to identify groups of associated or correlated taxa (Birks and Birks 1980, Birks and Gordon 1985). The appropriate routine is included in statistical software used to generate Late Quaternary pollen histograms, for example *Tilia*.

PCA can be useful in the reconstruction of both Cretaceous and Tertiary palaeoclimates in two ways. Firstly, it can help link taxa whose ecology is uncertain with taxa whose climatic preferences have been established by other means. Secondly, it can help identify areas with similar bioclimates by identifying recurrent groups of taxa.

3.   Biome analysis

The biomization method was developed to resolve problems arising from direct comparisons of Holocene and Quaternary palaeoecological data from very widely separated sites. Rather than focus on shared taxa (if any), the technique utilises the well-known phenomenon of functional convergence in the ecophysiology of unrelated plants growing in similar physical environments. This convergence may be expressed at the molecular or whole plant level. Examples are the evolution of the C_4 photosynthetic pathway in unrelated plant families occupying drier, warmer habitats and the evolution of a drip-tip on the leaves of many unrelated rainforest angiosperms.

The method involves: (1) assigning plants to plant functional types (*PFTs*); (2) defining biomes in terms of the PFTs of the constituent taxa; and (3) using observed bioclimatic relationships to reconstruct patterns of climate at a given time in the past. Mathematically, the method involves calculating the affinity (*affinity score*) of each fossil flora to each biome defined by PFTs and assigning the flora to the biome (and climate) with which it has the highest affinity (references in Prentice and Webb 1998). The formula used for Holocene microfloras combines presence/absence and relative abundance data weighted by threshold values, which take account of the different representation of the parent plants by pollen or spores. Prentice and Webb (1998) discuss how the technique can be applied to the mid Holocene. Horrell (1991) has used an analogous approach to reconstruct global climatic zones for the Maastrichtian.

Holocene floras are a special case in that almost all microfossil taxa can be assigned to plant functional types in the certain knowledge that the fossil plants possessed the same ecophysiological adaptations as living representatives. Only ~200 of the >300 described Tertiary fossil species have presumed NLRs whilst many more undescribed taxa have not been systematically recorded because of small size, simple morphologies and lack of (known) biostratigraphic value. Nevertheless sites that preserve both plant macrofossils and microfossils confirm the *general* applicability of modern relationships (phylogenetic and ecophysiological) to Tertiary situations (Macphail *et al.* 1994), even if this may not be the case for the earlier Cretaceous floras. Accordingly, with appropriate resources it would seem possible to develop a mathematical model along the lines of Prentice and Webb's (1998) formula, which could assign Tertiary and possibly Late Cretaceous floras to biomes defined by PFTs. Logically, any formal quantitative analysis would be empirical and begin with either the Pliocene microfloras, because of the significant number of taxa with moderately well known biome relationships, or the Oligo-Miocene macrofloras, because their ecophysiological adaptations to primary forcing factors such as humidity can be directly observed.

The method reduces often very large numbers of fossil taxa into more manageable eco-physiological types using the basic physiognomic characteristics of life-form, leaf-form and

phenology. The method also provides an ecological basis for comparing plants from different regions and times without having to assume phylogenetic relationships (cf. NLR methodology). However, like many modern plants, fossil taxa are likely to have occurred in more than one biome. In almost all instances the abundance of the parent plants will have differed from one biome to another but this may or may not be reflected by pollen abundance expressed in relative terms. Also, at least one major biome (Austral Conifer Forest) is extinct and, during the Cretaceous and Early Tertiary, ferns may have dominated niches that are now dominated by herbs such as grasses.

Palaeoecological research is often criticised for a "suck-it-and-see" descriptive approach that is at variance with the hypothetico-deductive methodology, which underpins the physical sciences. The generation of quantitative data and the application of innovative statistical techniques developed for the Quaternary seems to provide an opportunity to objectively mine the extant palaeobotanical database in ways that may assist end-users such as CRC-LEME.

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APPENDIX 1

CRETACEOUS DATA

1. TIME SLICE K-1

Age Range: **Berriasian – Barremian [141-115 Ma]**

Zones: *Cicatricosisporites australiensis* to *Foraminisporis wonthaggiensis* Zones (eastern)/*Biretisporites eneabbaensis* Zone (western) *Pseudoceratium iehensis* to *Muderongia australis* Zones

1.1 Macrofloras

1.1.1 *North-West Australia*

The Early Cretaceous possibly Necomian Bauhinia Downs Flora from the Northern Territory is dominated by bennettitaleans.

Inferred climate

The flora is indicative of overall humid conditions. Fronds of one species (*Otozamites bengalensi*s) are illustrated in White (1986), who suggests conditions were subject to occasional aridity. Temperatures are presumed to be at the lower end of the mesotherm range due to the moderate palaeolatitude (~ 60^0S).

1.1.2 *North-East Australia*

1. North-east Queensland

The ginkgophyte *Ginkgoites australis* is recorded in probable Necomian coal measures in the Mt. Morgan-Stanwell district, west of Rockhampton, Queensland (McLoughlin 1996). This, and the central Australian records of ginkgophytes (see below), appear to pre-date its first occurrences in Victoria.

2. Laura Basin

Macrofossils of several cryptogams and corystosperms (primitive seed plants first described from Triassic beds in South Africa) are present in the Laura Basin. The Dalrymple Sandstone flora from the same basin is now considered to be Jurassic.

Inferred climate

The data indicate conditions were humid. Temperatures are likely to have been seasonally cool-cold (microtherm range) due to the location of northeastern Queensland on the palaeo-southern margin at about palaeolatitudes 70-80^{0}S.

1.1.3 *Central Australia*

A number of formations previously regarded as Early Cretaceous, are now considered to be from the Late Jurassic, for example the Hooray sandstone (Eromanga Basin). The associated macrofloras are dominated by bennettitalean fronds and conifer twigs, but otherwise do not share any other taxa with the Cretaceous floras from Western Australia (S. McLoughlin pers. comm.).

Necomian plant impressions, which are preserved in silcrete (Algebuckina Sandstone) in the Eromanga Basin, imply that brachyphyll araucarians (*Brachyphyllum*) were canopy tree taxa.

Pteridosperms, cycads, bennettitaleans, ferns and fern allies, including isoetalean lycophytes, formed the understorey. Necomian macrofossil collections from the Surat Basin indicate conifers and ginkgophytes formed possibly open forests and woodlands. Here, the understorey included relations of the horsetails (sphenopsids), as well as pteridosperms, and ferns.

Inferred climate

The data indicate that conditions were humid. Temperatures are presumed to have been seasonally cool-cold (microtherm range) due to the relatively high palaeolatitudes and intraplate location. However the only firm evidence that temperatures fell below freezing point during winter is geological (see below).

1.1.4 *South-West Australia*

Abundant Early Cretaceous macrofossils occur in the Collie Basin (Nakina Formation), Perth Basin (Bullsbrook and Leederville Formations), Carnarvon Basin (Birdrong Sandstone and Nanutarra Formation), Canning Basin (Broome Sandstone and Callawa Formation) and Officer Basin (Cronin Sandstone) (references in McLoughlin 1996, McLoughlin and Hill 1996). The age of these formations vary but most pre-date the Aptian (Fig. 2 in McLoughlin 1996). Shared taxa suggest that many of the Western Australian macrofloras are correlatives of the Necomian (Zone B) macrofloras of southeastern Australia.

Brachyphyll araucarians and podocarps appear to have been the dominant tree taxa. Subcanopy taxa included bennettitaleans (abundant), pteridosperms, diverse ferns and fern allies. Ferns included Gleicheniaceae, Osmundaceae and a possible Dipteridaceae (a family whose one living representative is confined to tropical wet sclerophyll forest in northeastern Queensland). Fern allies included isoetaleans. The macrofloras differ from those in southeastern Australia in that ginkgophytes, equisetaleans and bryophytes had become extinct by the end of the Necomian.

Inferred climate

Climates were humid throughout the region whilst mean temperatures are presumed to have been relatively warm, possibly lower mesotherm, due to the relatively low palaeolatitude ($\sim$47-50^{0}S). Strong seasonal contrasts in climate are indicated by prominent growth rings in fossilised conifer wood preserved in Carnarvon and Perth Basins. Fungal growth, which also may have been seasonal, is evident in wood from the Carnarvon Basin (McLoughlin *et al*. 1995a).

1.1.5 *Centra southern Australia*

 No known record.

1.1.6 *South-East Australia*

Early Cretaceous floras preserved in the Otway and Gippsland Basins, then located on the palaeo-western margin, are amongst the best studied in Australia (references in Douglas and Williams 1982, Douglas 1994).

Macrofossils assigned to the Tithonian-Berriasian (Megafloral Zone A of Douglas 1969) in the Otway Basin are dominated by bennettitaleans, with sphenopsids forming the understorey. Significantly, a number of the bennettitalean leaf-forms are not found in coeval Western

Australian assemblages, located on the palaeo-northern margin. This provincialism is likely to reflect latitudinal gradients in climate.

Zone B macrofloras (Necomian-Barremian) are defined by the first appearance of *Ginkgoites* although the climatic significance of this, if any, is unclear. Associated fossils suggest ginkgophytes were a sub-canopy tree in podocarp-dominated forests. Other understorey and ground taxa included corystosperms, cycads, cycadeoids and pteridosperms/Pentoxylales.

One of the latter (*Taeniopteris daintreei*) was deciduous, and its leaves are the most commonly preserved Early Cretaceous macrofossils in Victoria (Douglas 1986). Their large leaf size (average length 15 cm) implies high rainfall. Fossil wood displays distinct growth rings.

Inferred climate

Until relatively recently, Early and Late Necomian climates were inferred to have been subtropical (humid, stormy) and warm temperate, respectively (Douglas 1986, 1994). These reconstructions have been challenged by Rich *et al*. (1988) who argue that the plant (and faunal) assemblages are more consistent with seasonally cool-cold (lower mesotherm) and humid conditions due to the high palaeolatitude ($\sim70^{0}$S).

1.2   Microfloras

Relative abundance data supports the macrofossil evidence that the Berriasian-Barremian vegetation was a form of Austral Conifer Forest dominated by araucarians (*Araucariacites*, *Balmeiopsis*) and podocarps (*Microcachrydites*, *Podocarpidites*). Cheirolepidaceae conifers appear to have been restricted to areas adjacent to the coasts.

Understorey taxa included pteridosperms (*Alisporites*, *Vitreisporites*), cycadophytes, ginkgophytes and bennettitaleans. Prominent ferns are Osmundaceae (*Baculatisporites*, *Osmundacites*), Cyatheaceae (*Cyathidites*, *Dictyophyllidites*), Dicksoniaceae and/or Matoniaceae (*Matonisporites*, *Dictyophyllidites*). Fern allies (sphenopsids, isoetaleans) are considered to have formed reed-beds along streams (references in Dettmann *et al*. 1992, Dettmann 1994). Some of these cryptogams were sclerophyllous and/or deciduous and appear to have been adapted to seasonally very cold and/or dry habitats.

1.2.1   *North-West Australia*

1.   North West Shelf

Changes in the lithology of sediments dredged from the continental shelf reflect an increasing marine influence on the northwestern margin during the Late Triassic and Early Cretaceous. However the associated Valanginian-Aptian palynofloras preserve little information on the terrestrial flora except to confirm the presence of schizaeaceous ferns (*Anemia*) and brachyphyll araucarians (Burger 1994).

Inferred climate

The limited data hint at humid conditions in coastal districts but provide no evidence of temperature regimes.

1.2.2   *North-East Australia*

No known record.

1.2.3 *Central Australia*

1. Eromanga and Surat Basins

Cicatricosisporites australiensis-Foraminisporis wonthaggiensis Zone microfloras preserved in the Eromanga and Surat Basins have been studied by Dettmann (1963) and Burger (1973, 1980, 1988). Commonly occurring taxa are cryptogams (Osmundaceae, Gleicheniaceae, Cyatheaceae, Lycopodiaceae, *Sphagnum*) and pteridosperms (*Alisporites*, *Vitreisporites*). Gymnosperm pollen are relatively rare but include Araucariaceae, Cheirolepidaceae and Podocarpaceae.

Dettmann *et al*. (1992) have concluded that the Eromanga Basin supported araucarian-podocarp dominated forests and woodlands (Austral Conifer Forest) in which the understorey was dominated by tree-ferns, ferns, lycopods and mosses. *Sphagnum* spores are a persistent to occasionally common element, indicating the development of peatmoss bogs in the south of the basin.

Correlative microfloras preserved in the western Surat Basin also point to the presence of Austral Conifer Forest although araucarians and podocarps are uncommon relative to pteridosperms, ferns (Cyatheaceae, Osmundaceae) and some fern allies (lycopods). *Sphagnum* and dinoflagellates occur only sporadically.

Inferred climate

The data point to humid to wet conditions. Plant growth is likely to have been limited by low light intensities and temperatures during winter months although increased cryptogam representation in the western Surat Basin hints that conditions closer to what was the palaeo-southern margin may have been more equable than those closer to the interior of the continent. Marine transgressions increased during the period but it is unclear from the palaeobotanical evidence that climates during the Berriasian were any more equable (less continental) than during the Valanginian-Barremian. However conditions were seasonally cold (microtherm range) and wet (humid-perhumid) to support the development of *Sphagnum* bogs.

1.2.4 *South-West Australia*

Early Cretaceous sequences are routinely intersected in petroleum exploration wells but the only systematic overviews of Berriasian-Barremian (*Biretisporites eneabbaensis* Zone) palynofloras comes from the Perth Basin (Backhouse 1988), and Jerboa-1, a well drilled in the Eyre Basin, western Bight (Powis and Partridge 1980). These sites were located at the extreme western end of the palaeo-northern margin between palaeolatitudes 50-54^{0}S.

1. Perth Basin

Interpretation of the Perth Basin microfloras is complicated by the high degree of variation between closely spaced sites. Cryptogams are usually abundant and diverse. Araucarians and podocarps are frequent to common (5-30%) but less abundant than in the Late Jurassic. Cheirolepidiacean conifers are rare (<2%). Araucariaceae (*Araucaria*, *Callialasporites*), Podocarpaceae (*Podocarpidites*), Cyatheaceae (*Cyathidites*) and lycopods (*Retitrileles*) are listed as being common to abundant in *B. eneabbaensis* Zone palynofloras in Jerboa-1.

2.   Officer Basin

Dinoflagellates indicate that Early Cretaceous palynofloras from the Samuel Formation, Officer Basin, are possible Barremian to Early Aptian (cf. Kemp 1976a, Backhouse 1988). Podocarps (*Microcachrys*, *Podocarpus-Prumnopitys*) are abundant, cryptogams are common, cheirolepidiacean conifers are uncommon and cycads are rare.

Inferred climate

The combined data confirm humid conditions extended along (and inland from) the palaeo-northwestern margin. Temperatures are presumed to have been equable (lower mesotherm) relative to regions at higher palaeolatitudes or within the centre of the continent due to the marine influence.

1.2.5   *Central southern Australia*

1.   Southern Eromanga Basin

Latest Jurassic to basal Valanginian microfloras from the Ooldea Range district in south-west South Australia, are dominated by spores (Alley *et al*. 1996). Major taxa include lycopods (19%), Osmundaceae (18%), and Cyatheaceae (13%). Gymnosperms are uncommon with *Microcachrys* (6%), Araucariaceae (9%) and Cheirolepidaceae (5%) being the only prominent taxa.

2.   Duntroon Basin

Foraminisporis wonthaggiensis Zone assemblages occur in the Troas-1 and Vivonne-1 wells, drilled in the offshore Duntroon Basin, eastern Bight (Morgan and Hooker 1993a, 1993b).

Dominant taxa are Cyatheaceae (*Cyathidites*) and pteridosperms (*Alisporites*). Common taxa include lycopods (*Ceratosporites/Nevesisporites*, *Retitriletes*), ferns such as Osmundaceae (*Osmundacites*), and a podocarp (*Microcachrys*).

Inferred climate

Both areas were located at a palaeolatitude of ~65^{0}S, close to or within the developing Australo-Antarctic Rift System, which then formed the palaeo-western margin. The high relative abundance of cryptogams to gymnosperms is atypical and it is possible that the mild conditions (humid, lower mesotherm) reflect the presence of freshwater lakes or marine environments to the palaeo-north, in the Valanginian.

1.2.6   *South-East Australia*

1.   Otway and Gippsland Basins

Microfloras preserved in the Gippsland and Otway Basins have been a focus for palynostratigraphic research for the past ~40 years (Dettmann 1963, Wagstaff and McEwen Mason 1989) but few quantitative data are available for the Berriasian to Barremian.

Inferred climate

Dettmann *et al*. (1992) have concluded that rift valleys in southeastern Australia were more densely vegetated (possibly forested) than the Eromanga and Surat Basins despite the similar

palaeolatitude (~70^{0}S). If correct, then climates will have been wet (perhumid) with relatively warm (lower mesotherm) winters compared to the Eromanga Basin.

1.3   Other records

1.3.1   *North-East Australia*

1.   Carpentaria Basin

Glendonites and dropstones in Valanginian and younger Early Cretaceous sediments in the Carpentaria Basin are firm evidence that temperatures fell below freezing point (microtherm range) during winter at palaeolatitudes of about 65-70^{0}S on the palaeo-eastern margin of the continent (Frakes 1999).

1.3.2   *Central Australia*

1.   Eromanga and Surat Basins

Glendonites and dropstones in Valanginian to possible Barremian sediments in the Eromanga and Surat Basins are interpreted as evidence for floating ice-floes in the Eromanga-Surat Seaway and, by extrapolation, for temperate glaciers on uplands south and west of the Eromanga Basin (Frakes *et al.* 1995, Frakes 1999).

2.   TIME SLICE K-2

Age Range: Aptian – Albian [115- 97.5 Ma]

  Zones: *Cyclosporites hughesii to Phimopollenites pannosus* Zones
                    Odontochitina operculata to lower *Xenascus asperatus* Zones

2.1   Macrofloras

Basins that preserve macrofossil records for the Berriasian-Barremian usually preserve Aptian-Albian macrofloras as well. However the only comprehensive records come from basins located along the present-day southern margin, then at high palaeolatitude (70-80^{0}S) along the palaeo-western margin (see Figure 5).

2.1.1 *North-West Australia*

No known record.

2.1.2 *North-East Australia*

1.   Marlborough Basin

A sparse macroflora preserved in the Marlborough Basin, southern Queensland, indicates that forests or woodlands on the northernmost of the four islands making up Australia during the Aptian included Araucariaceae*, Ginkgoites*, pteridosperms/Pentoxylales (*Taeniopteris*), sphenopsids and ferns. Dettmann and Clifford (2000a) have recorded propagules resembling gemmae produced by modern liverworts (Marchantiales) in latest Albian sediments from the south-east of the Eromanga Basin.

Inferred climate

Since the Marlborough Basin was located at a palaeolatitude of about 75^{0}S, it is reasonable to assume that conditions were humid and temperatures were below freezing (lower microtherm) during winter.

2.1.3 *Central Australia*

1.   Eromanga and Surat Basins

Palaeogeographic reconstructions indicate the depocentre of the Eromanga Basin was located at about 60^{0}S. The Euromanga and Surat Basins to the east were part of an extensive epicontinental seaway stretching from the palaeo-northern margin at about ~50^{0}S southwards to about palaeolatitude 80^{0}S. Silicified wood with narrow growth rings is preserved in carbonate concretions in the Early Albian, upper Bulldog Shale and Toolebuc Formation and a cycad is preserved in the Middle-Late Albian Allaru Mudstone in the Eromanga Basin but other macrofossils from this and the Surat Basin await identification (references in Dettmann *et al*. 1992).

The stems are believed to represent podocarp-dominated forests or woodlands (Austral Conifer Forest) growing under wet (humid) but strongly seasonal and cool-cold (microtherm range) conditions on uplands surrounding the Eromanga Basin (Francis and Frakes 1993).

2.1.4 *South-West Australia*

1.   Carnarvon and Perth Basins

Fossil macrofloras consisting of permineralised wood are preserved in the Early Aptian Muderong Shale and Middle Aptian-Albian Windalia Radiolarite in the Carnarvon Basin, and Early Aptian Dandaragan Sandstone in the Perth Basin (McLoughlin 1996).

Inferred climate

McLoughlin (*ibid*) suggests that araucarians and podocarps are likely to have dominated tree communities, implying conditions were humid. Based on the middle palaeolatitude location (~55^{0}S) on the palaeo-northern margin, mean annual temperatures may have been relatively warm (lower mesotherm) and seasonal contrasts less marked than in inland regions.

2.1.5 *Central southern Australia*

No known record.

2.1.6 *South-East Australia*

Aptian to Early Albian (Zone C) and Early to Late Albian (Zone D) macrofloras are widely preserved across the Otway and Gippsland Basins, which were located on the palaeo-western margin between latitudes 70-80^{0}S (Douglas 1969, 1973a, 1986, 1994). The most important of these floras is a Zone C macroflora preserved in the Koonwarra Beds, onshore Gippsland Basin. The Zone C/D boundary approximates to the Aptian/Albian boundary.

1.   Aptian to Early Albian

The Koonwarra Beds preserve a particularly diverse record of the earliest Aptian plants and animals living in and around a large (>2 km diameter) freshwater lake (Drinnan and Chambers 1986, Rich *et al*. 1988).

The flora includes most of the major plant taxa forming Austral Conifer Forest elsewhere in southern Australia during the early Cretaceous. These plants ranged in size from bryophytes to probably tall gymnosperms. Angiospermids are represented by a flower (Taylor and Hickey 1990) and fossil pollen. Important taxa include Araucariaceae, Podocarpaceae, *Ginkgoites*, pteridosperms/Pentoxylales (*Taeniopteris*), ferns and fern allies (*Adiantites*, *Gleichenites*), sphenopsids (*Equisetum*, *Phyllotheca*, *Sphenopteris*), isoetaleans (including *Isoetes*), lycopods (*Lycopodium*), mosses (including Sphagnales) and liverworts (Jungermanniales, Anthocerotae).

The woody flora included both deciduous and evergreen taxa. Many of the sphenopsids, ferns and fern allies closely resemble their nearest living relatives, e.g. *Equisetum*, *Gleichenia* and *Lycopodium*. The bryophyte flora included ground and epiphytic species. The remains of small 'polar' dinosaurs and birds are preserved in the Koonwarra Beds and correlative deposits elsewhere in southern Victoria.

The combined data indicate that Aptian to possible Early Albian climates were very wet (perhumid) and strongly seasonal, with temperatures possibly falling below freezing during winter months (cf. Rich *et al*. 1988, Dettmann *et al*. 1992).

2.   Early to Late Albian

The Aptian/Albian (Zone C/D) boundary is marked by the disappearance of several major plant groups, which had been present in Australia since the Jurassic, such as pteridosperms (including Pentoxylales), sphenopsids and, possibly bennettitaleans. Gymnosperms (Araucariaceae, Podocarpaceae, Taxodiaceae) continued to dominate Albian (Zone D) forests and woodlands, but many of the more prominent species were different from those recorded in the Aptian (cf. Cantrill 1991). For example the prominent species *Gingkoes australis* was replaced by ginkgophyte with smaller leaves. Osmundaceae appear to have been a common ground cover based on the high relative abundance of their fronds. Angiosperms, were present but uncommon.

Inferred climate

Floristic change within the Albian is suggested to reflect a high level of environmental disturbance caused by fluctuating sea level, and tectonic or volcanic activity (Gledow and Duddy 1981, Douglas 1986). Cantrill and Douglas (1988) interpret fungi associated with the conifer roots as evidence for nutrient-deficient soils. Climates are interpreted as wet (perhumid) and cool-cold (microtherm range) due to the high palaeolatitude. These palaeotemperature inferences are supported by isotopic data (Gregory *et al*. 1989) which indicate mean annual temperatures in the catchments of rivers flowing into the Otway and Gippsland Basins were less than 5^0C (lower microtherm) and possibly below freezing.

2.2   Microfloras

Marked differences exist in the composition of Aptian-Albian microfloras in the palaeo-southwestern (~Victoria) and palaeo-eastern (~Queensland) regions of the continent. These may reflect differences in topography, edaphic conditions and/or depositional regimes, as well as differences in climate (Dettmann *et al*. 1992).

Correlation of these microfloras with assemblages on the palaeo-northern margin (~Western Australia) is difficult due to absence of a number of biostratigraphically useful species in the latter region (Backhouse 1988, Burger 1994).

2.2.1   *North-West Australia*

Range data (Helby *et al*. 1987) indicate that a number of phytogeographically significant taxa entered Australia during Late Aptian-Albian time. Examples include a brachyphyll araucarian (*Hoegisporis*), and several cryptogams. The latter include *Cyatheacidites tectifera* whose NLR (*Lophosoria*) is restricted to cool temperate habitats in South America, *Plicatella* (al. *Appendicisporites*) *distocarinata* whose NLR (*Anemia* subgen. *Anemia*) is restricted to wet tropical habitats, and an extinct clade within the Gleicheniaceae (*Clavifera triplex*). Balme (1964) has recorded tricolpate angiosperm pollen in Albian sediments in Western Australia.

<u>Inferred climate</u>

The data confirm conditions were humid and probably warm (mesotherm range) relative to regions to the south. The environmental implications of the migration or expansion of angiosperms in northwestern Australia during the Aptian are unclear but may have been stimulated by transgression and regression events affecting the palaeo-northern margin.

2.2.2 *North-East Australia*

1.   <u>Carpentaria Basin</u>

Early Cretaceous palynofloras are preserved in the onshore Carpentaria Basin (M.K. Macphail pers. observations) but have not been systematically analysed or precisely dated. Thin coals accumulated at Nhulunbuy in the Northern Territory (palaeolatitude ~57^{0}S) during the Late Albian (P.R. Evans cited in Dodson 1967).

<u>Inferred climate</u>

Conditions were humid rather than wet, or alternatively peat bog development during the Late Albian was limited by seasonal variations in temperature.

2.   <u>North-east Queensland</u>

Coal measures accumulated in the Stanwell district in northeastern Queensland (palaeolatitude ~65^{0}S) and the Marlborough Basin in southeastern Queensland (palaeolatitude 70^{0}S) during the latest Aptian-Early Albian (Dettmann *et al*. 1992).

<u>Inferred climate</u>

The presence of coal beds implies effectively wet (perhumid) conditions. Temperatures are likely to have been cool-cold (microtherm range) due to the high latitude location.

2.2.3 *Central Australia*

Palynological data for the Eromanga (Alley 1998) and Surat Basin (Burger 1980, 1988) are the most detailed published record of Aptian-Albian floras available in Australia.

1.   <u>Eromanga Basin</u>

Palynofloras preserved in the marine Cadna-owie Formation deposited across the southwestern and central areas of the Eromanga Basin during Early Aptian time are dominated by podocarps (30-60%) and pteridosperms (4-18%). Araucarians and cheirolepidiacean pollen are less common (<4%). Large ferns such as Cyatheaceae (12-18%) and Osmundaceae (5-12%) are more common than the smaller-sized fern allies such as lycopods, and *Sphagnum* (<5%).

2.   <u>Surat Basin</u>

Relative abundance data from the Wyandra-1 well in the western Surat Basin confirm that Austral Conifer Forest was partly replaced by extensive fern heath and swamp communities during the Aptian although araucarians, podocarps and pteridosperms continued to be prominent in marine facies (Neves Effect). Prominent cryptogams included ferns (Cyatheaceae, Osmundaceae, Gleicheniaceae) and *Sphagnum*.

Dettmann *et al*. (1992) have argued that the trend reflects the colonisation of emergent areas by fern heath and swamp communities as the sea retreated from the Eromanga-Surat Seaway during the latest Aptian-Albian. If correct, then the link with climate is an indirect one. A complicating factor is that the Wyandra-1 data also show simultaneous increases in marine dinoflagellates, Gleicheniaceae and *Sphagnum* curves during the Early Aptian. A not-unlikely explanation is that other suitable habits for fern-dominated communities were created by the progradation of deltas during times of high relative sea level. *Sphagnum* bog development is likely to have been promoted by low mean temperatures (reducing water losses by evapo-transpiration) as well as by the high humidity. The expansion of primitive angiosperms within fern heath communities during the Albian is seen to be a consequence of marine regression exposing large open areas of mineral soils around the margins of the inland basins (Dettmann *et al ibid.*).

Inferred climate

Burger (1988, 1990) has proposed that climates were relatively constant (cool humid) throughout the Aptian but suggests that the rapidly diversifying tricolpate pollen flora is consistent with global warming during the Early Albian. Conversely the high relative abundances of *Sphagnum* are more consistent with geological evidence for seasonally cold (microtherm range) and effectively very wet (perhumid) conditions throughout Aptian-Albian time (see below).

2.2.4 *South-West Australia*

1. Perth Basin

The stratigraphic correlation proposed by Backhouse (1988) indicates that only the assemblages recovered from the top of the Leederville Formation are likely to represent Aptian time. These assemblages imply two distinctive vegetation types were present around the basin. These are: (1) mixed cheirolepidiacean conifer woodland and Austral Conifer Forest, dominated by podocarps (*Microcachrys*) and araucarians (*Araucariacites*, *Balmeiopsis*), which occupied uplands on the landward margin of the basin, and (2) fern swamp communities dominated by Cyatheaceae, Dicksoniaceae, Matoniaceae and Schizaeaceae, which grew in the coastal lowlands. Albian microfloras are dominated by pollen of the brachyphyll araucarian *Hoegisporis*.

Inferred climate

Climates are suggested to have been humid at low elevations whilst seasonally drier climates may have prevailed in adjacent uplands, assuming the ecological preferences of the Cheirolepidaceae have been correctly interpreted (Backhouse 1988). The relatively low palaeolatitude (~50^{0}S) implies temperatures were mild (lower mesotherm) whilst winter photoperiods are unlikely to have limited plant growth.

2.2.5 *Central southern Australia*

1. Duntroon Basin

Data provided by Morgan (1986a) and Morgan and Hooker (1993a, 1993b) indicate little change in the relative abundance of commonly occurring taxa between Necomian and Early Albian time. *Anemia* (*Cicatricosisporites*/*Ruffordiaspora*) spores become common (up to 25%) during the early Late Albian. Fern spores, especially Cyatheaceae (*Cyathidites*), are more abundant than gymnosperm pollen during the latest Albian (and Cenomanian).

<u>Inferred climate</u>

The data confirm that conditions remained wet to very wet (humid-perhumid) and cool-cold (microtherm range) throughout the Aptian and early Albian, but hint that seasonal contrasts in temperature was reduced during the Late Albian. This is consistent with global warming, but could equally well reflect the extension of maritime climates into high (~70^0S) palaeolatitudes along the Australo-Antarctica Rift System.

2.2.6 *South-East Australia*

Thick sequences of Aptian-Albian sediments occur in the Otway Basin (Eumeralla Formation) and the Gippsland Basin (Strzelecki Formation). These formations are routinely intersected by deeper exploration wells. Microfloral lists are available in open file well completion reports. Such data document plant successions along the palaeo-southwestern margin but seldom provide objective information on community dominance.

1.   <u>Otway Basin</u>

Few quantitative analyses are available but, based on unpublished observations, Dettmann (1994) has concluded that the gymnosperm and cryptogam communities were less diverse than equivalent communities making up Austral Conifer Forest in central Australia.

<u>Inferred climate</u>

Floristic impoverishment typically is associated with very wet microtherm climates. If these constraints, rather than extended periods of winter darkness, were the major factors influencing plant diversity in the Otway and Gippsland Basins, then climates at the extreme southern end of the palaeo-western margin are likely to have been perhumid and seasonally cold (lower microtherm).

The latter inference is in good agreement with Parrish *et al*. (1991) who conclude that mean air temperatures in the region were between 5-8^0C during the Albian. The restricted development of Gleicheniaceae fern heath in the Otway relative to the Gippsland Basin (Dettmann 1994) may reflect habitat differences rather than climate.

2.3   **Other records**

2.3.1 *North-West Australia*

Hallam (1984, 1985) has proposed that, beginning at the end of the Aptian, northern Australia, which then lay between latitudes of ~50^0S and 60^0S, was subject to intermittent or locally high precipitation due to the movement of warm water eastwards into the Tethys Seaway.

2.3.2 *Central Australia*

1.   <u>Eromanga and Surat Basins</u>

Direct evidence for freezing conditions during winter is provided by dropstones and glendonites preserved in Aptian-Albian strata in both basins. As for the Valanginian-Barremian interval, these are interpreted as evidence of a large seasonal influx of ice and cold fresh water from glaciers occupying uplands to the south and west of the Eromanga Basin (Frakes *et al*. 1995, Frakes 1999).

3. TIME SLICE K-3

Age Range: **Cenomanian [97.5-91 Ma]**

Zones: *Plicatella* (al. *Appendicisporites*) *distocarinatus* Zone
Xenascus asperatus to *Palaeohystrichophora infusorioides* Zones

3.1 Macrofloras

The only detailed macrofloral evidence for Cenomanian climates comes from the eastern Eromanga Basin in central southwestern Queensland. At this time, the region was located at about 60^0S and relatively close to the palaeo-eastern margin.

3.1.1 *North-West Australia*

No known record.

3.1.2 *North-East Australia*

No known record.

3.1.3 *Central Australia*

1. Eromanga Basin

Macrofossils preserved in the Winton Formation in central southwestern Queensland (McLoughlin *et al*. 1995b) include Araucariaceae, Taxodiaceae (including *Austrosequoia*), Podocarpaceae, *Ginkgo*, pteridosperms/Pentoxylales (*Taeniopteris*), sphenopsids (the youngest record in Australia) and ground ferns (Gleicheniaceae, Osmundaceae). Also present are leaves from eight broadleaf angiosperms. These are mostly of (possibly deciduous) betulaceous-fagaceous affinity. The communities these represent appear to be transitional between the gymnosperm (Austral Conifer Forest) and angiosperm-dominated floras in central Australia.

Inferred climate

Conditions appear to have been wet (humid-perhumid), possibly due to rivers draining the ranges along the (uplifted) eastern margin. Temperature are likely to have been seasonally cool (microtherm range) in winter due to the relatively high latitude (~60^0S) but there is no mineralogical evidence for ice.

3.1.4 *South-West Australia*

No known record.

3.1.5 *Central southern Australia*

No known record.

3.1.6 *South-East Australia*

No known record.

3.2 Microfloras

Partridge (1999) has challenged earlier interpretations that *Plicatella* (al. *Appendicisporites*) *distocarinata* Zone microfloras are preserved in the Gippsland Basin. If correct, then the only reliable palynostratigraphic evidence for the nature of the Cenomanian vegetation in southern Australia comes from basins in, or bordering, the Great Australia Bight (Otway, Duntroon, Eucla and Perth Basins). Most of these microfloras are preserved in marine facies and are likely to be biased towards well-represented species such as gymnosperms due to the Neves Effect.

The only detailed correlative records for northern Australia come from two boreholes (Bathurst-1, Bathurst-2) drilled on Bathurst Island, 65 km north of Darwin (Norvick and Burger 1975, Burger 1975) and in the Carpentaria Basin (BMR Dobbyn-1) in northwestern Queensland (Playford *et al*. 1975). During the Cenomanian, this region was part of a very shallow, regressive sea located at a palaeolatitude of ~49^0S on the palaeo-northwestern margin. Non-marine Cenomanian sediments are preserved further to the south in the Eromanga and Surat Basins.

3.2.1 *North-West Australia*

1. Bathurst Island

Microfloras recovered from the Bathurst-2 well (Norvick and Burger 1975) appear to represent two distinct vegetation types: (1) fern swamps growing along the palaeoshoreline and (2) mixed Communities of Cheirolepidiacean conifer woodland and Austral Conifer Forest, which may have been restricted to adjacent uplands.

Dominant taxa within the forests and/or woodlands were Cheirolepidaceae (*Corollinia*), pteridosperms (*Alisporites*, *Vitreisporites*), brachyphyll araucarians (*Balmeiopsis*, *Hoegisporis*) and *Microcachrys* (*Microcachrydites antarcticus*). It is possible the last species was a shrub. The relative abundance of individual angiosperm species is very low but the total angiosperm count is significant. The only types referable to modern taxa (in parentheses) are *Clavatipollenites* (Chloranthaceae), *Liliacidites* (Palmae, Iridaceae or Liliaceae) and *Dicolpopollis* (Palmae).

Coastal communities were dominated by cryptogams. The more common taxa are: *Triporoletes* (liverworts), *Perotriletes* and *Retitriletes* (Lycopodiales), *Crybelosporites* (aquatic ferns), *Laevigatosporites*, *Cyathidites*, *Clavifera* and *Gleicheniidites* (ferns). Two extinct species of *Anemia* (*Plicatella distocarinatus*, *Ruffordiaspora australiensis*) are common in many samples. *Sphagnum* spores occur only sporadically.

Inferred climate

Norvick and Burger (1975) suggest that the lowland vegetation grew in a temperate to warm, possibly dry climate. This is inconsistent with the observed high diversity of cryptogams (including obligate aquatic types).

The preferred explanation is that humidity was seasonally high (perhumid and/or monsoonal) due to warm sea surface temperatures off the palaeo-north coast. Whether rainfall was uniformly distributed or strongly seasonal is unclear. The relative paucity of Austral Conifer Forest and virtual absence of *Sphagnum* is consistent with very warm (upper mesotherm) temperatures and/or a pronounced dry season.

3.2.2 *North-East Australia*

1. Carpentaria Basin

Microfloras recovered from the Late Albian possibly to Cenomanian marine Allaru Mudstone (BMR Dobbyn-1) in northwestern Queensland (Playford *et al*. 1975) are dominated by gymnosperms, in particular araucarians (including *Araucaria*), brachyphyll araucarians (*Hoegisporis*) and podocarps (*Microcachrys*, *Podocarpus-Prumnopitys*), and ferns (chiefly Gleicheniaceae). Angiosperms are relatively rare but include Chloranthaceae (*Clavatipollenites*), Liliaceae (*Liliacidites*) and a diverse group of small tricolpate and tricolporate types.

Inferred climate

The source vegetation appears to have been araucarian-podocarp Austral Conifer Forest growing on uplands on the western margin of the basin. Climates were humid and probably warm (mesotherm range) but neither the palynofloras nor the associated foraminifera include taxa whose NLRs imply subtropical-tropical environments.

3.2.3 *Central Australia*

1. Eromanga Basin

Dettmann *et al*. (1992) note that the conifer/cycad woodlands and fern/angiosperm heath surrounding freshwater lakes and swamps in the Eromanga Basin during the Albian survived into Cenomanian time. Data from the Winton Formation (Martin 1998b) provide evidence that some ferns (Blechnaceae, Cyatheaceae, Gleicheniaceae) remained abundant, but indicate that araucarians may have been locally extinct whilst *Anemia* (*Plicatella*, *Ruffordiaspora*) pteridosperms, podocarps (*Microcachrys*) and angiospermids had become uncommon to rare.

Inferred climate

The continuing high relative abundance of ferns such as Gleicheniaceae is likely to reflect an expansion of fern heath into the depression formerly occupied by the Eromanga-Surat Seaway. Other taxa imply that climates remained locally, or seasonally, humid. Nonetheless, effectively drier climates and/or a rise in mean minimum temperatures (possibly to an upper microtherm) best explain the contraction in range and/or relative abundance of both canopy trees and ground ferns. The latter inference is supported by the absence of dropstones and other evidence for ice (Frakes 1999).

3.2.4 *South-West Australia*

1. Carnarvon Basin

Ingram and Morgan (1988) note that spores and pollen becomes slightly more common in marine sediments (5-10%) during the Late Cenomanian but the only named taxa are dinoflagellates. Little can be interpreted from these data.

2. Perth and Eucla Basins

Balme (1964) lists brachyphyll araucarians (*Balmeiopsis*, *Hoegisporis*) and Gleicheniaceae as one of the more commonly occurring types in Cenomanian microfloras from the Perth and Eucla Basins (palaeolatitude ~60-65^{0}S).

Inferred climate

Dettmann *et al*. (1992) propose these microfloras are evidence for seasonal but relatively warm (possibly lower mesotherm) and dry climates. This reconstruction, which is based on the prominence of Gleicheniaceae along modern subtropical and tropical rivers (M.E. Dettmann pers. comm.), is consistent with global warming at high latitudes. Dry conditions however are difficult to reconcile with microfossil data from the Duntroon Basin located further to the east within the same narrow seaway (see below).

3.2.5 *Central southern Australia*

1.   Duntroon Basin

Limited pollen evidence (Morgan and Hooker 1993a, 1993d) indicate that ferns (*Cyathidites*, *Cicatricosisporites*, *Ruffordiaspora*) dominated the coastal, riparian vegetation at about palaeolatitude 70^0S whilst pteridosperms (*Alisporites*) and podocarps (*Microcachrys*) may have formed forests and woodlands in adjacent uplands.

Araucariaceae (*Agathis/Wollemia*) appears to become common to abundant in Austral Conifer Forest close to the top of the *A. distocarinatus* Zone in some offshore wells (possibly due to the Neves Effect). Cheirolepidacean conifers are uncommon relative to north-west Western Australia. A contributing factor may be low light levels during winter months.

Inferred climate

The data strongly imply climates were humid and seasonally cool (upper microtherm-lower mesotherm) rather than cold. The expansion of araucarians towards the end of the Cenomanian is not inconsistent with more temperate conditions (higher mean minimum temperatures) in marine flooded regions in the rift valley between Australia and Antarctica (Australo-Antarctic Seaway).

3.2.6 *South-East Australia*

1.   Otway Basin

Pollen evidence from marine sediments in the western Otway Basin (palaeolatitude ~75^0S), indicate that Austral Conifer Forest communities were more diverse than those found in the Duntroon Basin (Macphail and Hos 1990). For example, the podocarp component included frequent to common *Podocarpidites* and *Podosporites* as well as *Microcachrys* although araucarians never become frequent.

Conversely, fern spores (*Anemia*, Cyatheaceae, Gleicheniaceae) are only sporadically frequent, although this may reflect limited opportunities for the development of fern-heath along the coast rather than climate *per se*. Spores of the important fern genus *Lophosoria* (*Cyatheacidites tectifera*) first appear in low numbers towards the top of the *A. distocarinatus* Zone.

Inferred climate

Climates were as humid, but probably seasonally cooler, (upper microtherm-possible lower mesotherm) than regions further to the west along the Australo-Antarctic Seaway.

4.   TIME SLICE K-4

Age Range: Turonian-Santonian [91-83 Ma]

Zones: *Phyllocladidites mawsonii* to *Tricolporites apoxyexinus* Zones
Palaeohystrichophora infusorioides to lower *Nelsoniella aceras*
Zones

4.1   Macrofloras

Douglas (1994) has noted that an unidentified cuticle is a major component in microfossil preparations.

4.2   Microfloras

Marine and non-marine sediments preserving Turonian-Santonian palynofloras occur in offshore basins along the southern, western and northern margins. Dettmann (1973) reviewed records of angiosperm pollen and noted that, unlike earlier geological intervals, it is possible to assign a number of newly evolved or arrived gymnosperms and angiosperms to modern genera with a moderate to good degree of confidence. For example it is highly probable that *Dilwynites* represents the araucarian genera *Agathis* and/or *Wollemia*, whilst *Lygistepollenites* and *Phyllocladidites* represent the podocarp genera *Dacrydium* and *Lagarostrobos*, respectively.

4.2.1   *North-West Australia*

1.   Bathurst Island

Dinoflagellate evidence does not support the claim (Norvick and Burger 1975) that palynosequences from Bathurst Island range into Early Turonian time. However, exploration wells drilled on the North West Shelf occasionally intersect Turonian-Santonian, *Phyllocladidites mawsonii* Zone Equivalent units, which preserve significant numbers of pollen and spores. None of these have been systematically documented thus far.

2.   Bonaparte Basin

Limited evidence from Jacaranda-1, in the Bonaparte Basin (Helby and Partridge 1985, M.K. Macphail unpubl. results) points to ferns (Cyatheaceae), podocarps (*Podocarpus-Prumnopitys*) and/or pteridosperms (*Alisporites*) being amongst the more common taxa during Santonian (*Isabelidinium cretaceum* Zone) time. Rare angiosperms include Callitrichaceae (*Australopollis obscurus*), *Gunnera* (*Tricolpites reticulatus*), Liliaceae (diverse), *Ilex*, Proteaceae and a probable palm (*Dicolpopollis* sp.) plus a range of extinct angiosperms producing small tricolpate and tricolporate pollen types.

Inferred climate

The combined data point to seasonally humid-perhumid and probably very warm (upper mesotherm) conditions along the palaeo-northern margin despite its palaeolatitude (~50^0S).

4.2.2 *North-East Australia*

Deposits of Turonian-Santonian age have not been identified and may not have been preserved due to deep weathering (Struckmeyer and Totterdell 1990).

4.2.3 *Central Australia*

No known record.

4.2.4 *South-West Australia*

1.   Carnarvon and Perth Basins

It is probable that Turonian-Santonian dinocyst-dominated assemblages from the Perth and Carnarvon Basins also preserve spores and pollen. However the terrestrial miospores have not been analysed due to the overwhelming industry focus on marine microfossils (Marshall 1984, Ingram and Morgan 1989).

4.2.5 *Central southern Australia*

1.   Duntroon Basin

Morgan (1986a) and Morgan and Hooker (1993a, 1993d) provide basic (raw count) data for microfossils occurring in a number of exploration wells drilled in this basin. These tabulations indicate a possible pteridosperm (cited as *Alisporites*), araucarians (*Agathis/Wollemia*) and podocarps (chiefly *Microcachrys*) continued to dominate gymnosperm vegetation types in the eastern Bight region during the Turonian to Early Santonian. The only common cryptogam is Cyatheaceae.

Lagarostrobos (*Phyllocladidites mawsonii*) and Gleicheniaceae become frequent during the later Santonian. Rare species include Callitrichaceae, *Lophosoria* (*Cyatheacidites tectifera*) and, recorded for the first time on the southern margin, *Dacrydium* (*Lygistepollenites florinii*). Other arrivals include *Dacrycarpus* (*Dacrycarpites australiensis*), *Tricolporites apoxyexinus* and a range of undescribed or extinct trifoliate and tricolporate types. Proteaceae (*Proteacidites*) only become frequent towards the top of the *T. apoxyexinus* Zone.

Inferred climate

Extant *Lagarostrobos* and *Dacrycarpus* often occur along riverbanks or form swamp forests. Migration of these taxa into the Australo-Antarctic Rift System implies rainfall increased or became more uniformly distributed during Turonian-Santonian time (humid-perhumid). Temperatures are likely to have remained seasonally cool-cold (upper microtherm-lower mesotherm), consistent with the relatively high palaeolatitude ($\sim70^0$S).

4.2.6 *South-East Australia*

Phyllocladidites mawsonii (Turonian-basal Santonian) and *Tricolporites apoxyexinus* Zone (Santonian) sediments are routinely intersected by the deeper exploration wells drilled in the offshore Gippsland, Bass and eastern Otway Basins. Santonian strata outcrop in submarine canyons in the Gippsland Basin (Marshall 1988). The most detailed records come from deep rift valley lakes, which also preserve a distinctive fresh-brackish water dinoflagellate assemblage (Marshall 1989).

1.   Otway Basin

Limited data (Macphail and Hos 1990, A.D. Partridge pers. comm.) indicate that uplands bordering the eastern Otway Basin were covered with Austral Conifer Forest dominated by possible pteridosperms (*Alisporites*), araucarians (*Agathis/Wollemia*) and podocarps (chiefly *Podocarpus-Prumnopitys*, *Microcachrys*). The only commonly recorded cryptogams, which are presumed to have formed coastal vegetation or lined inflowing rivers, were Gleicheniaceae and Cyatheaceae (*Cyathidites*, *Trilites*).

Proteaceae (*Proteacidites*) become common and occasionally dominant during the Santonian although the majority of specimens are small (<25 μm), morphologically simple types. For example, in Fenton Creek-1 and Mylor-1 in the Port Campbell Embayment, *Proteacidites* spp. are rarely recorded (<1%) in the *Phyllocladidites mawsonii* Zone but attain values of up to 12% by the upper *Tricolporites apoxyexinus* Zone (A.D. Partridge pers. comm.). Callitrichaceae are occasionally frequent (1-5%) in the *P. mawsonii* Zone and reaches their maximum relative abundance in the upper *T. apoxyexinus* Zone (10%). Blechnaceae-type ferns (*Laevigatosporites*) and *Sphagnum* are uncommon (>3%).

2.   Gippsland Basin

Much of the microfossil data preserved in the Gippsland Basin comes from large freshwater lakes occupying depressions within the rift valleys. The microfloras are biased towards well-represented gymnosperms and cryptogams (Neves Effect).

As in the Otway Basin, the regional/upland vegetation was Austral Conifer Forest in which the dominants were possibly pteridosperms (*Alisporites*), araucarians (*Agathis/Wollemia*) and podocarps (chiefly *Podocarpus-Prumnopitys*, *Microcachrys*) (Tulip and Macphail 1986). *Araucaria* (*Araucariacites*) is frequent to common in occasional samples: *Lagarostrobos* increases in relative abundance but never becomes common during the interval.

The diversity of angiosperms increases, especially during the Turonian, but simple monosulcate and tricolpate pollen types may dominate occasional samples in both the *P. mawsonii* and *T. apoxyexinus* Zones. Morphologically complex angiosperm types include *Tricolporites apoxyexinus*, *Liliacidites* and *Forcipites*. Commonly recorded cryptogams are Gleicheniaceae, Cyatheaceae (*Cyathidites*, *Trilites*) and *Sphagnum*.

Inferred climate

Dettmann and Playford (1969) argue that the relative prominence of *Lagarostrobos* and decrease in the number and diversity of schizaeaceous ferns such as *Anemia* imply climates were cool (upper microtherm) and uniformly wet (humid).

This conclusion is supported by higher abundances of *Sphagnum* spores relative to the Otway Basin, which in turn imply the Gippsland Basin was wetter (perhumid) than analogous environments in the Otway Basin and/or rainfall was more uniformly distributed. Mean annual values were adequate to support gymnosperm swamps and large permanent freshwater lakes: The high latitude (~75^{0}S) location indicates that that the composition and structure of the upland forests and woodlands also will have been influenced by extended periods of partial darkness during winter months. For the same reason, mean minimum temperatures are likely to have been within the lower microtherm range.

4.2.7 *Tasmania*

1.   <u>Bass Basin</u>

Turonian-Santonian microfloras are preserved in the Durroon Sub-basin, then lying at a palaeolatitude of about 77^0S off the north-east coast (Partridge 1999, M.K. Macphail and A.D. Partridge unpubl. data).   These are dominated by araucarians (chiefly *Agathis*/*Wollemia*) podocarps (*Podocarpus-Prumnopitys*) and Cupressaceae (*Cupressacites*). Values of the last taxon increase up-section (possible due to the Neves Effect) as do the relative abundance of angiosperms and a distinctive freshwater alga, *Rimosicysta*. Nevertheless, the cryptogam and angiosperm flora appear to be less diverse that in correlative microfloras from the Gippsland and Otway Basins.

<u>Inferred climate</u>

The combined data point to seasonally cool-cold (microtherm range) and wet (humid-perhumid) conditions in northern Tasmania although it is difficult to determine whether floristic impoverishment reflects freezing temperatures or prolonged darkness during winter.

4.3   Other records

4.3.1 *South-East Australia*

A Turonian ammonite from the Otway Basin yielded a palaeotemperature of 28^0C (megatherm range) although the associated foraminifera appear to represent a cold-water fauna (references in Dettmann 1973).

5.   TIME SLICE K-5

Age Range: Early Campanian [83- ~70 Ma]

Zones: *Nothofagidites senectus* Zone
Upper *Nelsoniella aceras* to *Xenikoon australis* Zones

5.1   Macrofloras

Douglas (1994) has noted that leaf cuticle is often a major component in microfossil preparations.

5.2   Microfloras

Marine and non-marine sediments, which preserve Early Campanian palynofloras, occur in offshore basins along the southern, western and northern margins. The first appearance of *Nothofagidites* is widely used as a marker for the basal Campanian and this may conceal diachronous or time-transgressive trends in the first occurrence of other botanically important species along the southern margin.

Like *Lagarostrobos* and *Dacrydium*, the first appearance of *Nothofagus* is of potentially major palaeoclimatic significance, as three of the four living subgenera (*Fuscospora*, *Lophozonia*, *Nothofagus*) are confined to relatively cool to cold (microtherm range) and uniformly wet climates in Australia, New Zealand and southern South America. The fourth subgenus (*Brassospora*), which is endemic to New Caledonia, New Guinea, is also confined to uniformly wet climates but is tolerant of a wider temperature range (upper microtherm-lower mesotherm).

The clade represented by Campanian *Nothofagidites* was ancestral to the four extant subgenera (Dettmann *et al*. 1990) and its palaeo-distribution makes it probable that the genus was adapted to extended periods of winter darkness (possibly deciduous) and high levels of environmental disturbance. The latter characteristic is retained by many living *Nothofagus* species whilst the deciduous trait occurs in several *Nothofagus* species that are confined to upper subalpine and alpine habitats, e.g. *N. gunnii* in Tasmania.

Accordingly, the spectrum of responses to modern drought and temperature extremes makes it unwise to rely too closely on modern bioclimatic data when interpreting Late Cretaceous palaeoclimates. For example, the possibility exists that ancestral *Nothofagus* species were (or included) shrubs occupying exposed and/or disturbed sites such as along rivers and therefore that the relative abundance of its pollen may reflect edaphic factors rather than climate *per se*. Conversely, there is weak evidence that some ancestral *Nothofagus* were growing in the Eastern Highlands, implying some ecotypes were adapted to more stable environments. An example is the high relative abundance of *Nothofagidites senectus* in the Wild Dog-1 well, located on the southwestern margin of the Gippsland Basin adjacent to the South Gippsland Range (Macphail 1993). Systematic analysis of Campanian microfloras across the Gippsland Basin would help resolve this point.

5.2.1 *North-West Australia*

1.	Bonaparte Basin

Pollen data from Jacaranda-1 show that ferns (*Cyathidites*), podocarps (*Podocarpus-Prumnopitys*) and/or possible pteridosperms (*Alisporites*) remained common during the Late Santonian-Early Campanian (*Nelsoniella aceras* Zone).

Newly arrived taxa include tree ferns (*Lophosoria*), gnetopsids (*Ephedra*), palms (*Longapertites*) and a fossil member of the Didymelaceae, now confined to angiosperm rainforest in Madagascar (*Schizocolpus marlinensis*). Pollen of an ancestral *Nothofagus* species (*Nothofagidites* sp. cf. *N. senectus*) are present but very rare.

Inferred climate

The presence of a palm implies humid-perhumid and seasonally very warm (upper mesotherm) conditions occurred along the palaeo-northern margin during the Campanian.

5.2.2 *North-East Australia*

No known record.

5.2.3 *Central Australia*

No known record.

5.2.4 *South-West Australia*

1.	Carnarvon Basin

Palynofloras are wholly dominated by dinoflagellates, e.g. Alpha North-1 (Ingram and Morgan 1989). No data are available from the Perth Basin whilst Campanian sediments are not preserved in the Eyre Basin (Jerboa-1).

5.2.5 *Central southern Australia*

1.	Duntroon Basin

Maastrichtian and/or Campanian microfloras are recorded in nearshore to marginal marine facies preserved in the Duntroon-1 (Morgan 1986a) and Vivonne-1 and Greenly-1 wells (Morgan and Hooker 1993b, 1993d). Dominants are ferns (Cyatheaceae), possible pteridosperms (*Alisporites*) and two podocarps (*Podocarpus-Prumnopitys*, *Podosporites microsaccatus*). Tertiary microfloral evidence indicates the latter species was produced by an extinct shrub related to *Microcachrys*, growing around or in freshwater swamps. Other gymnosperms are only sporadically common, e.g. araucarians (*Araucaria*, *Agathis*/*Wollemia*), or infrequent (*Lagarostrobos*, *Microcachrys*). *Sphagnum*, Osmundaceae, Proteaceae and ancestral *Nothofagus* values increase up section, with *Nothofagus* reaching up to 18% close to the top of the interval. Rare angiosperms include Callitrichaceae and unidentified taxa producing tricolpate and tricolporate grains.

Inferred climate

The data indicate that by the end of the Early Campanian, Austral Conifer Forest growing on the uplands had been partially replaced by *Nothofagus* (evergreen temperate rainforest), and/or that the *Nothofagus* and ferns co-dominated heath vegetation along the coast. There is no evidence for extensive freshwater swamps.

Because the palaeolatitude of the Duntroon Basin remained relatively constant at about 70^{0}S, it is reasonable to assume that climates remained seasonally cool to cold (upper microtherm to possibly lower mesotherm) throughout the Santonian-Campanian time. If its palaeoecology has been correctly interpreted, then the expansion of ancestral *Nothofagus* implies that summers are likely to have been wet (humid), despite the apparent limited extent of freshwater swamp and peat moss communities.

5.2.6   *South-East Australia*

1.   Otway Basin

Microfloras preserved in marine facies (Copa-1, Fenton Creek-1) indicate that the *Podocarpus-Prumnopitys* Austral Conifer Forest remained prominent in uplands around the western Otway Basin (Macphail and Hos 1990, A.D. Partridge pers. comm.). The coastal vegetation included significant numbers of Proteaceae (*Proteacidites*). Representation of ancestral *Nothofagus* and Callitrichaceae is more variable, with values ranging from zero to frequent (<5%).

2.   Gippsland Basin

The relative abundance of ancestral *Nothofagus* (*Nothofagidites endurus*, *N. senectus*) and *Callitrichaceae* is equally variable but mean values are usually higher and often increase up-section in many wells. For example values up to 30-40% are recorded in Late Campanian microfloras in Tuna-1 and Tuna-4 (Tulip 1985, Tulip and Macphail 1986). More generally, pollen dominance is shared between ferns, including Blechnaceae, gymnosperms (*Podocarpus-Prumnopitys*, *Podosporites microsaccatus*), small to medium diameter (<45 µm) Proteaceae and unidentified tricolpate types. Araucarians are rare relative to other gymnosperms.

Inferred climate

Assuming that the Otway and Gippsland Basin microfloras are broadly contemporary, the combined data point to either a strong west to east increase in precipitation, especially during summer months, over a relatively short distance or (preferred) that the expansion of *Nothofagus* within the rift valley systems was subject to strong edaphic control. Conditions in the Gippsland region almost certainly were very wet (perhumid) with summer rainfall sufficient to support extensive freshwater lakes and possibly the minor development of *Sphagnum* raised bogs.

Mean annual temperatures are likely to have remained in the microtherm range. If the inferred higher summer rainfall values were associated with an increased cloud cover, then conditions in the Gippsland Basin are likely to have been cooler than in regions to the west.

5.2.7   *Tasmania*

No known record.

6. TIME SLICE K-6

Age Range: Late Campanian-Maastrichtian [~70-65 Ma]

Zones: *Tricolporites lilliei* to *Forcipites longus* Zones
              Isabelidinium korojonense to *Manumiella druggii* Zones

6.1   Macrofossil Floras

Unidentified plant cuticle usually is a major component in microfossil preparations.

6.2   Microfossil Floras

Tricolporites lilliei and/or *Forcipites longus* Zone palynofloras are preserved in the offshore basins along the southern and northwestern margins and, less commonly, in central Australia. These provide evidence for massive adaptive radiation of the Proteaceae during the Late Campanian, and a marked north to south provincialism in the composition of the dryland vegetation during the Maastrichtian.

Examples of species that are common to abundant along the southern margin but only sporadically recorded in correlative microfloras from northern and central Australia are: *Dacrycarpus* (*Dacrycarpites australiensis*), *Dacrydium* (*Lygistepollenites balmei*, *L. florinii*), *Lagarostrobos*, *Agathis*/*Wollemia* (*Dilwynites*), *Gambierina* and *Nothofagidites senectus*. Many of these taxa first evolved or migrated into Australia from high latitude remnants of western Gondwana during the Campanian and it is reasonable to assume that all had strong preferences for humid-perhumid habitats and were adapted to seasonally cool-cold (microtherm range) temperatures and low light intensities. However the relative abundance of ancestral *Nothofagus* remains the primary indicator of seasonal humidity.

Fossil pollen types that are extremely rare (or absent) on the southern margin but which routinely occur in the North West Shelf assemblages include a robust variant of *Tricolporites lilliei* (*Neoscortechinia*-type), *Longapertites* (Palmae), *Integricorpus* (Triprojectacites), and *Anacolosidites* sp. cf. *A. acutullus* (*Anacolosa*). Most of these have NLRs that are confined to coastal and/or wet forest types in tropical Africa, Madagascar and Asia and it is reasonable to assume that the taxa indicate seasonally warm (mesotherm range) and seasonally perhumid (possibly monsoonal) conditions.

This conclusion is supported by distribution data.   For example, *Anacolosidites* and *Integricorpus* do not reach the southern margin basins until the Palaeogene whilst *Longapertites* is not recorded south of central Australia. One fossil spore type which first appears in the Campanian (*Cyathidites* s*plenden*s) is nearly identical to spores produced by the tropical mangrove fern *Acrostichum aureum*, although it is premature to assume the taxon is evidence for saline environments.

Many northern microfloras include significant numbers of very small (<15 µm) tricolpate/tricolporate pollen types which resemble morphotypes found in Aptian-Cenomanian microfloras. Because of their size and relatively simple morphology it is unclear whether the types represent angiospermids or more highly evolved angiosperms.

6.2.1 *North-West Australia*

Late Campanian-Maastrichtian sediments are widely preserved on the North West Shelf but few have been sampled for fossil pollen and spores during exploration programs. Exceptions include Cobra-1, Darwinia-1 and Heyward-1 (M.K. Macphail unpubl. results). Because of low yields and suspected down-hole contamination, it is uncertain whether observed trends in relative abundance reflect changes in the source vegetation or variation in miospore transport and/or accumulation in shallow marine environments.

1.   Bonaparte Basin

The most detailed record to date for northern Australia comes from undifferentiated *Isabelidinium korojonense-Manumiella druggii* Zone microfloras preserved in Jacaranda-1 (palaeolatitude ~50^0S) in the Bonaparte Basin (Helby and Partridge 1985, M.K. Macphail unpubl. results).

Taxa that are more common within stratigraphically deeper (Late Campanian-possibly Early Maastrichtian) levels include *Ephedra*, brachyphyll araucarians (*Balmeiopsis*), podocarps (*Podocarpus-Prumnopitys*), small (<15 mμ) tricolpate/tricolpate types, Callitrichaceae, and ferns (Cyatheaceae).

Fossil species that are more frequent at higher (possible Late Maastrichtian) levels include: *Dacrydium* (*Lygistepollenites florinii*), *Neoscortechinia*-type (*T.* spp. cf *T. lilliei*), a small unidentified apiculate/triporate sp. (cf. *Compositoipollenites*), tricolporate pollen grains that may or may not include Cunoniaceae and Elaeocarpaceae, and a diverse, often highly ornamented but mostly undescribed Proteaceae component. The cryptogam flora is usually diverse but no single fossil species or group of species dominates the assemblages. Rare angiosperms found in this section are: *Anacolosa* (*Anacolosidites* cf. *A. acutullus*, Palmae (*Dicolpopollis*, *Longapertites*, *Nupharipollis*), *Beauprea* (*Beaupreaidites*), Chloranthaceae (*Clavatipollenites hughesii*), Cupanieae (*Cupanieidites*), Didymelaceae (*Schizocolpus* sp. cf. *S. marlinensis*), Epacridaceae-Ericaceae (*Ericipites*, *Gillbeea* (*Concolpites leptos*), *Guettarda* (*Guettardidites*), *Gunnera*, *Ilex*, Lactoridaceae (*Lactoripollis*) and diverse Liliaceae (*Liliacidites*).

2.   Browse Basin

Late Maastrichtian (Upper *Forcipites longus* Zone Equivalent) palynofloras from the Prudhoe-1 well (M.K. Macphail unpubl. results) are dominated by araucarians (*Agathis*/*Wollemia*) and brachyphyll araucarians (*Balmeiopsis*). The next most commonly occurring taxa are podocarps (*Podocarpus-Prumnopitys*, *Podosporites microsaccatus*), tree- and ground-ferns including Cyatheaceae, *Acrostichum*-type, Gleicheniaceae and Dicksoniaceae (*Trilites tuberculiformis*) and fern allies (*Camarozonosporites*). Proteaceae and undescribed tricolpate/tricolporate types are frequent to common and usually diverse. Rare angiosperms include *Anacolosa* (*Anacolosidites* cf. *A. acutullus*), Callitrichaceae, *Gunnera*, *Ilex* and palms (*Arecipites*, *Dicolpopollis*, *Longapertites*, *Nupharipollis*).

Inferred climate

The Jacaranda-1 microfloras imply araucarian-dominated Austral Conifer Forest and/or angiosperm-fern heath communities growing in the Bonaparte Basin during the Late Campanian had been replaced by subtropical seasonal (possibly monsoonal) rainforest by Late Maastrichtian time. Conversely, the Prudhoe-1 microfloras imply Austral Conifer Forest remained relatively prominent into Late Maastrichtian time. Trace to frequent occurrence of Callitrichaceae and/or *Azolla* implies that freshwater swamps were present in both basins.

Contrary to global cooling trends during the Late Campanian-Maastrichtian, the Jacaranda sequence is ecologically more consistent with the development of seasonally humid-perhumid (possibly monsoonal) and very warm (upper mesotherm-megatherm) conditions. Conditions along the coast in the Browse Basin to the south-west were slightly cooler unless the better representation of gymnosperms is due to the Neves Effect. The data are inadequate to determine whether very warm to hot conditions on the palaeo-northwestern margin are due to local factors, e.g. warm water currents, or whether global cooling did not affect low palaeolatitude regions. The only (very weak) evidence that temperatures decreased during the Late Maastrichtian is a small increase in *Dacrydium* at the top of the Bonaparte Basin section.

3.   Kimberley region

Possible Maastrichtian microfloras preserved in lignitic sediments in the Goats Paddock meteor crater provide a record of a local microclimate on the inland (southeastern) margin of the Kimberley Block (L. Sharman unpubl. data).

Re-examination of the assemblages (M.K. Macphail unpubl. data) confirms that the diversity is high, with some 34 cryptogam, 8 gymnosperm and 68 angiosperm taxa being present. Pollen dominance is shared between the Proteaceae and *Araucaria*; rare taxa include *Dacrydium* (*Lygistepollenites florinii*), *Lagarostrobos*, *Anacolosa*, *Beauprea*, *Gunnera*, *Ilex*, Lactoridaceae, Liliaceae and *Sphagnum*. Most of these taxa are likely to have grown on or around the (swampy) site. An exception is *Araucaria*, which may have formed woodland or scrub communities on the crater walls. Palms are absent but otherwise the sequence is not dissimilar to the Prudhoe-1 assemblages.

Inferred climate

The microflora is evidence that microclimates within the crater were humid to perhumid. This may or may not have been the case regionally since the moisture available to plants growing on the floor of the crater almost certainly will have been enhanced by the inward drainage of rainwater. It is not improbable that deep fracturing of the subsurface rocks will have allowed groundwater to discharge within the crater. The absence of palms is weak evidence that mean annual temperatures were cooler (lower mesotherm) or the temperature range was more extreme than on the coast.

6.2.2   *North-East Australia*

No known record.

6.2.3   *Central Australia*

1.   Alice Springs district

Thin organic-rich strata, which preserve Late Maastrichtian (Upper *Forcipites longus* Zone Equivalent) microfloras, have been intersected in boreholes drilled in two informally named microbasins (Ayers Rock Basin, Huckitta Basin) located on the margins of the Arunta Block (Twidale and Harris 1977, Harris and Twidale 1991, Truswell 1987a, Macphail 1997a).

Pollen dominance is variably shared between podocarps (*Microcachrys*, *Podocarpus-Prumnopitys*, *Podosporites microsaccatus*), Proteaceae and cryptogams, including (Huckitta Basin) high frequencies of *Sphagnum* and Gleicheniaceae. Uncommon to rare taxa include fern allies and ferns (*Camarozonosporites*, Cyatheaceae), possible pteridosperms (*Alisporites*), cheirolepidacean conifers, araucarians (*Araucaria*), podocarps (*Lagarostrobos*,

Dacrydium and its extinct relation *Lygistepollenites balmei*) and *Ephedra*. Uncommon to rare angiosperms include: *Anacolosa* (*Anacolosidites* cf. *A. acutullus*), *Beauprea* (*Beaupreaidites elegansiformis*, *B. verrucosus*), Callitrichaceae, Chloranthaceae (*Clavatipollenites hughesii*), Ericaceae-Epacridaceae, *Gambierina*, *Integricorpus*, Liliaceae, Trimeniaceae (*Periporopollenites demarcatus*), tricolporates including *Neoscortechinia*-type (*Tricolporites lilliei*, *Tricolporites* cf. *T. lilliei*), and Winteraceae (*Pseudowinterapollis*). Four probable palm genera are present (*Arecipites*, *Longapertites*, *Nupharipollis*, *Spinizonocolpites*).

Inferred climate

These assemblages are difficult to interpret ecologically since palms, which imply very warm to hot, upper mesotherm temperatures, were growing in the Ayers Rock Basin, at approximately the same time as *Sphagnum* bog, which imply microtherm range conditions surrounded the Huckitta Basin. The most likely explanation is that microclimates in the two basins were different. For example the Ayers Rock microflora includes a dinoflagellate that is usually found in marine sediments (*Ceratopsis obliquipes*) and discharge of warm saline groundwater may explain the presence of a possible mangrove palm (*Spinizonocolpites*), even if mean air temperatures were cool (lower mesotherm). The presence of podocarp-dominated Austral Conifer Forest is evidence regional climates were seasonally humid-perhumid in both basins.

6.2.4 *South-West Australia*

1.   Carnarvon Basin

Microfloras preserved in marine sediments in Alpha North-1 provide a record of the Late Campanian to Maastrichtian plant communities growing on the margins of the Carnarvon Basin (M.K. Macphail unpubl. results). Fossil spores and pollen are uncommon relative to dinoflagellates but the sequence has the advantage that the individual microfloras have been precisely dated using nannofossils (Rexilius 1989).

Samples yielding statistically significant (>150) numbers of miospores range in age from the latest Late Campanian to basal Middle Maastrichtian. Dominant taxa are Proteaceae and cryptogams. The angiosperm component lacks many of the distinctively ornamented *Proteacidites* spp. found in the northern and southern margin basins and, apart from Proteaceae, only unidentified tricolpate and tricolporate types occur in above-trace numbers. Rare taxa include *Beauprea*, Chloranthaceae (*Clavatipollenites hughesii*, *C.* sp. cf. *C. glarius*), *Gambierina*, *Ilex* and Liliaceae. Uncommon to rare cryptogams include *Lophosoria, Anemia* and Lycopodiaceae. Palms and temperate rainforest taxa such as *Nothofagus* are absent. The only frequent to common gymnosperms are podocarps (*Podocarpus-Prumnopitys*, *Podosporites microsaccatus*) and possible pteridosperms (*Alisporites*). Uncommon to rare gymnosperms include cheirolepidiacean conifers, *Ephedra*, podocarps (*Dacrydium* including *Lygistepollenites balmei*, *Lagarostrobos*, *Microcachrys*) and araucarians (chiefly *Agathis/Wollemia*). Common cryptogams include Cyatheaceae, Gleicheniaceae (*Clavifera*, *Gleicheniidites*) and *Sphagnum*.

The palaeovegetation appear to have been a floristically impoverished variant of the fern heath and Austral Conifer Forest communities recorded further to the north in the Browse and Bonaparte Basins.

<u>Inferred climate</u>

The relatively good development of *Sphagnum* bog implies climates were cool-cold (possibly upper microtherm) and probably wet (humid) with a strong seasonal bias. Since the Carnarvon Basin was located at 'mid' (~60^{0}S) rather than very high palaeolatitudes during Campanian-Maastrichtian time, the preferred explanation is the cool conditions reflect cold currents flowing along the western margin.

2.   <u>Pilbara region</u>

A thin lignite recovered during exploration drilling (B. Balme pers. comm.) provides the only known record of climates in the Pilbara region during the Late Campanian or Early Maastrichtian (M.K. Macphail, unpubl. results). The age is based on *Tricolporites* cf. *T. lilliei* in an assemblage lacking *Stereisporites* (*Tripunctisporis*) sp. An undescribed lycopod spore previously recorded only in Late Cretaceous microfloras in central Australia is present in low to frequent numbers.

Spores, in particular *Sphagnum*, Gleicheniaceae and the putative brackish to freshwater algal cyst *Amosopollis cruciformis* dominate the microflora. Otherwise the only frequently recorded taxa are *Lagarostrobos* and Proteaceae. The diversity of the latter is very low relative to coastal assemblages. Rare taxa include *Dacrydium* (*Lagarostrobos florinii*) *Dacrycarpus*-type (*Trisaccites* sp.) and Callitrichaceae. An unusual feature is the high relative abundance of fully opaque black particles that appear to be carbonised wood. The source vegetation is interpreted to be a spring or river-fed freshwater swamp surrounded by *Sphagnum* bog and heath. *Lagarostrobos* was either a rare shrub or tree growing in the swamp or on the banks of local streams.

<u>Inferred climate</u>

The assemblage broadly resembles microfloras found in central Australia during the Maastrichtian. Local conditions were seasonally cool-cold (microtherm range) and prone to droughts (and wildfires). Pollen data (Macphail *et al*. 1999) indicate peat mounds developed under very wet (perhumid) climates at Port Davey in far southern Tasmania are analogous to the Pilbara swamp in that these also dry out and are burnt during infrequent droughts.

6.2.5 *Central southern Australia*

1.   <u>Duntroon Basin</u>

Late Campanian-Maastrichtian microfloras are preserved in nearshore to marginal marine sediments intersected in Greenly-1 (Morgan and Hooker 1993d). Maastrichtian microfloras are preserved in the Borda-1 well in the same basin (Morgan and Hooker 1993b) and also in samples dredged from the seafloor in the Great Australian Bight (Alley and Clarke 1992).

Raw pollen counts indicate that a number of the taxa that were prominent in the *Nothofagidites senectus* Zone microfloras had declined in relative abundance by the Early/Late Campanian boundary. These include araucarians (*Agathis*/*Wollemia*), podocarps (*Microcachrys*, *Podosporites microsaccatus*), *Nothofagus*, Callitrichaceae, ferns, fern allies (*Retitriletes*) and peat moss (*Sphagnum*).

The only consistently common taxa found in the Late Campanian and Maastrichtian microfloras in Greenly-1 are Proteaceae, possible pteridosperms (*Alisporites*) and ferns (Cyatheaceae). *Dacrydium* (*Lygistepollenites florinii*), *Lagarostrobos*, *Gambierina*, ancestral *Nothofagus* (*Nothofagidites senectus*), Gleicheniaceae and Osmundaceae and *Sphagnum* are

frequent only in occasional samples. Maastrichtian microfloras in Borda-1 are dominated by Proteaceae, podocarps and ferns (Cyatheaceae, Gleicheniaceae), with lesser abundances of *Sphagnum*. The combined data indicate that Austral Conifer Forest expanded at the expense of *Nothofagus* communities during the Late Campanian-Maastrichtian, whilst coastal communities continued to be dominated by mixed angiosperm-fern heath.

Inferred climate

Trends in the relative abundance of *Nothofagus* are likely to reflect drier (humid) conditions during summer months (cf. Alley and Clarke 1992) and probably cooler (upper microtherm) temperatures during winter given the persistent presence of *Sphagnum*, the absence of palms, and the high latitude position of the basin (~70^0S). Cooler ocean currents flowing into the Australo-Antarctic Seaway are one explanation.

6.2.6 *South-East Australia*

1.   Northern Tablelands

Undocumented samples submitted to the New South Wales Department of Mines indicate that Maastrichtian coals outcrop somewhere near Kempsey on the Northern Tablelands, northeastern New South Wales (McMinn 1986a). Neither the site, nor plant microfossils recovered from the samples, can be relocated (A. McMinn pers. comm.).

Inferred climate

Unpublished notes (McMinn 1986a) only indicate the microflora included *Gambierina*. The record is consistent with cool and probably humid climates. Whether these conditions reflect topography or the mid latitude position (~60^oS) is unknown.

2.   Otway Basin

Presence/absence data from Copa-1 (Macphail and Hos 1990) demonstrate Maastrichtian (*Manumiella druggii* Zone) flora in the western Otway Basin included *Dacrydium* (*Lygistepollenites balmei*), *Gambierina*, ancestral *Nothofagus* (*Nothofagidites brachyspinulosus*, *N. senectus*), and a possible palm (*Monosulcites gemmatus* ms). These data confirm climates were wet (humid-perhumid) and relatively cool (upper microtherm).

3.   Gambier Basin

Rowett (1997b) has recorded a Cyatheaceae-Proteaceae dominated *Forcipites longus* Zone Equivalent microflora in (onshore) McNicol-1 well. Rare taxa include *Agathis/Wollemia*, *Gambierina*, *Forcipites longus* and *Tricolporites lilliei*.

4.   Gippsland Basin

Detailed counts for the Sunfish-2, Tuna-1 and Tuna-4 wells (Tulip 1985, Tulip and Macphail 1986) indicate podocarps and *Nothofagus* populations were mostly replaced by floristically complex communities dominated by *Forcipites*, *Gambierina* and Proteaceae. Many of the latter produced large and/or highly ornamented pollen types that are likely to indicate insect-pollination (Macphail 1994a). Cryptogam values are more variable. For example Cyatheaceae and *Sphagnum* are uncommon in Tuna-1 but remain frequent in Tuna-4.

<u>Inferred climate</u>

As for regions to the west along an Australo-Antarctic Rift System, the collapse of *Nothofagus* and reduced presence of gymnosperms and (locally) *Sphagnum* in southeastern Australia (74-77^{0}S) is best explained by drier (but still humid) summers and seasonally cool-cold (upper microtherm) temperatures. Cool to cold ocean currents flowing along the eastern margin provide a link between the collapse of *Nothofagus* populations in the Gippsland and Bass Basins and global cooling. Whether cooling climates are consistent with the observed adaptive radiation of the Proteaceae is less clear.

6.2.7 *Tasmania*

1.   <u>Bass Basin</u>

Microfloral successions recorded in the northern Bass Basin (A.D. Partridge and M.K. Macphail unpublished data) and northeastern Tasmania (Moore *et al*. 1984) appear to be identical to those recorded in non-marine sites in the Gippsland Basin.

<u>Inferred climate</u>

The data imply relatively cool (upper microtherm) temperatures and effectively drier (humid) summers.

6.3   Other Evidence

6.3.1 *North-West Australia*

Shafik (1993) has noted that Maastrichtian nannofossil assemblages may have palaeoclimatic implications.

APPENDIX 2

TERTIARY DATA

1. TIME SLICE T-1

Age Range: **Paleocene [65-54.8 Ma]**

Zones: Lower to Upper *Lygistepollenites balmei* Zones
              Trithyrodinium evittii to Lower *Apectodinium hyperacanthum* Zones

1.1   Macrofloras

Lack of outcrop limits information on Paleocene macrofossils to scattered sub-basaltic localities in the Southeastern Highlands and Northern Tablelands of New South Wales.

1.1.1   *North-West Australia*

No known record.

1.1.2   *North-East Australia*

1.   Northern Tablelands of New South Wales

Braided stream deposits, which preserve numerous leaf impressions and charcoal fragments, are associated with Late Paleocene (~54 Ma) basalts on the Mount Royal Range near Barrington Tops in the Upper Hunter River district (Martin *et al*. 1987).

Inferred climate

The macrofossils have not been studied but charcoal may be the result of local wildfires ignited by volcanic eruptions.

1.1.3   *Central Australia*

No known record.

1.1.4   *South-West Australia*

No known record.

1.1.5   *Central southern Australia*

No known record.

1.1.6   *South-East Australia*

1.   Southeastern Highlands

Early Paleocene (est. 58-60 Ma) fossil wood and leaves are preserved at Cambalong Creek (Vadala and Drinnan 1998) and in a 150 m thick lacustrine sequence on the Monaro Plains, Southeastern Highlands (Taylor *et al*. 1990). The latter (Palaeolake Bungarby) predates Late Paleocene-Early Eocene basalts with K/Ar dates of 45-53 Ma. Gymnosperms include *Acmopyle* (Podocarpaceae), whose NLRs are confined to New Caledonia and Fiji, and *Libocedrus* (Cupressaceae), whose NLRs are endemic to New Zealand and New Caledonia (Hill and Brodribb 1999, Whang and Hill 1999). Angiosperms able to be identified to extant

genera are *Gymnostoma* (Casuarinaceae) and *Eucryphia* (Eucryphiaceae); extinct genera include *Banksieaephyllum* (Proteaceae) (Hill 1991, Carpenter *et al*. 1994b, Scriven and Hill 1995, Taylor and Hill 1996).

The flora is an important one, not only because it includes taxa whose NLRs are widely separated in the South-west Pacific region, but also because of the diversity of morphological adaptations. For example the closest relatives of *Gymnostoma* (G. *antiquum*) and *Banksieaephyllum* (*B. taylorii*) occur in relatively dry areas in (tropical) New Guinea and (humid) southwestern Western Australia, respectively. The latter is the earliest known example of scleromorphy recorded in an Australia Tertiary angiosperm.

Inferred climate

Well-defined growth rings in the fossil gymnosperm wood point to tree growth being controlled by strong seasonal fluctuation in mean temperature since neither photoperiod nor precipitation are likely to have been limiting factors. Based on bioclimatic data from extant NLRs, Taylor *et al*. (1990) propose that mean annual temperatures were mesotherm (~14-20^0C) but frost-free. To what degree the cool/wet conditions at Palaeolake Bungarby were due to elevation and orographic cloudiness reducing evapo-transpiration on the Southeastern Highlands of New South Wales is uncertain.

1.1.7 *Tasmania*

No known record.

1.2   Microfloras

Early and/or Late Paleocene marine sediments are widespread in the offshore Carnarvon, Canning and Bonaparte Basins but are seldom sampled (Apthorpe 1988). Dredge samples from the continental shelf off the central and northern New South Wales coast include some rocks that preserve Paleocene dinoflagellate floras (R. Helby pers. comm.) but information on the associated spore-pollen content is unavailable. Other Paleocene sequences in the same category occur off the western margin of Tasmania margin, and in north-west Tasmania (e.g. Sorell Basin) and south-west Western Australia (Kings Park Shale). For this reason what is currently known about the Paleocene flora and vegetation mostly comes from *Lygistepollenites balmei* Zone microfloras preserved in subcrop in southeastern Australia.

1.2.1 *North-West Australia*

No known record.

1.2.2 *North-East Australia*

1.   Northern Tablelands of New South Wales

Palaeosols and braided stream deposits underlie latest Paleocene [~54 Ma] basalts at elevations above 800 m on the Mt. Royal Range and sites near Tamworth on the Northeastern Tablelands (Morgan 1978, Martin *et al*. 1987).

Microfloras recovered from Mt. Royal are dominated by araucarians (*Araucaria*), podocarps (*Dacrydium*, *Lagarostrobos*, *Podocarpus-Prumnopitys*) and ferns (Cyatheaceae, Gleicheniaceae). Angiosperm pollen are relatively rare, with the most common taxon being small, nondescript Proteaceae. *Nothofagus* is absent. The Tamworth assemblages are dominated by Podocarpaceae (*Dacrycarpus*, *Lagarostrobos*, *Podocarpus-Prumnopitys*), but

also include relatively frequent *Nothofagus* (*Fuscospora*) spp. and tricolpate angiosperms. Rare taxa include *Sphagnum*, probable shrub podocarps (*Microcachrys*, *Podosporites*), *Gambierina*, *Ilex*, and a probable Caryophyllaceae (*Periporopollenites polyoratus*). Charcoal is common in the Mt. Royal assemblage, and this microflora and those from Tamworth also preserve halophytic dinoflagellate cysts (*Ceratopsis* spp.) similar to those found in the Lake Eyre Basin (see below).

Inferred climate

During the Late Tertiary, Araucariaceae are typically associated with weakly seasonal, warm and wet climates (Macphail and Truswell 1989). Paleocene araucarians may have had similar preferences, based on the higher relative abundance of *Araucaria* in Late Paleocene microfloras on the Northeastern Tablelands than in correlative assemblages on the Southeastern Highlands (see below). If correct, seasonally warm (mesotherm range) and wet (humid-perhumid) climates were in existence in northeastern New South Wales sometime during the Late Paleocene despite isotope data indicating cooler (microtherm) SSTs in northeastern Queensland.

1.2.3 *Central Australia*

1. Lake Eyre Basin

Probable Late Paleocene (Upper *Lygistepollenites balmei* Zone Equivalent) microfloras are preserved at the base of the Eyre Formation in the Clayton-3 well (Alley 1986) and BMR Muloorina-2 and Poonarunna-1 wells in the Lake Eyre Basin (Sluiter 1991, Martin 1998b). The latter wells preserve the earliest recorded evidence of extensive burr-reed (Sparganiaceae) swamps in inland Australia (Alley 1998).

The Clayton-3 microfloras are co-dominated by ferns (Blechnaceae, *Cyathea*, *Cyathidites*, Gleicheniaceae), Podocarpaceae (*Dacrydium*, *Lagarostrobos*, *Microcachrys*, *Podocarpus-Prumnopitys*) and Callitrichaceae. Rare taxa include the extinct *Dacrydium* clade (*Lygistepollenites balmei*) as well as taxa that are more typical of Early Eocene microfloras, e.g. Cupanieae, Pandanaceae (*Freycinetia*), Sapotaceae and extinct species such as *Tricolpites incisus* (possibly Loranthaceae) and *Tricolporites leuros* (possibly Meliaceae). Rare taxa in Lake Eyre Bore 8A include a probable early species of *Eucalyptus* (*Myrtaceidites tenuis*) and *Proteacidites pachypolus* (Alley 1983a).

The Muloorina-2 and Poonarunna-1 sequences are equally difficult to date due to the co-occurrence in the same assemblage of species that are used to subdivide Late Paleocene and Early Eocene time in the Gippsland Basin. Relative abundance data compounds this problem since the closest analogues of the Paleocene assemblages in Poonarunna-1 occur in an interval (17-34 m) in Muloorina-2, which may be Early Eocene in age (M.K. Macphail, unpubl. observ.). Other unusual features of the two palynosequences are:

a.   The only common gymnosperm(s) in Muloorina-2 are families (Cupressaceae and/or Taxodiaceae) that now are most common on the sub-humid-humid Southeastern Highlands and adjacent central west slopes of New South Wales and in the alpine zone in Tasmania. Podocarps are rare (*Dacrydium*, *Lagarostrobos*) to frequent (*Microcachrys*, *Podocarpus*) whilst Araucariaceae occur in isolated samples only. Correlative microfloras in Poonarunna-1, located 280 km to the south of Muloorina-2, are dominated by podocarps, chiefly *Podocarpus* but include frequent to common (up to 10%) *Dacrydium*, *Lagarostrobos* and *Microcachrys*. Conversely, Cupressaceae-Taxodiaceae pollen occur in trace numbers only.

b.   The dominant angiosperm types in Muloorina-2 are Cunoniaceae (now characteristic of warm temperate rainforest in New South Wales and southern Queensland), Myrtaceae and Proteaceae whilst Casuarinaceae and ancestral *Nothofagus* (*Nothofagidites endurus*) occur in low to trace numbers only. Cyatheaceae and Callitrichaceae are common to abundant in the lower and upper samples, respectively. Cryptogams are frequent to common overall in Poonarunna-1 but the individual species are uncommon or rare.

c.   Some microfloras include a dinoflagellate cyst (*Morkallacysta* spp.) that is closely related to the marine species, *Deflandrea obliquipes* and *D. pachyceros*. High salinity values are inconsistent with the presence of rainforest species but may have arisen due to infrequent or short-term droughts or (preferred) the local discharge of possibly warm saline groundwater.

Inferred climate

Because of the poor age control, it is uncertain whether the data represent floristic successions during the Late Paleocene-Early Eocene transition or heterogeneous (mosaic) plant communities growing at about the same time during the Late Paleocene (cf. Macphail *et al.* 1994, Alley 1998). The data confirm conditions were wet (humid) and warm (mesotherm range) but are not inconsistent with a short dry season. Mean values inferred by Sluiter (1991) are >1400 mm pa and 18-19^{0}C (upper mesotherm), respectively.

1.2.4   *South-West Australia*

1.   Carnarvon Basin

Basal Early Paleocene microfloras in Alpha North-1 are dominated by dinoflagellates. The low spore-pollen yield is dominated (>50%) by extinct species of Proteaceae (M.K. Macphail, unpubl. results). Rare taxa include Lycopodiaceae, Gleicheniaceae, podocarps (chiefly *Podocarpus-Prumnopitys*), Casuarinaceae (*Haloragacidites harrisii*) and *Anacolosa* (*Anacolosidites acutullus*). Early Late Paleocene assemblages are similar but include *Dacrydium* (*Lygistepollenites florinii*) and at least one Proteaceae (*Propylipollis annularis*) that can be linked to a living shrub (*Xylomelum occidentale*) confined to south-west Western Australia. *Anacolosa* indicates very warm (upper mesotherm) and humid conditions, possibly with a pronounced dry season.

By mid Late Paleocene time, Casuarinaceae (*Gymnostoma*) had become the dominant pollen type (50%). Proteaceae comprise 20%, and unidentified angiosperms and cryptogams 7-9%, of the pollen sum. Rare to frequent taxa include shrubs and herbs characteristic of modern coastal wetlands, e.g. Restionaceae (*Milfordia*) and Sparganiaceae (*Aglaoreidia*). Rainforest trees and shrubs include Araucariaceae (*Dilwynites*), Cupressaceae, Podocarpaceae (*Lygistepollenites florinii*), *Austrobuxus*-type (*Malvacipollis* spp.), *Ilex* and *Nothofagus* (*Nothofagidites brachyspinulosus*, *N. emarcidus*). The same assemblage preserves the earliest confirmed record in Australia of the mangrove palm *Nypa* (*Spinizonocolpites prominatus*).

2.   Perth Basin

Kemp (1978) has reported *Nothofagus* pollen from the probable Late Paleocene-Early Eocene Kings Park Shale, near Perth but few other details are available. Microfloras from the Langley-1 bore which intersected a 200 m thick section of the Kings Park Shale are dominated by Gleicheniaceae and Proteaceae but appear to be extensively contaminated by older and younger palynomorphs (M.K. Macphail pers. observ.). Many of the Proteaceae appear to be undescribed or are geographical variants of described species.

<u>Inferred climate</u>

Some differences between the Early and mid Late Paleocene vegetation may reflect (possibly eustatic-forced) changes in depositional environment (nearshore to marginal marine). Nevertheless the paucity of rainforest species and cryptogams such as Gleicheniaceae and *Sphagnum* relative to Casuarinaceae and Proteaceae is consistent with rainfall being either sub-humid or humid with a pronounced dry season (possibly monsoonal). The presence of *Nypa* indicates conditions were very warm to hot (upper mesotherm to possibly megatherm) in the Carnarvon basin and may reflect general global warming since it predates the Paleocene-Eocene thermal maximum. The presence of *Nothofagus* in these conditions is anomalous. Whether similar or cooler conditions prevailed in the Perth Basin is unknown.

1.2.5 *Central southern Australia*

1.   <u>Duntroon Basin</u>

Early Paleocene (Lower *Lygistepollenites balmei* Zone Equivalent) microfloras are preserved in nearshore facies intersected by the Borda-1 and Greenly-1 wells (Morgan and Hooker 1993c, 1993d). Taxa that are common in both wells include Cyatheaceae (*Cyathidites*), Gleicheniaceae, Araucariaceae (*Dilwynites*), Podocarpaceae (*Dacrydium*, *Lagarostrobos*, *Podocarpus-Prumnopitys*) and Callitrichaceae. Ericales and Proteaceae are frequent, and *Gambierina* is present in low numbers, in Borda-1 whilst *Sphagnum* and a Myrtaceae (referred to *Eucalyptus*) are frequent to common in Greenly-1. Two species of *Nothofagus* (*Nothofagidites brachyspinulosus*, *N. deminutus*) are recorded in the same well.

<u>Inferred climate</u>

The presence of extensive freshwater swamps, tree- and ground-fern communities, and podocarp-dominated rainforest demonstrate conditions within the Bight were much wetter (humid-perhumid) than the present arid climate. Rainfall may have been seasonal but any dry period was shorter or less severe than in northwestern Australia. Temperatures during the Early Paleocene were relatively warm (lower mesotherm) but it is uncertain whether the increased abundance of Araucariaceae relative to aquatic herbs such as Callitrichaceae and mesophytic cryptogams during the Late Paleocene reflects global warming or is due to an enhanced Neves Effect. Circumstantial evidence for local warming is provided by the earlier prominence of Myrtaceae and Euphorbiaceae (*Austrobuxus*-type) in the Bight than in the Otway and Gippsland Basins to the east.

1.2.6 *South-East Australia*

1.   <u>Southeastern Highlands</u>

Late Paleocene (~58-60 Ma) microfloras preserved in Lake Bungarby (Taylor *et al.* 1990) are co-dominated by Gleicheniaceae, Araucariaceae (*Agathis*/*Wollemia*), Podocarpaceae (chiefly *Podocarpus-Prumnopitys* and extinct spp. of *Dacrydium* and *Lagarostrobos*), ancestral *Nothofagus* (*Nothofagidites endurus*), *Nothofagus* (*Fuscospora*) spp., several Proteaceae (*Basopollis*, *Proteacidites*) and the probable Caryophyllaceae (*Periporopollenites polyoratus*).

The diversity is low but the rare angiosperm component includes a number of types that are more typical of sites at low elevations, for example *Anacolosa* (*Anacolosidites acutullus*), Casuarinaceae, Euphorbiaceae (*Austrobuxus*-type), *Gambierina*, *Ilex*, Winteraceae and *Xylomelum occidentale*-type. *Sphagnum* is uncommon. Carbonaceous shales of possibly similar (possible Late Paleocene) age from Bowral are dominated by Osmundaceae,

Araucariaceae (*Araucaria*) and Podocarpaceae (*Dacrydium*) with minor *Gambierina*, Callitrichaceae and Casuarinaceae (McMinn 1989a). This gymnosperm-dominated community appears to have been similar to coastal communities in the Gippsland Basin and implies that Austral Conifer Forest formed the regional forest vegetation across southeastern Australia during the Paleocene. Conditions appear to have been relatively cool (lower mesotherm) and wet to very wet (humid-perhumid) but not to the extent of allowing extensive *Sphagnum* raised bogs to develop across the uplands.

Inferred climate

The expansion of Araucariaceae and a diverse group of rainforest angiosperms during the Late Paleocene is consistent with significant warming although mean temperatures are likely to have remained within the lower mesotherm range. Rainfall appears to have remained high (perhumid) with no pronounced seasonal bias.

2.   South Coast of New South Wales

Sediments of probable Late Paleocene age have been dredged from the continental shelf off Jervis Bay (Ocean Science Institute FR 5/91-30 DB13) on the South Coast of New South Wales (M.K. Macphail and A.D. Partridge, unpubl. results).

The spore-pollen component is dominated by Casuarinaceae and podocarps, in particular *Dacrydium* (*Lygistepollenites balmei*), *Microcachrys*, *Podocarpus-Prumnopitys* and *Podosporites*. Blechnaceae and *Lagarostrobos* are frequent. Rare taxa include Gleicheniaceae, *Dacrydium* (*Lygistepollenites florinii*), *Halocarpus*, *Phyllocladus*, Callitrichaceae, probable Caryophyllaceae (*Periporopollenites polyoratus*), *Gambierina*, ancestral *Nothofagus*, Proteaceae and several angiosperm types with no known NLRs. Taxa with modern mesotherm affinities are absent, including Araucariaceae. Pollen dominance almost certainly has been skewed by the Neves Effect. Nevertheless the results demonstrate that a form of Austral Conifer Forest extend northwards along the eastern margin to about palaeolatitude 57^0S during the Paleocene. *Dacrydium* (*Lygistepollenites balmei*, *L. florinii*) and Casuarinaceae appear to have lined coastal rivers or formed extensive swamp communities on the coastal plains.

Inferred climate

Climates are interpreted to have been relatively wet (humid) and within the lower mesotherm range. Low photoperiod is unlikely to have been ecologically significant at this latitude but conditions may have been influenced by cool currents flowing northward along the eastern margin.

3.   Gambier Basin

Rowett (1997a) has recorded a possible *Lygistepollenites balmei* Zone Equivalent microflora in McNicol-1 but few details are available.

4.   Otway Basin

Late Paleocene microfloras from Copa-1, offshore western Otway Basin (Macphail and Hos 1990) are dominated by Araucariaceae (*Araucariacites*, *Dilwynites*) with frequent *Austrobuxus*-type and Casuarinaceae. *Gambierina* is present in low numbers. Otherwise the only detailed data on Paleocene floras come from outcrops of the Pebble Point and Dilwyn Clay Formations (Wangerrip Group) near Princetown on the Otway coast (see Table 1 in Harris 1965a, Partridge 1999). Foraminifera and dinoflagellates provide independent age control.

Microfloras preserved in the Lower *Lygistepollenites balmei* Zone interval (Pebble Point Fm.) are dominated by Podocarpaceae (*Podocarpus-Prumnopitys*, *Lagarostrobos*) with lesser amounts (3-8%) of Araucariaceae (*Agathis/Wollemia*), *Dacrydium*, *Microcachrys*, *Phyllocladus*, Blechnaceae-type, Gleicheniaceae and *Sphagnum*. *Nothofagus* (*Brassospora*, *Fuscospora*) increases from ~1% to 4% up-section. Other angiosperms are uncommon except for Proteaceae (up to 8%) and Callitrichaceae (3-4%) but rare types include Casuarinaceae, *Austrobuxus*-type, *Gambierina*, and *Xylomelum occidentale*-type.

Microfloras from the overlying Upper *L. balmei* Zone (Dilwyn Clay) are dominated by gymnosperms and cryptogams but are more diverse due to the increasing angiosperm component. Species first appearing in this interval include *Anacolosa* (*Anacolosidites acutullus*) and Tiliaceae (*Intratriporopollenites notabilis*). *Nothofagus* and Callitrichaceae become rare whilst Myrtaceae (*M. eugeniioides*) comprises up to 17% of the total pollen count. *Nothofagus* is uncommon in a similar Proteaceae and Myrtaceae-dominated Late Paleocene microflora in the Latrobe-1 well in the Port Campbell Embayment.

Microfloras from the onshore Torquay Sub-basin to the east of Princetown include correlatives of the Lower and Upper *Lygistepollenites balmei* Zones (M.K. Macphail unpubl. data). The earlier zone is dominated by ancestral *Nothofagus* and Proteaceae spp., with frequent Araucariaceae (*Araucaria*, *Agathis/Wollemia*) but Casuarinaceae and *Gambierina* are rare. The younger zone is dominated by Araucariaceae (*Araucaria*, *Agathis/Wollemia*), Podocarpaceae (*Podocarpus-Prumnopitys*) and Gleicheniaceae, associated with Cyatheaceae, Matoniaceae, Dicksoniaceae, *Dacrycarpus*, *Dacrydium*, *Halocarpus*, *Lagarostrobos*, *Anacolosa* (*Anacolosidites acutullus*, *A.* sp. nov.) and an undescribed member of the Northern Hemisphere Triprojectites group (*Integricorpus*).

Inferred climate

The Lower *Lygistepollenites balmei* Zone assemblages represent a form of Austral Conifer Forest growing under relatively cool (lower mesotherm) and uniform to weakly seasonal and wet (humid) conditions. The expansion of angiosperms during Upper *L. balmei* Zone time is consistent with warming temperatures although the absence of palms indicates mean values remained within the mesotherm range.

5.   Gippsland Basin

Paleocene sediments reach thicknesses of up to 950 m in the offshore Gippsland Basin and have been intersected in some 650 wells. A review of the well data (Macphail *et al.* 1994, A.D. Partridge pers. comm.) indicates that *Lygistepollenites balmei* Zone microfloras primarily are dominated by podocarps (*Podocarpus-Prumnopitys*, *Lagarostrobos*) and Proteaceae, with lower, but still high, relative abundances of *Dacrydium* (including *L. balmei*), ancestral *Nothofagus* (*Nothofagidites endurus*) and Callitrichaceae. Araucariaceae (predominantly *Dilwynites*) are most abundant in distal marine facies, due to the Neves Effect.

Comparisons of Lower and Upper *L. balmei* Zone sequences, for example in the Tuna Field wells (I.R. Sluiter and M.K. Macphail unpubl. data), indicate that angiosperms such as *Gambierina*, *Peninsulapollis gillii* and *Tetracolporites verrucosus* are more common in the Early Danian than in younger (Late Danian-Early Thanetian) assemblages. The reverse is true of ancestral *Nothofagus,* Callitrichaceae and several extinct Proteaceae. By Late Thanetian, Gleicheniaceae, Cyatheaceae, Proteaceae and ancestral *Nothofagu*s had replaced *Lagarostrobos, Dacrydium* and Callitrichaceae as the most common taxa.

Inferred climate

The sequence records the progressive replacement of Austral Conifer Forest by floristically complex angiosperm-dominated rainforest. The succession is ecologically consistent with warming followed by transient cooling although mean temperatures appear to have remained within the lower mesotherm range. Rainfall was high (perhumid) throughout the year. To what extent plant community evolution was shaped by low light intensities or possible microtherm temperatures during winter months is unclear.

1.2.7 *Tasmania*

Paleocene sediments occur in subcrop in the Bass Basin (lower Eastern View Coal Measures) and along the western margin of Tasmania but few reliable quantitative data are available in open-file reports.

1.   <u>Bass Basin</u>

Non-marine correlatives of the Lower and Upper *Lygistepollenites balmei* Zone in Yolla-1 well, Bass Basin, are dominated by Araucariaceae (*Agathis*/*Wollemia*) with trace amounts of *Lagarostrobos*, *Dacrydium* (*Lygistepollenites balmei*) and *Gambierina* (Morgan 1986b). *Nothofagus* (*Brassospora*) pollen in the same microfloras are suggested to be Eocene contaminants introduced during processing.

Evans and Mulholland (1969) have recorded Podocarpaceae-dominated possibly Upper *L. balmei* Zone Equivalent microfloras in the Clam-1 well, drilled in the King Island Sub-basin near King Island, and also in northwestern Tasmania. Rare taxa include Casuarinaceae, Callitrichaceae, Ericales, *Gambierina*, ancestral *Nothofagus*, nondescript Proteaceae and a much more diverse group of ferns and gymnosperms. Correlative assemblages occur in the Longford and Port Sorell Sub-basins in northern Tasmania, and in an onshore extension of the Sorell Basin south of Macquarie Harbour (S. Forsyth pers. comm.). Microfloras from Rose Rivulet near Launceston and other unspecified localities in the same (Launceston) sub-basin, dated as Paleocene by Harris (1967), include Tiliaceae (*Intratriporopollenites notabilis*) and are either contaminated with Eocene taxa or are Early Eocene (Lower *Malvacipollis diversus* Zone Equivalent).

2.   <u>West Coast</u>

Macphail (unpubl. results) has recorded an apparently uncontaminated Upper *L. balmei* Zone Equivalent microflora in cuttings in the Cape Sorell-1 well, offshore Sorell Basin. Pollen dominance is shared between Araucariaceae (*Agathis*/*Wollemia*), Podocarpaceae (*Lagarostrobos*, *Podocarpus-Prumnopitys*), ancestral *Nothofagus* and Cyatheaceae (*Cyathidites*), with lesser amounts of Gleicheniaceae, Proteaceae and undescribed tricolporate angiosperms. Rare taxa include *Dacrydium* (*Lygistepollenites balmei*, *L. florinii*), Callitrichaceae, Casuarinaceae, Cupanieae, Cunoniaceae (*Gillbeea*), Euphorbiaceae, *Gambierina* and Myrtaceae.

<u>Inferred climate</u>

Within the limits of the data, relative pollen dominance points to Austral Conifer Forest being the dominant vegetation type on the Bassian Plain and in northern and western Tasmania during the Paleocene. The diversity is low relative to the Gippsland Basin, possibly due to reduced photoperiods during winter months. Species with modern warm temperate or

subtropical affinities are rare, hinting that conditions are likely to have been relatively cool (upper microtherm) and uniformly wet (perhumid).

1.3 Other Records

1.3.1 *North-West Australia*

The trend from clastic to predominately carbonate sedimentation indicates Early Paleocene climates on the North West Shelf were wetter in the south and drier in the north-east (Apthorpe 1988).

1.   Bonaparte Basin

Late Paleocene climates in the southern Bonaparte Basin are suggested to have been very warm to hot (upper mesotherm) and moderately dry (subhumid), based on the deposition of interbedded dolomite sequences. Tropical species of planktonic foraminifera imply warm water currents flowed southwards along the western margin.

2.   Browse Basin

Wind-blown quartz sands hint at arid conditions inland of the Browse Basin although summer rainfall remained adequate (subhumid to humid) to support marsh development on the coast during the Paleocene.

1.3.2 *North-East Australia*

1.   North-east Queensland

Feary *et al.* (1991) have estimated surface water temperatures off the north-east coast during the Early Paleocene were within the upper microtherm range (12-14^{0}C). Values for the Late Paleocene were similar (12.5-15^{0}C), consistent with the global data that only minor warming occurred at mid to low palaeolatitudes during the PETM.

1.3.3 *Central Australia*

1.   Lake Eyre Basin

Alley (1998) records widespread deep weathering and silcrete development in the Lake Eyre Basin during the Danian and Thanetian. This is consistent with seasonally warm and wet climates across inland South Australia.

1.3.4 *South-East Australia*

1.   Otway Basin

Apectodinium-dominated dinocyst floras found in the Upper *Lygistepollenites balmei* (and Lower *Malvacipollis diversus*) Zones are suggested to be precisely coincident with the beginning of the PETM (H. Brinkhuis pers. comm.).

2.   TIME SLICE T-2

Age Range: Early Eocene [54.8-49 Ma]

Zones: *Malvacipollis diversus* to *Proteacidites asperopolus* Zones
                  Upper *Apectodinium hyperacanthum* to *Homotryblium tasmaniense*
                  Zones

2.1   Macrofloras

Preservation of diverse macrofossil assemblages was probably better and more widespread during the Eocene than for any other epoch in the Tertiary. To date, studies have tended to focus on Tasmania, the onshore Gippsland Basin (Yallourn and Morwell Open Cuts), the Dilwyn Formation (Wangerrip Group) and Anglesea deposits in Victoria, and Maslin Bay, South Australia. The majority of these sites accumulated during the Middle-Late Eocene. Others cannot be securely dated to a particular epoch within the Eocene. An important exception is the late Early Eocene Regatta Point site, west coast of Tasmania.

Much emphasis has been placed on the description and evolutionary significance of the macrofossils, in particular gymnosperms, where evolutionary trends in stomatal distributions appear to reflect long-term palaeoclimatic trends (Hill and Carpenter 1991, Carpenter *et al*. 1994, Hill and Brodribb 1999). With the possible exception of cycads, the NLRs are rainforest trees and shrubs. Most of these are extinct within the region, e.g. *Araucaria* in Tasmania, or Australia as a whole, e.g. *Acmopyle* and *Dacrycarpus* (Podocarpaceae).

2.1.1   *North-West Australia*

Christophel (1994) cites *Banksia* (Proteaceae) as one of the taxa present in an Early Eocene macroflora preserved at Merlinleigh in the Kennedy Ranges.

Inferred climate

Sclerophyll taxa such as *Banksia* may reflect strongly leached soils as much as seasonally dry climates (Beard 1990, Hill 1998a, 1998b).

2.1.2   *North-East Australia*

A probable Early Eocene macroflora from Moranbah, Queensland, includes Araucariaceae (*Agathis*), Casuarinaceae (*Gymnostoma*), Lauraceae and Proteaceae.

Inferred climate

Conditions appear to have been warm (mesotherm range) and seasonally wet (humid-perhumid).

2.1.3   *Central Australia*

No known record.

2.1.4 *South-West Australia*

Inferred climate

Epiphyllous fungal germlings (Lange 1978a) indicate warm (mesotherm) and wet (humid-perhumid) climates.

2.1.5 *Central southern Australia*

No known record.

2.1.6 *South-East Australia*

1. Otway Basin

An Early Eocene macroflora from Deanes Marsh, Victoria (Demon's Bluff Formation) includes probable Lauraceae and Proteaceae leaves (Christophel 1994).

Inferred climate

Mean leaf sizes are smaller than leaf sizes preserved in the Middle Eocene Anglesea Flora and may reflect relatively cool (possibly lower mesotherm) conditions.

2.1.7 *Tasmania*

1. West Coast

Carbonaceous mudstones outcropping at Regatta Point, Macquarie Harbour, preserve a diverse late Early Eocene (Upper *Malvacipollis diversus-Proteacidites asperopolus* Zone) macroflora associated with equally diverse pollen, spores and dinoflagellates. In spite of the high (~66^0S) palaeolatitude, taxa identified so far include cycads (*Bowenia*, *Pterostoma*), which may have adapted to low photoperiods or other stresses associated with high latitudes (Hill 1990a, Hill and Pole 1994), *Araucaria* and a genus intermediate between *Araucaria* and *Agathis* (Bigwood and Hill 1985, Hill and Bigwood 1987, Hill 1990b), *Dacrycarpus* (Hill and Carpenter 1991) and *Nypa* (Pole and Macphail 1996).

Inferred climate

Nypa populations confirm that air and sea surface temperatures within Macquarie Harbour were in the upper mesotherm or megatherm range (~$20-24^0$C). A slightly lower mean temperature is possible is climates were highly equable (see Table 2). Associated taxa have subtropical-tropical NLRs and indicate that mean rainfall values were high to very high (perhumid). Pole (in Pole and Macphail 1996) suggests that rainfall was seasonal or possibly monsoonal.

2. East and North Coasts

Early possible Eocene mudstones from Buckland on the east coast preserve macrofossils of *Acmopyle*, a podocarp now confined to rainforest occupying mild (13-17^0C) but very wet (>5000 mm pa) montane habitats in New Caledonia and Fiji (Townrow 1965a, Hill and Carpenter 1991). A leaf of a deciduous species of *Nothofagus* is preserved in probable *Proteacidites asperopolus* Zone sediments at Deloraine on the central north coast (R.S. Hill pers. comm.).

Climates appear to have been very wet (perhumid) but cool (lower mesotherm) relative to western Tasmania and probably with a stronger seasonal bias.

2.2 Microfloras

Sites preserving Early Eocene microfloras are widely distributed along the southern margin and extend northwards into central Australia although only rudimentary data were available for some important sections, e.g. for the Kings Park Shale, Perth. Carbonate facies accumulating off the northwestern coast rarely preserve plant microfossils other than dinoflagellates and information for this region is due to fortuitous preservation of miospores in two offshore exploration wells (M.K. Macphail unpubl. data). Early Eocene sediments are either absent due to erosion and/or non-deposition, or have not been sampled in wells drilled in the offshore Bight basins.

Whether or not the Upper *Lygistepollenites balmei*/Lower *Malvacipollis diversus* Zone boundary coincides with the Paleocene-Eocene Thermal Maximum is unproven but the microfloral data provide reliable evidence that maximum Tertiary warmth occurred during the Early Eocene in southern Australia.

2.2.1 *North-West Australia*

1. Bonaparte Basin

Probable late Early Eocene sediments at 582-690 m in Jacaranda-1 preserve diverse microfloras dominated by Casuarinaceae (*Haloragacidites harrisii*), Euphorbiaceae (*Malvacipollis diversus*) and Restionaceae (*Milfordia homeopunctata*). These are associated with frequent Cyperaceae (*Cyperaceaepollis neogenicus*) and sporadically frequent to common Myrtaceae (*Myrtaceidites parvus-mesonesus*), Proteaceae, and unidentified tricolpate and triporate types (one resembling the warm temperate rainforest tree *Celtis*). Gymnosperms are uncommon, with the only genus recorded being *Araucaria*. Other rare taxa include aquatic and semi-aquatic freshwater ferns and fern allies (*Azolla*, *Selaginella, Isoetes*, *Stenochlaena*), Sparganiaceae (*Aglaoreidia qualumis*), Palmae (*Arecipites*, *Dicolpopollis*, *Longapertites*, *Nypa*), *Anacolosa* (*Anacolosidites acutullus*), Cunoniaceae, Droseraceae, *Guettarda*, *Gunnera*, *Ilex* Liliaceae, Poaceae, *Polygonum* (*Glencopollis*) and *Xylomelum occidentale*-type. Some of these taxa do not appear in the southeastern basins until the Late Eocene or Early Oligocene and the herbaceous component is unusually prominent relative to southern Australia as a whole.

2. Browse Basin

Abundant spores of *Azolla* in possible Early Eocene assemblages in Prudhoe-1 (1010-1274 m) suggest freshwater swamps fringed the coastline. The only gymnosperm recorded is *Araucaria*.

Inferred climate

The combined microfloral data primarily represent freshwater coastal swamp communities fringed by angiosperm-dominated rainforest. Climates appear to have been hot (megatherm) and seasonally very wet (perhumid).

2.2.2 *North-East Australia*

1.   Southern Queensland

Revised dating (this study) indicate that microfloras recovered from 270 ft. in Borehole NS 5 near Brisbane (Harris 1965d) and 6380-7334 ft. in the AGO Aquarius-1 well in the Capricorn Basin (Hekel 1972) are Early Eocene.

If correct, then the Early Eocene vegetation bordering the Capricorn Basin comprised floristically impoverished possibly temperate forests dominated by podocarps, and riparian communities dominated by Casuarinaceae Euphorbiaceae and tree-ferns (Cyatheaceae). The only evidence for a warmer (subtropical-tropical) element is a spinose diporate pollen grain, which <u>might</u> represent *Nypa*.

Microfloras preserved near Brisbane appear to be more diverse and include taxa whose NLRs range from cool temperate (gymnosperms) to subtropical-tropical (angiosperms) rainforest. Examples are Araucariaceae (*Agathis*/*Wollemia*), *Dacrycarpus*, *Dacrydium*, *Lagarostrobos* (*Phyllocladidites mawsonii*), *Microcachrys*, and *Anacolosa* (*Anacolosidites acutullus*) and Tiliaceae, respectively.

Inferred climate

The data point to relatively warm (mesotherm range) and seasonally very wet (perhumid) conditions in southern Queensland although mean temperatures were cooler than in southeastern Australia. One possible explanation is that cool-cold currents flowing up the eastern margin extended as far north as the Capricorn Basin.

2.   Northern New South Wales

Sediments of latest Early or basal Middle Eocene (*Proteacidites asperopolus* Zone Equivalent) age have been dredged from the continental shelf off Coffs Harbour (Ocean Science Institute C14/84 7DB6) on the central north of New South Wales (M.K. Macphail unpubl. results).

Although dominated by dinoflagellates, in particular *Homotryblium tasmaniense*, sufficient pollen and spores were recovered to indicate that the coastal vegetation was dominated by angiosperms and cryptogams, not gymnosperms. Frequent to common taxa are *Lygodium* (*Crassiretitriletes vanraadshoovenii*), *Pteris* (*Polypodiaceoisporites* spp.), Casuarinaceae, diverse Proteaceae and Euphorbiaceae (*Austrobuxus*-type). Rare taxa include Blechnaceae (including the now tropical endemic *Stenochlaena*), Gleicheniaceae, Dennstaedtiaceae (*Histiopteris*), Araucariaceae (*Araucaria*, *Agathis*/*Wollemia*), Cupanieae, *Ilex*, Myrtaceae, *Nothofagus* (*Brassospora, Nothofagus*), Tiliaceae and Trimeniaceae. *Nypa* is absent.

Inferred climate

The relatively high values of fern spores reflect water transport. Nevertheless the results point to a complex, angiosperm-dominated rainforests occupying the coast at about palaeolatitude 53^0S. Climates appear to have been relatively warm (mesotherm range) and uniformly very wet (perhumid).

3.   Northern Tablelands

McMinn (1989c) has recorded a possible late Early Eocene, *Proteacidites asperopolus* Zone equivalent, palynoflora from below tuffs and basalt in Glen Innes DDH-105, near Inverell, in

northern New South Wales. The assemblage is dominated by monolete and trilete ferns and fern allies, associated with infrequent Casuarinaceae, Euphorbiaceae, *Nothofagus* and (one specimen) Tiliaceae.

Inferred climate

The source vegetation appears to have been fern-dominated wet scrub growing under uniformly wet (perhumid) and probably cool (lower mesotherm) conditions. Whether the cryptogam dominance reflects a recent wildfire (fire succession) or highly fertile soils (edaphic disclimax) is unknown.

2.2.3 *Central Australia*

Tertiary basins in the Alice Springs district and Lake Eyre Basin (Eyre Formation) preserve thin carbonaceous units of probable Early Eocene age (age range latest Paleocene-late Early Eocene).

Many of these preserve very diverse microfloras, some of which also include dinoflagellate species that are usually associated with saline conditions (Sluiter 1991, Macphail 1996c, 1997a, Alley 1998). The reason for this is unclear but salinity levels may have been raised due to discharge of saline groundwater, leaching of salt from outcrops of Early Cretaceous or older marine sediments, e.g. the Bitter Springs Formation, or deposition within hydrologically-closed basins. Microfloras from the Eyre Formation are similar to those recorded in the Late Paleocene and, apart from the absence of mangroves, are also similar to Early Eocene assemblages found in coastal northwestern Australia.

1.   Alice Springs district

Early Eocene microfloras from the Santa Teresa and Ti-tree Basins, Alice Springs district are dominated by Casuarinaceae, Proteaceae including large (mostly described) and many small (undescribed) types, and tricolporate types. These are associated with occasional high values of monolete spores, *Acrostichum*-type (*Cyathidites splendens*), Gleicheniaceae and other trilete fern spores, and Euphorbiaceae (*Malvacipollis*). Araucariaceae, *Dacrydium*, *Lagarostrobos* (*Phyllocladidites reticulosaccatus*), Cupanieae and a member of the otherwise wholly Northern Hemisphere Triprojectites group (*Integricorpus*) are frequent in some samples. Rare taxa include *Pteris*, *Lygodium*, *Lagarostrobos*, Palmae (*Arecipites*, *Longapertites*, *Nupharipollis*), Anacardiaceae (*Striacolporites* cf. *cephalus*)*, Anacolosa* (*Anacolosidites acutullus*), *Beauprea*, *Callitrichaceae*, *Gunnera*, *Ilex*, Sapotaceae (*Sapotaceoidaepollenites latizonatus*) and Tiliaceae. *Nothofagus* is very rare and the records may be due to downhole contamination.

2.   Lake Eyre Basin

Microfloras dated as Paleocene in Lake Eyre Bore 8A drillhole (Alley 1983a) are more likely to be Early Eocene, based on *Myrtaceidites tenuis* and *Proteacidites pachypolus*, which first occur in the Gippsland Basin in the Lower *Malvacipollis diversus* Zone. The assemblages are dominated by small angiosperm pollen types (possibly Cunoniaceae, Elaeocarpaceae) associated with Gleicheniaceae, Cupressaceae, Podocarpaceae (*Dacrydium*, *Lagarostrobos*, *Microcachrys*, *Podocarpus-Prumnopitys*), *Ascarina*, Casuarinaceae, Euphorbiaceae, Myrtaceae, *Nothofagus* (*Nothofagidites flemingii*), and diverse Proteaceae.

Pollen data from the Muloorina-2 and Poonarunna-1 wells (Sluiter 1991) hint that Myrtaceae, Proteaceae, a wholly extinct lineage of *Lagarostrobos* (*Phyllocladidites reticulosaccatus*) and *Podocarpus-Prumnopitys* expanded at the expense of Cunoniaceae, Cupressaceae-

Taxodiaceae and Araucariaceae during the Early Eocene. Cyatheaceae are rare relative to the underlying Late Paleocene microfloras.

Inferred climate

The high degree of variation between assemblages points to the source being a mosaic of ecologically disparate taxa whose affinities may lie anywhere from modern tropical (megatherm) to cool-cold temperate (microtherm) rainforest. The combined evidence, however, implies that conditions were very warm (upper mesotherm) and seasonally very wet (perhumid). Sluiter (1991) has interpreted ecological trends in the Lake Eyre Basin as indicating the complex angiosperm rainforest types evolved in response to an increase in the mean annual rainfall and temperature (to ~22^{0}C).

2.2.4   *South-West Australia*

1.   Carnarvon Basin

Basal Early to basal Middle Eocene sediments at 1135-1257 m in Alpha North-1 preserve diverse microfloras, which are dominated by Casuarinaceae (*Haloragacidites harrisii*), and unidentified tricolporate types and include frequent to common Euphorbiaceae (*Malvacipollis diversus*) and Proteaceae (M.K. Macphail unpubl. data). The gymnosperm flora is more diverse than in Jacaranda-1 (Bonaparte Basin). Gymnosperms (*Araucaria*, Cupressaceae, *Dacrydium*, *Podocarpus-Prumnopitys*, *Agathis/Wollemia*) are much more common and Myrtaceae, Cupanieae, *Nypa* and Restionaceae (*Milfordia homeopunctata*) less common than in the Bonaparte Basin. Rare taxa include Lycopodiaceae, *Selaginella*, *Acrostichum*-type (*Cyathidites splendens*), Gleicheniaceae, *Lygodium*, *Pteris*, *Sphagnum*, Anacardiaceae (*Ailanthipites*, *Striacolporites* cf. *cephalus*) *Anacolosa* (*Anacolosidites acutullus*), *Banksia* (*Banksieaeidites elongatus*), Convolvulaceae (*Perfotricolpites*), a possible *Eucalyptus* (*Myrtaceidites tenuis*), Euphorbiaceae (*Malvacipollis* spp.), *Gunnera*, *Ilex*, Musgraveinae (*Banksieaeidites arcuatus*), *Nothofagus* (*Brassospora*, *Fuscospora*), *Nypa*, Poaceae, Polygalaceae (*Polycolporopollenites esobalteus*), *Santalum* (*Santalumidites cainozoicus*) and Stylidiaceae (*Tricolpites stylidioides*).

Inferred climate

The paucity of megatherm taxa such as *Nypa*, the relatively prominent representation of gymnosperms and cryptogams, and the presence of *Nothofagus* indicates that mean air temperatures within the Carnarvon Basin were slightly cooler (upper mesotherm) than in the Bonaparte Basin (possibly megatherm). Rainfall may have been similar, i.e. very wet (perhumid), with a (pronounced) dry season. The apparent poor development of coastal swamps may be due to local tidal regimes rather than the regional rainfall.

2.   Perth Basin

Abundant angiosperm pollen, including Proteaceae, is reported to occur in dinoflagellate-dominated assemblages from the Kings Park Shale interval intersected in the Sir James Mitchell Park-2A bore, Perth (Backhouse 1981). The age of this microflora is uncertain (possible Early Eocene) but Churchill (1973) and Jarzen and Pocknall (1993) have reported *Nypa* and Strasburgeriaceae (*Bluffopollis scabratus*) pollen, respectively, from the same formation.

Inferred climate

Assuming that the record of *Nypa* is correct, then conditions within the southern Perth Basin (palaeolatitude ~60^{0}S) were very warm to hot (upper mesotherm) and seasonally very wet (perhumid).

2.2.5 *Central southern Australia*

Harris and Foster (1972) report a Proteaceae-dominated palynoflora of possible late Early Eocene age from the Polda Basin, western Eyre Peninsula. Few other details are provided beyond the comment that *Nothofagus* is uncommon in this non-marine assemblage.

Inferred climate

Mean temperatures are likely to have been within the mesotherm range.

2.2.6 *South-East Australia*

1.   Gambier Basin

Lower to possible Upper *Malvacipollis diversus* Zone microfloras are preserved in non-marine and marginal marine facies intersected in the Douglas Point-1 and McNichol-1 wells, Gambier Basin in South Australia (Harris 1973, Rowett 1997a). From the limited information provided, vegetation at Douglas Point-1 was dominated by diverse Proteaceae with minor (<5%) *Nothofagus*. Rare taxa include Araucariaceae (*Agathis/Wollemia*), Callitrichaceae, Cupanieae, Didymelaceae, Euphorbiaceae, Loranthaceae and Sapotaceae. Microfloras in McNicols-1 are dominated by ferns (*Cyathidites*) and Euphorbiaceae (*Austrobuxus*-type). Common taxa include Podocarpaceae (unspecified), Casuarinaceae and non-eucalyptoid Myrtaceae. Less common taxa include *Nypa*.

Inferred climate

Sea surface and air temperatures were sufficiently warm (upper mesotherm) to support *Nypa* whilst summer rainfall was adequate (humid-perhumid) to support *Nothofagus*.

2.   Otway Basin and Torquay Embayment

The Dilwyn Formation (Wangerrip Group) in the Otway Basin is correlated with the Early Eocene *Malvacipollis diversus* Zone (Harris 1965a, Morton *et al*. 1994) although the precise age of outcrop samples analysed by Harris (*ibid*) is uncertain (cf. Harris 1971a). Based on *Cyathidites gigantis*, The highest sample (S218) is no younger than Lower *M. diversus* Zone. If correct, then the early Early Eocene flora was dominated by angiosperms (75%), in particular Myrtaceae (11%), with *Agathis/Wollemia* (15%) and *Podocarpus-Prumnopitys* (5%) being the only frequent-common gymnosperms. Many of the less common angiosperms cannot be related to extant plants. Exceptions include *Anacolosa* (*Anacolosidites acutullus*), Callitrichaceae, Cupanieae, *Eugenia*-type (*Myrtaceidites eugeniioides*), Euphorbiaceae, *Nothofagus* (*Brassospora*, *Fuscospora*), diverse Proteaceae, and Tiliaceae. *Nypa* is not recorded.

Microfloras from the onshore Torquay Sub-basin (Torquay Embayment) in southwestern Victoria appear to include correlatives of the Middle *Malvacipollis diversus* and Upper *M. diversus* Zone as well as the Lower *M. diversus/Apectodinium hyperacanthum* Zones (M.K. Macphail, unpubl. results).   Pollen dominance varies from Proteaceae-Gleicheniaceae assemblages with frequent unidentified tricolporates, *Sphagnum* and (marine facies) Callitrichaceae and rare ancestral *Nothofagus* in the early Early Eocene section, to diverse Proteaceae-Araucariaceae (*Araucaria*, *Agathis/Wollemia*) assemblages with frequent *Podocarpus-Prumnopitys*, Casuarinaceae, Cupanieae, Euphorbiaceae (including *Alchornea*), *Nothofagus* (*Brassospora*) spp., Pandanaceae (*Freycinetia*), Tiliaceae and Trimeniaceae, in the middle and/or late Early Eocene sections. Many more taxa have no identified NLRs and

pollen dominance almost certainly was influenced by marine flooding. For example, high values of Callitrichaceae in *Apectodinium hyperacanthum* Zone assemblages may reflect coastal freshwater swamps that were periodically inundated by saltwater.

Inferred climate

SSTs within the Otway Basin and Torquay Embayment appear to have been below the (upper mesotherm) threshold required to support *Nypa* despite the presence of this mangrove palm in the Gambier Basin, Gippsland Basin and on the West Coast of Tasmania (see below). Nevertheless the data are consistent with the expansion of evergreen rainforest communities whose closest modern equivalent is Araucariaceae (dry) rainforest. If this conclusion is applicable to the region as a whole, then it is difficult to avoid concluding that mean temperatures were within the upper mesotherm range as well as being overall wet to very wet (humid-perhumid) during the Early Eocene, and that summer rainfall remained adequate to support *Nothofagu*s on, for example, the Otway Ranges.

3.   Gippsland Basin

Early Eocene sediments have been recorded from 120 wells in the offshore Gippsland Basin and reach a maximum thickness of ~350 m (A.D. Partridge, pers. comm.). Much thinner correlative sections occur at depth onshore but are sampled only by cuttings.

A number of taxa which had been present in the Bass Strait region since Late Cretaceous times became extinct at or shortly after the Paleocene/Eocene boundary, e.g. *Lygistepollenites balmei*, *Phyllocladidites reticulosaccatus*, *Gambierina* spp. and *Australopollis obscurus*. The base of *Malvacipollis diversus* Zone is defined by the first appearance of three typically megatherm taxa – *Lygodium* (*Crassiretitriletes vanraadshoovenii*), *Nypa* and Tiliaceae. Microfloras are usually dominated (>50%) by angiosperms, chiefly Euphorbiaceae (*Malvacipollis* spp.) with variable amounts of Casuarinaceae, Proteaceae and undescribed tricolpate and tricolporate types. The highest values of the *Malvacipollis* spp. (>40%) occur in coals, indicating the Euphorbiaceae (*Austrobuxus*), like Casuarinaceae (*Gymnostoma*), were prominent in coastal swamp or riparian communities. Gleicheniaceae and *Acrostichum*-type (*Cyathidites splendens*) may dominate other swamp assemblages. *Agathis*/*Wollemia* is the most abundant gymnosperm, and Cyatheaceae, Gleicheniaceae and indeterminate trilete (*Cyathidites*) and monolete (*Laevigatosporites*) ferns are the most abundant cryptogams. Rare to uncommon taxa include a possibly extinct species of the now wholly tropical genus *Bombax* (Bombacaceae) and *Intratriporopollenites notabilis* (Tiliaceae), which in a marginal marine context may represent the mangrove *Brownlowia*.

Nypa and a possible extinct species of *Freycinetia* (Pandanaceae) are most prominent during the early Early Eocene *M. diversus* Zone but become rare during Middle and Upper *Malvacipollis diversus* Zone time: Proteaceae and Euphorbiaceae increase in diversity and relative abundance at the same time. Over the same interval, the now extinct *Proteacidites* species complex (*P. grandis-leightonii*) was replaced by another extinct complex (*P. pachypolus-nasus-asperopolus*). Since *Proteacidites pachypolus* first appears in marginal marine facies, it is reasonable to assume that the succession reflects eustatic forcing (cf. Macphail *et al*. 1994). Subsequently *Proteacidites pachypolus* expanded into a very wide range of dryland habitats and elevations, including around peat swamps on the Atherton Tableland in northeastern Queensland during the Pliocene.

Notable first appearances in the Gippsland Basin during the late Early Eocene (Upper *Malvacipollis diversus-Proteacidites asperopolus* Zones) are *Santalum* (*Santalumidites cainozoicus*), Sapotaceae (*Sapotaceoidaepollenites* spp.), the putative early eucalypt *Myrtaceidites tenuis* and mistletoes (*Gothanipollis*). Podocarpaceae (*Lagarostrobos*) and *Nothofagus* (*Brassospora*) increase in relative abundance (~5-7%) whilst *Nypa*, Tiliaceae and

a number of distinctive Proteaceae species become extinct within or at the top of the *Proteacidites asperopolus* Zone (equivalent to tropical Foram zones P8-P10).

Inferred climate

The data point to the rapid (geologically abrupt) establishment of evergreen megatherm rainforest communities in the Gippsland Basin and their slower replacement by less thermophilous (mesotherm) communities during the mid and late Early Eocene. Based on the maximum relative abundance of *Nypa*, mean annual temperatures peaked within the lower megatherm range (~24^{0}C) during the earliest Early Eocene tropical Foram Zone P6 (A.D. Partridge pers. comm.). By the end of the Early Eocene mean temperatures appear to have cooled but remained within the upper mesotherm range (<24^{0}C). Rainfall almost certainly was very high (perhumid) in all seasons.

2.2.7 *Tasmania*

Early Eocene sediments crop out at Buckland (east coast) and Regatta Point on the west coast (M.K. Macphail unpubl. results). Correlative facies (Eastern View Coal Measures) have been intersected at depth in many offshore wells, e.g. Squid-1 and Tasmanian Devil-1 in the offshore Bass Basin, onshore extensions such as the Wesley Vale Sub-basin in northwestern Tasmania, and Clam-1 and Cape Sorell-1 in the offshore Sorell Basin. Late Early Eocene microfloras are preserved in marginal marine sediments that have been carried by rotational slipping to water depths of 3000-4000 m off the western margin of Tasmania (Truswell 1997, M.K. Macphail unpubl. data). These range in age from Upper *Malvacipollis diversus* to *Proteacidites asperopolus* Zone. Much of the data presented in the well completion reports are difficult to reconcile with the Gippsland data because of the inexperience of the palynologists involved. Down hole caving is common but diversities are lower than in the Gippsland Basin, in part due to deposition in marginal to open marine environments.

1.   Bass Basin

Microfloras (Morgan 1986b) from the Yolla-1 well, located approximately midway between King and Flinders Islands, indicates that *Nothofagus* and Araucariaceae (*Agathis/Wollemia*) were less common during *M. diversus* Zone Equivalent time than during the Paleocene. Casuarinaceae and *Nothofagus* (*Lophozonia*) are consistently present but are uncommon to rare, whilst the only taxa with strong thermophilous affinities are Cupanieae and an extinct species of Dicksoniaceae or Matoniaceae (*Cyathidites gigantis*). Martin (1985) lists *Nothofagus* (*Brassospora*) as 'common but possibly caved [downhole]' in assemblages assigned to the *P. asperopolus* Zone in the Squid-1 well. The Clam-1 microflora (Evans and Mulholland 1969) includes *Anacolosa*, Cupanieae and *Myrtaceidites tenuis* but not *Nypa*. *Nothofagus* (*Brassospora*) is cited as uncommon.

2.   North Coast

Information on correlative sequences preserved in the onshore sub-basins in northwestern Tasmania is unavailable apart from comments (Harris 1967) that probable Early Eocene assemblages from the Launceston area are dominated by Proteaceae and include *Anacolosa* (*Anacolosidites acutullus*), *Gambierina*, *Nothofagus* and Tiliaceae.

A late Early Eocene (*Proteacidites asperopolus* Zone Equivalent) is preserved at Deloraine in the central north (M.K. Macphail unpubl. results). The microflora is dominated by *Nothofagus* (*Brassospora*) spp. and *Proteacidites pachypolus* and includes mesotherm rainforest elements such as Cupanieae, *Santalum*, Sapotaceae and possibly Meliaceae: *Anacolosa*, *Ilex* and Tiliaceae are not recorded. If correctly dated, the microflora is evidence

that *Nothofagus* (*Brassospora*) spp. remained common in the regional vegetation of inland Tasmania during the Early Eocene warm period.

3.   West Coast

Upper *Malvacipollis diversus-Proteacidites asperopolus* Zone Equivalent assemblages recovered from Cape Sorell-1 and co-eval sediments deposited on the continental slope and abyssal plain off the west coast (M.K. Macphail unpubl. data) are dominated by Casuarinaceae and Proteaceae associated with frequent Euphorbiaceae (*Austrobuxus*-type), Cupanieae and *Nothofagus* (*Brassospora*, *Fuscospora*).   Rare taxa include: Alangiaceae, *Anacolosa* (*Anacolosidites acutullus*, *A. luteoides*, *A. rotundus* ms), *Ascarina*, Convolvulaceae (*Wilsonia*), *Compositoipollenites*, the putative eucalypt *Myrtaceidites tenuis*, *Nypa*, *Santalum*, Strasburgeriaceae and Tiliaceae. Araucariaceae (*Araucaria*) is common near the base of the late Early Eocene interval where rare taxa also include *Anacolosa* (*Anacolosidites luteoides*) and a genus of palms (*Longapertites*) previously only recorded in Early Eocene deposits in central and northern Australia.

Slightly younger (*Proteacidites asperopolus* Zone) microfloras from Regatta Point are dominated by Casuarinaceae, Euphorbiaceae and Proteaceae (including frequent *Proteacidites grandis*), associated with frequent *Nothofagus* (*Nothofagidites emarcidus-heterus*), Trimeniaceae (*Periporopollenites demarcatus*) and extinct podocarp shrubs (*Podosporites* spp.) (Macphail *et al*. 1993, M.K. Macphail unpubl. data). Rare taxa with modern mesotherm-megatherm affinities include *Anacolosa* (*Anacolosidites rotundus* ms), Palmae (*Arecipites*, *Dicolpopollis*), *Ascarina*, Cunoniaceae, *Dysoxlum*, *Myrtaceidites tenuis*, *Freycinetia*, *Ilex*, Loranthaceae (*Gothanipollis*), Meliaceae and Strasburgeriaceae (*Bluffopollis scabratus*). Mangroves include *Nypa* (frequent), *Acrostichum*-type, *Sonneratia*-type (*Florschuetzia levipoli*) and, probably, *Brownlowia* (Tiliaceae).

4.   East Coast

The probable Early Eocene microflora at Buckland is dominated by *Nothofagus* (*Brassospora*), *Podocarpus-Prumnopitys* and unidentified tricolporate types, with low (< 5%) amounts of *Araucaria*, *Dacrydium*, Proteaceae and Myrtaceae. Rare taxa include *Dacrycarpus, Ephedra*, *Lagarostrobos*, *Phyllocladus*, *Agathis/Wollemia*), *Ascarina* (*Clavatipollenites* sp.), Cunoniaceae, Elaeocarpaceae, Euphorbiaceae, *Ilex*, and a spinizonocolpate pollen type, which may or may not be related to *Nypa*. Like the Deloraine site, the microflora is evidence that *Nothofagus* (*Brassospora*) spp. remained common in the regional vegetation of inland Tasmania during the Early Eocene warm period.

5.   South-east

A probable early Early Eocene (Lower *Malvacipollis diversus* Zone Equivalent) is preserved at the Styx River in the south-east (M.K. Macphail unpubl. results). Pollen dominance is shared between some five taxa, of which Podocarpaceae (40%), Araucariaceae (12%) and Myrtaceae (*Eugenia*-type) are the most abundant – *Araucaria* (10%), *Agathis/Wollemia* (2%), *Podocarpus-Prumnopitys* (24%), *Podosporites* (15%) and *Eugenia*-type (8%). Frequent taxa are Proteaceae (5%), *Nothofagus* (*Brassospora*) spp. (4%), *Dacrydium* (3%), Ericales (3%) and ferns (chiefly *Cyathidites*).   Unidentified tricolporate types and *Compositoipollenites* reach values of 8% and 3% respectively.   Uncommon to rare taxa include *Sphagnum*, Lycopodiaceae*, Dicksonia*, *Ephedra*, a possible pteridosperm (*Alisporites simplis*), Podocarpaceae (*Dacrycarpus*, *Lagarostrobos*, *Microcachrys*, *Phyllocladus*), Casuarinaceae, Cunoniaceae (*Gillbeea*-type), Euphorbiaceae, Myrtaceae (*Austromyrtus*-type), *Nothofagidites* (*Fuscospora*, *Lophozonia*, *Nothofagus*), diverse Proteaceae and Restionaceae (*Milfordia homeopunctata*).

Inferred climate

The Regatta Point data are compelling evidence that very warm (upper mesotherm) conditions persisted within Macquarie Harbour into late Early Eocene time. Explanations include warm oceanic currents flowing southward down the West Coast of Tasmania or (preferred) that water temperatures within Macquarie Harbour remained atypically warm. Conditions on the East Coast of Tasmania appear to have been cooler (lower mesotherm) during the Early Eocene. Climates overall appear to have been wet to very wet (perhumid) but the paucity of cryptogams and variable representation of *Nothofagus* between Buckland and Deloraine may indicate that summers were relatively dry (weakly seasonal) in the south-east.

2.3   Other Records

2.3.1   *North-East Australia*

1.   North-east Queensland

Feary *et al.* (1991) have estimated SSTs off the north-east coast of Queensland during the early Early Eocene were up to 16.0-18.0^{0}C (lower mesotherm range).

2.   South-east Queensland

Skeletal remains of arboreal fructivores, frogs, snakes, a possible freshwater crocodile and turtles (Tingamarra Local Fauna) are preserved below an early Early Eocene (54 Ma) basalt near Murgon in southeastern Queensland (Godthelp *et al.* 1992). Archer *et al.* (1994) suggest the climate was mild to warm (mesotherm range) throughout the year.

2.3.2   *South-West Australia*

1.   Carnarvon Basin

Foram and lithostratigraphic evidence indicate a cooling in oceanic temperatures and increased continental run-off during the Early Eocene. The latter implies increasing wet (possibly humid) conditions in the northern Carnarvon Basin (Apthorpe 1988).

2.3.3   *South-East Australia*

1.   Otway and Gippsland Basins

Episodic excursions of dinoflagellates belonging to the warmer water Wetzelielliodeae group indicate sea surface temperatures were generally warmer during the Early Eocene than during the Paleocene or Middle Eocene (Partridge 1976, A.D. Partridge pers. comm.).

3. TIME SLICE T-3

Age Range: **Middle to Late Eocene [49-33.7 Ma]**

Zones: Lower to Middle *Nothofagidites asperus* Zones
Rhombodinium waipawaense to *Gippslandica extensa* (*Corrudinium incompositum*) Zones

3.1 Macrofloras

Macrofossils vary from perfectly preserved organic specimens to silcrete casts. Many taxa can be assigned to extant families or genera although almost all specimens represent extinct species within these higher order taxa.

As additional material is described, it is probable some fossil gymnosperms assigned to extant taxa will be reassigned to form genera, e.g. Hill and Pole (1992). In other instances the macrofossils confirm that living species are of considerable antiquity. Examples are: (1) the extant Tasmanian species *Phyllocladus aspleniifolius* (Podocarpaceae) and *Cenarrhenes nitida* (Proteaceae), whose fossil remains occur in a Middle-Late Eocene macroflora at Hasties, northeastern Tasmania (Pole 1992); (2) the South American *Lophosoria quadrapinnata*, a ground fern, whose fossil remains are found in an Oligo-Miocene deposit at Balfour on the north-west coast of Tasmania (R.S. Hill pers. comm.). The last species almost certainly migrated into Tasmania during the Eocene-Oligocene transition. Other trends that become apparent (or more sharply defined) in the macrofossil record during the Middle-Late Eocene are:

a. An increase in the lapse rate. For example, Christophel and Greenwood (1989) conclude that 'foliar physiognomic signatures' indicate that warm temperate to tropical rainforest communities growing at lower latitudes in New South Wales were replaced by cool temperate rainforest types at higher latitudes and elevations in Victoria and Tasmania.

b. An increase in the number of taxa with scleromorphic features. Hill and Merrifield (1993) and Hill (1998a, 1998b) have proposed that the Australian sclerophyll flora evolved during the Eocene primarily in response to low soil nutrient levels, especially of phosphorus, and were pre-adapted to xeric conditions developing during the Late Palaeogene and Neogene.

Recent publications dealing with fossil macro- and microfossil records (of individual taxa are: Alangiaceae (Martin *et al*. 1997), Aquifoliaceae (Martin 1977), Araucariaceae (Bigwood and Hill 1985, Hill and Bigwood 1987, Hill 1990b, 1995), Casuarinaceae (Christophel 1980, Scriven and Christophel 1990, Scriven and Hill 1995), Convolvulaceae (Martin 2000), Cunoniaceae (Barnes and Hill 1999a, 1999b, Barnes and Jordan 2000), Cupressaceae (Hill and Carpenter 1989, Hill 1995, Hill and Whang 1996), cycads (Hill 1978, 1980, Carpenter 1991a), Droseraceae (Truswell and Marchant 1986), Ebenaceae (Christophel and Basinger 1982), Elaeocarpaceae (Rozefelds and Christophel 1996), Euphorbiaceae (Martin 1974), Ginkgoaceae (Hill and Carpenter 1999), Isoetaceae (Hill 1988d), Lactoridaceae (Macphail *et al*. 1999), Menispermaceae (Hill 1989b), Myrtaceae (Lange 1978b, Christophel and Lys 1986), Nothofagaceae (Christophel 1985, Hill 1983a, 1983b, 1984, 1987, 1988a, 1988b, 1992a, 1994a, 1994b, Scriven *et al*. 1995, Scriven and Hill, 1996, Swenson *et al*. 2000), Podocarpaceae (Greenwood 1987, Hill 1989a, 1995, Wells and Hill 1989, Hill and Carpenter 1991, Hill and Pole 1992, Hill and Whang 1996, 2000, Hill and Scriven 1999), Proteaceae (Christophel 1984, Carpenter and Hill 1988, Hill 1988c, 1990c, Hill and Christophel 1988, Rozefelds 1992, 1995), Psilotaceae (Carpenter, 1988), Schizaeaceae (Rozefelds *et al*. 1992),

and Taxodiaceae (Hill *et al*. 1993, Hill 1995). McGowran (1989) has provided a valuable review of Eocene eustatic change southern Australia.

3.1.1 *North-West Australia*

Leaf and fruit impressions are preserved in the Tertiary Van Dieman Sandstone, Melville Island, Northern Territory (Pole and Bowman 1996). These are unlikely to be older than Eocene although the minimum age is unclear. The impressions are thought to include fossil species of Cupressaceae, Proteaceae (*Grevillea* and a genus, *Dilobia*, which is endemic to Madagascar) and Myrtaceae (*Melaleuca*). The parent vegetation is suggested to be an open-canopied, non-rainforest community.

Inferred Climate

Pole and Bowman (*ibid*) propose the vegetation type implies strongly seasonal to monsoonal (humid-perhumid) rainfall and, less certain warm to hot (megatherm) temperatures.

3.1.2 *North-East Australia*

1.   Northern Tablelands of New South Wales

Late Eocene (Middle *Nothofagidites asperus* Zone Equivalent) macrofloras are preserved in 'deep leads' at Vegetable Creek on the New England Tablelands. These have been studied since the 1880s although a number of early identifications are incorrect, e.g. beech (*Fagus*). Re-examination of archived material by Hill (1988a, 1988b) and Hill and Carpenter (1991) confirm the presence of Lauraceae and an extinct *Nothofagus* (*Lophozonia*) species related to the extant dominants of cool temperate rainforest in Tasmania (*N. cunninghamii*) and in the Eastern Highlands in central-northern New South Wales and southern Queensland (*N. moorei*). Early collections also preserve probable specimens of *Phyllocladus*, an extinct Araliaceae and Proteaceae cf. *Darlingia*, which is now endemic to Queensland (cf. Blackburn 1981, Christophel 1994).

Inferred Climate

The specimen of a *Nothofagus* (*Lophozonia*) sp. is considered to be the earliest macrofossil evidence for a cool temperate (microtherm) element in the Eocene vegetation of mainland Australia. If correct, then local conditions were uniformly wet (perhumid) and cool (upper microtherm).

3.1.3 *Central Australia*

1.   Lake Eyre Basin

Organic impressions (leaves and fruits), which have been dated by the associated fossil pollen as Middle Eocene (Lower *Nothofagidites asperus* Zone Equivalent), occur at Nelly Creek (Christophel *et al*. 1992, Christophel 1994, Callen *et al*. 1995, Alley *et al*. 1996, Greenwood 1996). Identified taxa include Araucariaceae (*Agathis*), Podocarpaceae (extinct genus), Casuarinaceae (*Gymnostoma*), Lauraceae, Myrtaceae (extinct genera), Proteaceae and Sterculiaceae (*Brachychiton*). A possible correlative flora is preserved in silcrete at Stuart and Poole Creek (Greenwood *et al*. 1990, Greenwood 1991).

2.   Lake Torrens Basin

Abundant leaf impressions are preserved in probable Middle Eocene channel fill deposits (Willalinchina Sandstone) in the Billa Kalina Basin, north-west of Lake Torrens. These include the oldest confirmed remains of *Eucalyptus* in Australia as well as the casts of a reed-like plant (Callen and Cowley 1995). Probable correlatives of the Willalinchina Sandstone in the Woomera and Andamooka areas further to the west also preserve silcrete casts, in particular the moulds of leaves, and fruits (Offler 1969, cited in Callen and Cowley 1995, Lange 1978b). Fossils provisionally assigned to extant genera include Cupressaceae, Podocarpaceae (cf. *Dacrycarpus*, cf *Podocarpus*), Casuarinaceae, Myrtaceae (*Angophora*, *Eucalyptus*, *Callistemon*, *Calathamnus*, *Leptospermum* and *Melaleuca*), Proteaceae (cf .*Banksia*) and Santalaceae (*Santalum*).

Inferred Climate

The source vegetation was a mosaic of mesotherm rainforest and sclerophyll communities, which are presumed to have grown along rivers and across interfluves, respectively (Christophel 1994, Benbow *et al.* 1995). Foliar physiognomic analyses (Christophel and Greenwood 1989, Greenwood 1994, 1996) indicate mean air temperatures were within the upper mesotherm range (~18-21^{0}C) in the southern Eyre Basin and possibly warmer (~21^{0}C) at Poole Creek. Rainfall is seen as being moderate (1000 mm pa) but strongly seasonal (possibly monsoonal).

3.1.4 *South-West Australia*

1.   Yilgarn Craton

Palaeochannels incised into the south-western margin of the Yilgarn Craton preserve abundant plant impressions and petrifactions, e.g. the Kojunup, Pallinup and West Dale Floras (Hill and Merrifield 1993, Scriven *et al.* 1995, Barnes and Hill 1999b). These have been assigned a Middle Eocene-Oligocene age range, based on similarities with eastern Australia. Although the Middle-Late Eocene age is supported by microfloras preserved in other palaeochannels in the region, it is noted that the *minimum* age could be as young as mid Pliocene based on the similarities between the West Dale Flora and the independently-dated Yallalie flora in the same district (cf. Dodson and Macphail in press).

The West Dale Flora is dominated by Myrtaceae and Proteaceae. Species assigned to extant families and genera include *Agathis*, *Dacrycarpus*, Cunoniaceae, *Gymnostoma*, Cunoniaceae (*Codia*), Lauraceae, Myrtaceae, *Nothofagus* and Proteaceae (cf. *Banksieaephyllum*). Sclerophyll features are present in many leaves but adaptations that minimize water loss through the stoma are absent (xeromorphic features). This suggests water was readily available but the parent plants were growing in nutrient-deficient soils.

Inferred Climate

The source vegetation appears to be a form of dry rainforest growing under seasonally wet (humid) and relatively warm (mesotherm range) conditions. If correct, then the presence of plicate *Nothofagus* leaves in the Late Eocene Kojunup flora (*N. plicata*) is anomalous since plicate leaves are more typical of deciduous species growing in cool-cold (microtherm range) climates.

3.1.5 *Central southern Australia*

1.   St. Vincent Basin

Leaves, fruit and flowers preserved at Maslin Bay and Golden Grove on the Fleurieu Peninsula, South Australia have been studied since the 1970s (Lange 1970, Christophel and Blackburn 1978, Blackburn 1981, Alley 1987, Christophel and Greenwood 1987b, Barrett and Christophel 1990, Christophel 1994, Rozefelds *et al*. 1992, Scriven 1994, Benbow *et al*. 1995). Both deposits are reliably dated by pollen as Middle Eocene (Lower *Nothofagidites asperus* Zone Equivalent). Many of the remains represent extinct species of taxa whose NLRs are confined to the subtropics and tropics. Examples are: Schizaeaceae (*Lygodium*), Araucariaceae (*Agathis*), Podocarpaceae (extinct genus), Araliaceae (extinct genus), Palmae (Maslin Bay only) Casuarinaceae (*Gymnostoma*), Cunoniaceae (*Ceratopetalum*), Ebenaceae (*Diospyros/Austrodiospyros*), Elaeocarpaceae (cf. *Elaeocarpus/Sloanea*), Lauraceae, Myrtaceae (extinct genera), Proteaceae (*Banksieaephyllum*, cf. *Beauprea*, cf. *Neorites*) and Sterculiaceae (*Brachychiton*). The closest modern analogue is warm temperate to subtropical rainforest growing on the north coast of New South Wales and Queensland (cf. Benbow *et al*. 1995).

Inferred Climate

Blackburn (1981) has proposed the climate at Maslin Bay was subtropical (upper mesotherm) and either uniformly wet (perhumid) or only weakly seasonal. Foliar physiognomic analyses (Greenwood (1994, 1996) indicate mean temperatures were in the upper mesotherm megatherm range at Maslin Bay (est. 20-27^{0}C) and at Golden Grove (est. ~18^{0}C). These estimates are inconsistent with the microfossil evidence.

3.1.6 *South-East Australia*

1.   Southeastern Highlands

Basalt with a minimum age of ~45 Ma (late Middle Eocene) overlie lacustrine mudstones at Nerriga on the Southeastern Highlands, New South Wales. The maximum age is Early Eocene, based on pollen (J. Owen cited in Hill 1978). The associated macroflora includes a Menispermataceae cf. *Legnephora*), Lauraceae and two cycads (*Bowenia* spp.) now restricted to northeastern Queensland and New Guinea (Hill 1978, 1980, 1986).

Inferred Climate

Foliar physiognomic analysis (Greenwood 1994) indicates wet to very wet (perhumid) climates with mean temperatures in the mesotherm range (est. 16-21^{0}C).

2.   Otway and Gippsland Basins

Middle Eocene (Lower *Nothofagidites asperus* Zone) macrofloras are preserved in clay lenses in thick lignitic (brown coal) measures at Anglesea in the Torquay Sub-basin (Christophel *et al*. 1987, Christophel 1994) and in the Morwell Open-cut Mine (Traralgon 2 seam), in the Gippsland Basin (references in Holdgate and Sluiter 1991, Blackburn and Sluiter 1994, Holdgate *et al*. 2000). Both sequences appear to have accumulated in lowland freshwater swamps that were subject to marine flooding. The floras represent a mosaic of wetland and dryland communities.

Dominance is highly variable. For example at Anglesea, individual assemblages can be dominated by cycads (including *Bowenia*), podocarps (including *Podocarpus* and *Falcatifolium*: Hill and Scriven 1999), Palmae, Casuarinaceae (*Gymnostoma*), Ebenaceae (*Austrodiospyros*), Elaeocarpaceae, Escalloniaceae, Lauraceae, Myrtaceae, Proteaceae and Sterculiaceae (*Brachychiton*), or a mix of these taxa. Most of the organic remains represent extinct species and/or extinct genera. Christophel (1994) has proposed that the closest modern analogue is a form of subtropical rainforest (simple notophyll vine forest) found in northeastern Queensland. Some fossil taxa have megatherm NLRs and epiphyllous fungal germlings preserved in the deposits are more typical of those found in montane tropical rainforest (Greenwood 1994).

Inferred Climate

Germling data and foliar physiognomic analysis (Greenwood 1994) indicates conditions were very wet (perhumid) but relatively cool (lower mesotherm). Holdgate *et al*. (2000) have concluded that the Traralgon Formation accumulated at specific marine high stands (i.e. under relatively warm, wet conditions) towards the end of the Middle and Late Eocene.

3.1.7 *Tasmania*

Middle to Late Eocene age macrofloras are preserved at Loch Aber and Hasties in northeastern Tasmania (Carpenter *et al*. 1994a). Both floras include leaves of an evergreen species of *Nothofagus* similar to extant *N. moorei* (Hill 1990a). A macrofossil site at Richmond in the south-east of the Midlands appears to be of the same broad age.

1.   North-east

The Loch Aber Flora includes *Eucryphia* (Eucryphiaceae) remains, which are closely related to extant *E. lucida* (cool temperate rainforest) and *E. milliganii* (subalpine-alpine heath), and unidentified Proteaceae (Hill 1991). The more diverse Hasties Flora (Bigwood and Hill 1985, Pole 1992) includes Podocarpaceae (*Acmopyle*, *Dacrycarpus*, *Lepidothamnus*, *Phyllocladus aspleniifolius*, *Podocarpus*, *Prumnopitys* and an extinct genus *Smithtonia*), Casuarinaceae (*Gymnostoma*), Cunoniaceae, Lauraceae and Myrtaceae (cf. *Xanthomyrtus*). Proteaceae in the same deposit include the oldest known remains of the endemic species, *Cenarrhenes nitida*.

Inferred Climate

Pole (1992) has concluded the Hasties Flora represented a podocarp (*Lepidothamnus*) swamp forest growing under seasonally cool (possibly microtherm) and very wet (perhumid) and cloudy conditions. Average leaf lengths in the Hasties and Loch Aber Floras are smaller than in Early Eocene floras, consistent with a general decrease in mean air temperatures during the Middle-Late Eocene (Carpenter *et al*. 1994a).

2.   South-east

The Richmond Flora includes a probably deciduous species of *Nothofagus* and the youngest known record of *Gingko* in Australia (Hill and Carpenter 1999).

Inferred Climate

Climates are likely to have been seasonally cool-cold (microtherm range) and wet (humid-perhumid).

3.2   Microfloras

Many of the macrofossil deposits preserve diverse microfloras, leading to parallel, albeit often different palaeoclimatic interpretations. Regions for which only microfossil data are available are the Bight region (Eucla Basin) and Alice Springs district (Ayers Rock, Hale, Huckitta, Santa Teresa, Ti-tree Basins) (Milne 1988, Macphail 1996c, 1997a, Clarke 2000).

Of particular importance are Middle (Lower *N. asperus* Zone) and Late (Middle *N. asperus* Zone) Eocene sequences preserved in the offshore Gippsland and Bass Basins. Reasons include the high exposure of the basins to events occurring in the Southern Ocean, the unequalled density of drilling and sampling (up to 120 conventional and sidewall core samples per well) and concomitant highly detailed lithostratigraphic and geophysical database (cf. Glenie 1986, Macphail *et al*. 1994). Unlike basins in central, western and northern Australia, sufficient assemblages have been analysed over the past three decades to be certain that a number of fossil species found in central Australia and the Murray Basin during the Middle-Late Eocene had not migrated as far south as the Gippsland and Bass Basins.

Elsewhere, much potentially fossiliferous material recovered in western New South Wales, Victoria and South Australia in the 1970s-1980s, was discarded before being pollen-analysed. Nevertheless the existing microfossil database for the Murray-Darling Basin is second only to the Gippsland Basin in terms of sample numbers. The basin covers a greater geographic area (~300,000 km^2) than any other Cenozoic basin in Australia (Macphail 1999). Foraminiferal data provide independent age control in the south-west of the basin (Lablack 1991) but some age determinations and species time distributions may have compromised by the nature of the material (cuttings) made available for analysis. Detailed reviews of the microfloras have been published for the western (Truswell *et al*. 1985, Martin 1991a), central (Macphail and Truswell 1989, 1993, Macphail 1999) and eastern (Martin 1973, 1987, 1993) sectors of the Murray Basin. Martin (1993) has summarized changes in the relative proportion of major vegetation types within five sectors of the basin via pollen groups averaged for each palynological zone.

A feature common to all microfloral assemblages from southern and central Australia, is the high relative abundance and diversity of *Nothofagus* (*Brassospora*) spp., especially *Nothofagidites emarcidus-heterus*. Nevertheless floristic differences point to significant bioclimatic gradients between the north/west and south/east regions of the continent. For example, megathermal taxa such as *Nypa* are confined to northern Australia and the eastern Eucla Basin whilst *Nothofagus* (*Lophozonia*) spp. are frequent only in eastern Australia and Tasmania but are rare or absent in southwestern and northwestern Australia (Stover and Partridge 1982).

3.2.1 *North-West Australia*

Middle-Late Eocene microfloras are preserved in some bioclastic carbonate facies in the Bonaparte Basin (Cobia-1, Jacaranda-1). These are dominated by dinoflagellates, and the minor spore and pollen component almost certainly represents the more prolific pollen and spore producers in the riparian and regional dryland vegetation. Because of poor preservation, processing may have concentrated downhole contaminants. Age determinations are mostly based on marine microfossils.

1.   Bonaparte Basin

Yields from Cobia-1 (365-380 m) are inadequate to determine relative abundance but the most frequently recorded taxa are Casuarinaceae (*Gymnostoma*) and unidentified tricolporate

types (M.K. Macphail unpubl. data). Rare taxa include Blechnaceae, *Cyathea*, Gleicheniaceae, Schizaeaceae (*Lygodium*), Araucariaceae (*Araucaria*), Podocarpaceae (*Dacrydium*, *Dacrycarpus*, *Podocarpus-Prumnopitys*), Palmae (*Longapertites*), Anacardiaceae (*Simpsonipollis*), Euphorbiaceae (*Austrobuxus*-type, *Mallotus*-type), *Ascarina*, Convolvulaceae (*Merremia*-type), *Ilex*, Myrtaceae (including *Eucalyptus*), Sapindaceae (*Dodonaea*), and a mangrove (Rhizophoraceae).

A much more diverse Middle-Late Eocene microflora is preserved at 582 m depth in Jacaranda-1 (M.K. Macphail unpubl. results). These appear to represent coastal swamp communities dominated by Cyperaceae (*Cyperaceaepollis neogenicus*), Restionaceae (*Milfordia homeopunctata*), Casuarinaceae and/or Euphorbiaceae (*Austrobuxus*-type). Rare taxa include *Isoetes*, Blechnaceae, *Cyathea*, Gleicheniaceae, Schizaeaceae (*Lygodium*), Araucariaceae (*Araucaria*, *Agathis/Wollemia*), Palmae (*Nupharipollis*), Caesalpinaceae (*Margocolporites vanwijhi*), Cunoniaceae, Didymelaceae, Droseraceae, cf. Elaeocarpaceae, Euphorbiaceae (*Micrantheum*, *Mallotus*-type), *Gunnera*, *Ilex*, Myrtaceae (including *Austromyrtus*-type, *Eugenia*, *Leptospermum*), *Nypa*, Poaceae, Polygonaceae (*Glencopollis*), Proteaceae, Rubiaceae (*Guettarda*), Sparganiaceae (*Aglaoreidia*) and Ulmaceae (cf. *Celtis*).

Inferred Climate

The presence of the subtropical-tropical family Rhizophoraceae and at least three palms (*Longapertites*, *Nypa*, *Nupharipollis*) indicates climates the Bonaparte Basin were very warm to hot (megatherm) and seasonally wet (humid) during Middle and possible Late Eocene.

3.2.2 *North-East Australia*

Microfloras with confirmed or probable Middle to Late Eocene ages are preserved in half-graben basins on the central and north-east coast of Queensland., e.g. the Yaamba, Capricorn and Duaringa Basins (Hekel 1972, McMinn 1980, Foster 1982, Dudgeon 1983), and on the Northern Tablelands in New South Wales.

1. Duaringa Basin

Microfloras preserved in oil shale deposits are dominated by *Botryococcus* but include low to trace numbers of ferns (cf. Blechnaceae, Cyatheaceae), Podocarpaceae (*Microcachrys*, *Podocarpus-Prumnopitys*), Cupanieae, Euphorbiaceae, *Nothofagus* (*Brassospora*) spp., Proteaceae and *Santalum*.

2. Yaamba Basin

Middle-Late Eocene microfloras are dominated by Araucariaceae (*Araucaria Agathis/Wollemia*), Casuarinaceae, and, sporadically, by, Podocarpaceae (*Dacrydium*, *Podocarpus-Prumnopitys*), Palmae (*Arecipites*): Myrtaceae, Proteaceae and *Nothofagus* are infrequent (<6%) but diverse, with the latter including three of the four extant subgenera (*Brassospora*, *Fuscospora*, *Lophozonia*). Rare taxa include *Azolla*, *Lygodium*, *Pteris*, Podocarpaceae (*Microcachrys*), Alangiaceae (*Alangium villosum*-type), Anacardiaceae (*Simpsonipollis*), *Anacolosa* (*Anacolosidites sectus*), Apocynaceae (*Parsonsia*), Palmae (*Dicolpopollis*), Bombacaceae (*Camptostemon*), Caesalpinaceae, Convolvulaceae (*Merremia*-type), Cupanieae, Euphorbiaceae, *Ilex*, Loranthaceae, Malvaceae, Onagraceae, Polygalaceae, cf. *Quintinia*, Restionaceae (*Milfordia homeopunctata*), *Santalum* and Sapotaceae. The microfloras primarily represent a form of Araucariaceae (dry) rainforest.

3.   Capricorn Basin

Relative abundance data from the Aquarius-1 well imply Podocarpaceae-dominated forests were replaced by Casuarinaceae (*Gymnostoma*) dominated communities during the possible Late Eocene. Associated taxa include Araucariaceae, *Nothofagus*, Myrtaceae, Cupanieae and Poaceae (cf. Hekel 1972, Foster 1982). Rare taxa include Loranthaceae, Poaceae, *Nypa* and Rhizophoraceae. Correlative microfloras from the Capricorn-1A well include Podocarpaceae (*Dacrydium*), *Anacolosa*, Palmae (*Arecipites*), Cupanieae, Loranthaceae (*Tricolpites thomasii*), Malvaceae (*Malvacearumpollis*), *Nothofagus* (*Brassospora, Fuscospora*) spp., *Nypa* and the earliest record of Onagraceae (cf. *Epilobium*) in Australia. Except for *Nothofagus*, which is likely to represent temperate rainforest on the upper slopes and summit of the Eastern Highlands, the microfloras preferentially represent plants growing along the major coastal rivers.

Inferred Climate

The presence of extensive brackish water lakes and subtropical-tropical mangroves, including *Nypa* in the Capricorn Basin, implies conditions were very warm (upper mesotherm-megatherm) and seasonally very wet (perhumid). Rainfall at higher elevations almost certainly was more uniform due to orographic effects and temperatures were cooler (lower mesotherm) for the same reason.

4.   Northern Tablelands

Organic deposits are preserved under basalt flows on Mt. Tamborine on the New South Wales/Queensland Border (Cookson and Pike 1954, Harris 1965d), and on the Northern Tablelands of New South Wales (McMinn 1989b, 1989c, 1989e, Pickett *et al*. 1990).

Pollen dominance is highly variable, consistent with the microfloras being sourced from plant communities growing close to the sites. For example, sporadically common taxa in Lower *Nothofagidites asperus* Zone Equivalent microfloras from Glen Innes (New England district) include ferns (Blechnaceae, *Calochlaena*/*Culcita*, *Cyathea*, Polypodiaceae), Podocarpaceae (*Podocarpus-Prumnopitys*), *Nothofagus* (*Brassospora*) spp., Casuarinaceae, Ericales, and unidentified tricolporate types. Other gymnosperms, including Araucariaceae, *Dacrydium* and *Lagarostrobos*, are relatively uncommon; rare angiosperms include Cupanieae, Euphorbiaceae (*Austrobuxus*-type), *Ilex*, *Santalum* and Tiliaceae. The regional vegetation is likely to have been temperate rainforest with fern communities occupying disturbed sites.

Inferred Climate

Mean annual temperatures are suggested to have been relatively cool (lower mesotherm). Effective precipitation appears to have high to very high (perhumid) due to orographic effects.

5.   North-west plains of New South Wales

Late Eocene microfloras are preserved at Tilpa (DWR Bore 30685) in a palaeovalley of the Darling River near Bourke (Martin 1997b), and other palaeodrainage systems e.g. Darling Bore DWR 36839 and BMR Wilcannia DDH 86839 (M.K. Macphail unpubl. results). Rare occurrences of *Anacolosidites sectus*, *Cranwellia striata*, *Proteacidites reticulatus* and *Tricolpites thomasii* indicate the age range of the deposits is Middle-Late Eocene.

Pollen dominance is shared between *Nothofagus* (*Brassospora*) species (15-51%), Casuarinaceae (8-40%) and Trimeniaceae (3-13%). Frequent to common (1-10%) taxa include Podocarpaceae (*Dacrydium*, *Podocarpus-Prumnopitys* and occasionally

Dacrycarpus), Euphorbiaceae (*Austrobuxus*-type), Ericales, non-eucalypt Myrtaceae and *Nothofagus* (*Fuscospora*). Taxa occurring in low to trace numbers in most samples are Proteaceae, Sapotaceae, *Santalum*, Sapotaceae, unidentified tricolporates and two extinct morphotypes (*Dicotetradites meridianus*, *Polyorificites oblatus*). Less frequent taxa are: Araucariaceae (*Araucaria*), Podocarpaceae (*Lagarostrobos*), *Anacolosa* (chiefly *Anacolosidites sectus*), Cupanieae, Euphorbiaceae (*Micrantheum*), *Ilex*, Loranthaceae (*Gothanipollis*, *Tricolpites thomasii*), Meliaceae (cf. *Dysoxylum*) Proteaceae (*Beauprea*, Musgraveinae, *Xylomelum occidentale*-type) and Sapindaceae (*Dodonaea*). Rare records include *Halocarpus* (*Parvisaccites catastus*), *Phyllocladus*, Alangiaceae, Palmae (*Dicolpopollis*), *Eucalyptus*, *Nothofagus* (*Lophozonia*, *Nothofagus*), Menyanthaceae (*Striacolpites laxus*), Polygalaceae, Sterculiaceae (*Cissus*) and Strasburgeriaceae. Occurrences of cryptogam spores are equally variable, with *Cyathea* (*Cyathidites paleospora*, *C. splendens*) being present in many samples and *Sphagnum*, lycopods, *Dicksonia*, Gleicheniaceae *Histiopteris* and *Pteris* being present only in a few samples.

Unlike the highlands to the east, trends in relative abundance appear to be somewhat systematic. For example, between 127 to 116 m depth in Darling Bore DWR Casuarinaceae decrease from 30% to 8%, *Dacrydium* decreases from 9% to trace values and *Lagarostrobos* disappears from the pollen record. Taxa showing consistent increases over the same interval are *Araucaria* (trace to 4%), *Nothofagus* (*Fuscospora*) spp. (2% to 7%), Myrtaceae (2% to 5%), Sapotaceae (trace to 2%) and Trimeniaceae (3% to 13%). Whether climatic change is responsible or whether the succession is due to a switch from one sediment source to another source in unknown.

Inferred Climate

Conditions within the pollen source area (palaeovalley) were relatively cool (lower mesotherm) with year-round high humidity probably maintained by river water. The Darling Bore data hint that climates became warmer (mesotherm range) and seasonally drier during the period represented by the interval 116-127 m.

3.2.3 *Central Australia*

Thin carbonaceous units are preserved below the weathering front (>30 m) in many of the small Cenozoic Basins in the Alice Springs district (Kemp 1976b, Truswell and Marchant 1986, Macphail 1996c, 1997a) and in the much larger Lake Eyre and Torrens Basins to the south (Harris 1971b, Sluiter 1991, Alley *et al*. 1996, Martin 1998b).

In a number of instances, reworking of plant microfossils may have resulted in mixed-age assemblages, e.g. in the Santa Teresa and Ti-tree Basins. An exception occurs in the Hale Basin where carbonaceous clays and lignites of the Ulgnamba Lignite Member of the Hale Formation are impervious to water due to hydrocarbons derived from *Botryococcus* and other algae. The result is excellent preservation of plant microfossils at depths as shallow as 15 m.

All assemblages are dominated by Casuarinaceae and/or *Nothofagus* (*Brassospora*) spp. Species whose first occurrence is used to distinguish between the Lower and Middle *Nothofagidites asperus* Zone in the Gippsland Basin, e.g. *Anacolosidites sectus*, *Proteacidites reticulatus*, and *Tricolpites thomasii*, may have extended ranges in central Australia,. For this reason Middle *Nothofagidites asperus* Zone Equivalent microfloras are assigned a broader (Middle-Late Eocene) age range.

1.   Alice Springs district

Middle *Nothofagidites asperus* Zone Equivalent microfloras in the Hale and other basins near Alice Springs are dominated by *Nothofagus* (*Brassospora*) spp. but include variable relative

abundances (1-30%) of Podocarpaceae (*Dacrydium*) and *Nothofagus* (*Fuscospora*). Frequent to common taxa include Gleicheniaceae, Araucariaceae (chiefly *Araucaria*), Podocarpaceae (*Podocarpus-Prumnopitys*), Cupanieae, Cyperaceae and Sparganiaceae (*Aglaoreidia*).

The majority of rare taxa have NLRs that are confined to warm temperate to subtropical rainforest but also present are a significant number of taxa with temperate, sclerophyll and wetland NLRs. Examples are: Lycopodiaceae, Selaginellaceae, *Calochlaena/Culcita*, Cyatheaceae, Dicksoniaceae, *Lygodium*, Polypodiaceae (*Belvisia*-type), *Pteris*, Cupressaceae, Podocarpaceae (*Dacrycarpus*, *Halocarpus*, *Lagarostrobos*, *Microcachrys*, *Phyllocladus*, *Podosporites*, *Trisaccites*), *Agathis/Wollemia*, *Anacolosa* (*Anacolosidites sectus*), Aquifoliaceae (*Ilex*), Palmae (*Arecipites*), Bombacaceae (*Camptostemon*), Caesalpinaceae, Convolvulaceae (*Wilsonia*), Cunoniaceae, Elaeocarpaceae, Droseraceae, Ericales, Euphorbiaceae (*Austrobuxus*-type, *Croton*, *Mallotus*-type, *Micrantheum*), Gyrostemonaceae, Haloragaceae (*Haloragodendron*-type), *Gunnera*, Liliaceae, Loranthaceae, Meliaceae (*Dysoxylum*), cf. Menispermaceae?, Menyanthaceae (cf. *Villarsia*), Myrtaceae (including *Austromyrtus*- and *Eugenia* types), Pandanaceae (*Freycinetia*), Proteaceae (*Banksia/Dryandra*, *Isopogon*, Musgraveinae, *Persoonia*, *Telopea*-type and numerous now extinct or locally extinct taxa such as *Proteacidites pachypolus*, Polygonaceae, *Quintinia*, *Santalum*, Restionaceae (*Milfordia homeopunctata*), Rubiaceae (*Guettarda*), Sapindaceae (*Dodonaea*), Sapotaceae, Sparganiaceae, Strasburgeriaceae, Sterculiaceae (*Ungeria*), Trimeniaceae and Vitaceae (*Cissus*).

2.   Lake Eyre Basin

Correlative microfloras from the Eyre Formation in the northern Lake Eyre Basin (Sluiter 1991, Martin 1998b) and at Nelly Creek in the south of the Lake Eyre Basin (Alley *et al*. 1996) are virtually identical in composition but include greater relative abundances of gymnosperms such as *Agathis/Wollemia* (23%), Cunoniaceae and Myrtaceae (chiefly non-eucalypt types). *Nothofagus* is relatively rare (5-10%) in the south, but occasionally reaches up to 30% in the north of the basin. Rare taxa that are present in this basin but apparently absent in the Alice Springs basins include Aquifoliaceae (*Sphenostemon*), *Ascarina*, Callitrichaceae, Didymelaceae, a possible *Eucalyptus* (*Myrtaceidites tenuis*) and Winteraceae.

3.   Torrens Basin

Harris (1971b) has recorded a marked increase in the relative abundance of *Nothofagus* (*Brassospora*) spp. between 270.1 to 184.4 m in the Lake Torrens-3A Bore. Occurrences of *Aglaoreidia qualumis*, *Cranwellia striata, Myrtaceidites tenuis*, *Nothofagidites falcatus*, *Proteacidites reticulatus*, *Tricolpites thomasii* and *Triorites magnificus* indicate the section is Late Eocene.

Inferred Climate

The high degree of geographic variation in relative pollen dominance within central Australia may reflect climatic gradients across central Australia, differences in geological age, or merely be due to site-specific factors such as area of the pollen source area and sedimentary basin. For example, Martin (1998b) has proposed that the high diversity of microtherm-mesotherm taxa are likely to represent gallery rainforest growing along the river systems and therefore may not reflect regional climates. Sluiter (1991) has proposed that the high relative abundance of *Nothofagus* (*Brassospora*) spp. implies mean annual temperature were in the mesotherm range (17-18^{0}C) and very wet (1500-2800 mm pa). Kemp and Marchant (1986) and Macphail (1997a) suggest low energy, brackish water conditions and noted that minor taxa are more consistent with seasonally warm-hot, dry conditions. A consensus position is that climates were sufficiently cool (lower mesotherm) and wet (humid) during summer to support temperate rainforest in uplands such as the MacDonnell Ranges but were warmer

(possibly upper mesotherm) and drier (humid) to the south where meandering river systems were bordered by sedge and burr-reed swamps and brackish to freshwater lakes.

3.3.4   *South-West Australia*

Except for three samples from the offshore Carnarvon Basin and adjacent Pilbara region, the microfossil data come from coastal and palaeochannel deposits in southern south-west Australia, e.g. the Officer and Eucla Basins and southern margin of the Yilgarn Craton. The majority of described and undescribed species are found in Late Eocene microfloras in southeastern Australia (cf. Stover and Partridge 1982).

1.   Carnarvon Basin

Basal to early Middle Eocene microfloras recovered from Alpha North-1 in the Carnarvon Basin are dominated by dinoflagellates but two cuttings samples (1060-1105 m) yielded statistically significant numbers of spores and pollen (M.K. Macphail unpubl. data). These imply the coastal plain vegetation was dominated by Casuarinaceae, Proteaceae (diverse, including *Proteacidites pachypolus*) and unidentified tricolporate types, with a variable presence of ferns (*Cyathidites*), gymnosperms (*Araucaria*, *Agathis/Wollemia*, *Dacrydium*, *Podocarpus-Prumnopitys*) and sclerophyll angiosperms such as Euphorbiaceae (*Austrobuxus*) and Myrtaceae (*Myrtaceidites parvus-mesonesus* but also including a possible *Eucalyptus*). Rare taxa include *Cyathea*, Gleicheniaceae, *Pteris*, *Ephedra*, Dicksoniaceae, *Anacolosa* (*Anacolosidites acutullus*), Palmae (*Arecipites*), *Banksia/Dryandra,* Cupanieae, Liliaceae (*Liliacidites bainii*), *Nothofagus* (*Brassospora*), *N.* (*Fuscospora*), Restionaceae (*Milfordia homeopunctata*), Sapindaceae (*Dodonaea*), and Stylidiaceae (*Tricolpites stylidioides*).

2.   Pilbara region

A possible Late Eocene palynoflora is preserved at Glenflorrie on the lowland plain between the Hamersley Ranges and the Exmouth Gulf in the Pilbara region (Truswell 1987b). The microflora is dominated by *Nothofagus* (*Brassospora*) spp. (47%), Casuarinaceae (25%), Proteaceae (~7%) and a periporate type that may represent Trimeniaceae (3%). Rare taxa include Gleicheniaceae, Podocarpaceae (*Dacrydium*, *Lagarostrobos*, *Microcachrys*), Agavaceae (*Phormium*), Palmae (*Arecipites*), Cupanieae, Ericales, Escalloniaceae (*Quintinia*), Euphorbiaceae, Gyrostemonaceae (*Gyropollis psilatus*), Restionaceae (*Milfordia* spp.), and Santalaceae (*Santalumidites cainozoicus*). The association of *Santalumidites cainozoicus* (Santalaceae) and *Proteacidites reticulatus* (*Ungeria*) makes it improbable that the flora is older than Middle Eocene although it could be as young as Oligo-Miocene if these taxa survived into Neogene time in northwestern Australia. For example, *Santalum* spp. are widespread in the present-day floras of Western and South Australia and the Northern Territory. The Glenflorrie assemblage appears to mark the northwestern limit reached by *Nothofagus* during the Tertiary in Australia.

Inferred Climate

Rainfall was adequate (humid) to support wetland communities but the mixture of sclerophyll and rainforest trees suggests precipitation in the northern Carnarvon Basin was high (perhumid) but strongly seasonal. Since palms such as *Nypa* are no longer recorded, mean temperatures were cooler (lower mesotherm) than in northwestern Australia.

Microflora from the adjacent Pilbara region is likely to represent at least two geographically distinct vegetation types: *Nothofagus* temperate rainforest communities growing at higher elevations on the Hamersley Ranges (max. elevation 700-950 m) and warm temperate-subtropical rainforest communities lining rivers on the coastal plain. If correct, conditions in the uplands were relatively cool (lower mesotherm) and uniformly wet (perhumid) possibly

due to orographic uplift of moist air masses whilst conditions in the lowlands were relatively warm (possibly upper mesotherm) and with a stronger seasonal bias.

3.   Officer Basin

Probable Middle-Late Eocene microfloras from Poynton Creek-2 borehole (Officer Basin), include *Proteacidites pachypolus* (Backhouse 1986).

4.   Norseman District

Diverse *Nothofagus* (*Brassospora*)-Casuarinaceae dominated microfloras preserved in fluvial sediments at the base of palaeochannels in the Norseman area, are similar to those found in the Bremer and Eucla Basins (Backhouse 1978, 1989, M.K. Macphail unpubl. results). Intact anther sacs (from intact flowers) confirm the local presence of *Nothofagus* and other taxa such as Anacardiaceae and Proteaceae (*Proteacidites pachypolus*) in the riparian flora.

5.   Eucla Basin

Exceptionally diverse (up to 200 identifiable taxa) microfloras of Middle *Nothofagidites asperus* Zone Equivalent age are preserved in marginal marine facies in the Werrillup Formation in south-west Western Australia and on the eastern margin of the basin (Crae-2, Ooldea Range-6) in south-west South Australia (Stover and Partridge 1982, Milne 1988, Alley and Benbow 1989, Alley and Beecroft 1993). Cookson (1954) and Balme and Churchill (1959) have recorded probable Late Eocene *Nothofagus* (*Brassospora*)-Casuarinaceae dominated microfloras in marine-influenced facies in the Nornalup-Denmark and Coolgardie districts, respectively.

Palynological dominance is shared between *Nothofagus* (*Brassospora*) spp. (up to 60%) and Casuarinaceae (up to 35%), associated with significant relative abundances of *Dacrydium* (up to 16%), *Lagarostrobos* (up to 8%), *Podocarpus-Prumnopitys* (up to 10%), Euphorbiaceae (up to 8%), Myrtaceae (up to 12%), Proteaceae (up to 10%), Restionaceae (up to 12%), Trimeniaceae (up to 6%) and *Xylomelum occidentale*-type (up to 8%). Rare to sporadically frequent taxa include: *Sphagnum*, Lycopodiaceae, *Cyathea*, *Dicksonia*, *Pteris*, Araucariaceae (*Araucaria*, *Agathis*), *Ephedra*, Podocarpaceae (*Dacrycarpus*, *Halocarpus*, *Microcachrys*, *Phyllocladus*, *Podosporites*), Anacardiaceae, *Anacolosa* (*Anacolosidites sectus*), *Ascarina*, Caesalpinaceae, Cunoniaceae (including *Gillbeea*), Cupanieae, Cyperaceae, Didymelaceae, Ericales, *Ilex*, Liliaceae, Loranthaceae (*Gothanipollis*, *Tricolpites thomasii*), Meliaceae (*Dysoxylum*), Mimosaceae (*Archidendron*-type), Myrtaceae (including *Eucalyptus* and ?*Eugenia*), *Nothofagus* (*Fuscospora*), *N.* (*Lophozonia*) spp., Onagraceae, Pandanaceae (*Freycinetia*), Poaceae, *Phormium*, Polygalaceae, Rubiaceae (*Canthium*, *Coprosma*), *Santalum*, Sapotaceae, Sparganiaceae (*Aglaoreidia*), Strasburgeriaceae, and very diverse Proteaceae (including *Banksia*/*Dryandra*, *Beauprea*, Musgraveinae, *Telopea*). A number of these do not appear in southeastern Australia until Early Oligocene time, e.g. *Archidendron*-type and Onagraceae. Most have NLRs in warm temperate rainforest to tropical montane (mesotherm) vegetation types.

Inferred Climate

The combined evidence indicates relatively cool (lower mesotherm) climates with probable high year round high humidity.

3.2.5   *Central southern Australia*

Sparse Middle to Late Eocene microfloras are preserved in offshore wells in the Duntroon Basin. More diverse microfloras are preserved in marginal marine facies at Venus Bay (Polda

Basin) on the Eyre Peninsula (Alley 1993, Rowett 1997b) and at Port Pirie near the head of Spencer Gulf (Harris 1971b). Data from the St. Vincent Basin comes from marine and non-marine sediments at Maslin Bay (North Maslin Sands) and on the Adelaide Plains, Fleurieu Peninsula (Harris 1964a, 1965b, 1985, Alley and Broadbridge 1992).

1.   Duntroon Basin

Middle Eocene, Lower *Nothofagidites asperus* Zone Equivalent and Late Eocene, Middle *N. asperus* Zone Equivalent microfloras are recorded in Vivonne-1 and Greenly-1 wells (Morgan and Hooker 1993b, 1993d), and Troas-1 and Borda-1 wells (Morgan and Hooker 1993a, 1993c), respectively. The dominant taxon is *Nothofagus* (*Brassospora*). Other frequent to common types are ground ferns (*Cyathidites*, Gleicheniaceae), Araucariaceae (*Agathis/Wollemia*), Podocarpaceae (*Dacrydium*, *Podosporites*), Cupanieae, extinct Proteaceae (including *Proteacidites pachypolus*), Euphorbiaceae and Casuarinaceae. Rare taxa include *Sphagnum*, Podocarpaceae (*Lagarostrobos*, *Microcachrys*) *Anacolosa* (*Anacolosidites acutullus*) and some Proteaceae with close living relatives (*Beauprea*, *Xylomelum occidentale*-type).

2.   Polda Trough and surrounds

Triorites magnificus demonstrates that assemblages from Venus Bay in the Polda Trough are Late Eocene, Middle *Nothofagidites asperus* Zone Equivalent. Pollen dominance is variable, with the only common to abundant taxa being ferns (*Cyathidites*), Araucariaceae (*Araucaria*), Podocarpaceae (*Lagarostrobos*), Casuarinaceae, *Nothofagus* (*Brassospora*) spp., Proteaceae and Myrtaceae. *Nypa* is sporadically well represented. W. Harris (undated) reports abundant *Nothofagus* in marginal marine sediments from Streaky Bay between the Eucla and Polda Basin.

A probable correlative microflora from Tarcoola ca. 200 km north of Streaky Bay is dominated by *Nothofagus* (*Brassospora*) with common Casuarinaceae and Myrtaceae (Alley 1983b). The latter include the putative eucalypt *Myrtaceidites tenuis* as well as *Eucalyptus* sensu stricto (*M. eucalyptoides*). Gymnosperms include Araucariaceae (*Araucaria*) and Podocarpaceae (*Dacrydium*, *Lagarostrobos*, *Microcachrys*, *Phyllocladus*) but none are listed as being frequent. Rare angiosperms include Cupanieae, Ericales, *Santalum* and (diverse) Proteaceae. Microfloras from 147.8-160 m in a bore at Port Pirie are no older than Middle Eocene, based on *Nothofagidites falcatus* and *Proteacidites reticulatus*, and may be Late Eocene based on the high relative abundance of *Nothofagus*. Estimates of relative abundance for other taxa are not provided but the species composition and high diversity of *Nothofagus*, Proteaceae and tricolporate types are comparable with Middle *Nothofagidites asperus* Zone Equivalent microfloras elsewhere in South Australia.

3.   Tallaringa Trough

Pitt *et al.* (1976) have recorded marine dinoflagellates (1-5%) and *Triorites magnificus* in *Nothofagus* (*Brassospora*)-dominated microfloras from the Tallaringa Trough – demonstrating that saltwater extended up to 200 km inland of the present-day coastline in the Bight during the Late Eocene. Harris and Foster (1972) report a *Nothofagus* (*Brassospora*)-Proteaceae microflora of possible Late Eocene age from the Mt. Wedge area on the northern Eyre Peninsula.

4.   St. Vincent Basin

Differentiating between Middle and Late Eocene microfloras preserved in the St. Vincent Basin, Fleurieu Peninsula, is complicated by presence of early Middle Eocene (Lower *Nothofagidites asperus* Zone Equivalent) foraminifera in some microfloras that include the

index species of the Middle *N. asperus* Zone, *Triorites magnificus* (cf. Lindsay and Harris 1964, McGowran *et al.* 1970, Alley and Broadbridge 1992). Examples occur in the North Maslin Sand, Maslin Beach, and outliers at Golden Grove (Alley 1987) and One Tree Hill (Alley and Broadbridge 1992) in the Willunga Embayment. Correlative formations are routinely intersected on the northern Adelaide Plain, e.g. Harris (1964a, 1965b).

Microfloras recovered from the North Maslin Sand (Noarlunga sandpit) are dominated by Proteaceae (abundant, diverse), Casuarinaceae and *Nothofagus* (*Brassospora*) spp. (common) and Cupanieae (frequent) (M.K. Macphail unpubl. data). Rare taxa include Podocarpaceae (*Dacrycarpus*, *Dacrydium*, *Lagarostrobos*, *Podosporites* sp. cf. *Microstrobos*), *Anacolosa* (*Anacolosidites luteoides*, *A. sectus*), Palmae (*Arecipites*), Caesalpinaceae, Didymelaceae, Euphorbiaceae (*Austrobuxus*-type, *Micrantheum*), *Ilex*, Loranthaceae, *Nothofagus* (*Fuscospora*, *Lophozonia*, *Nothofagus*), Pandanaceae (*Freycinetia*), Polygalaceae, Restionaceae (*Milfordia homeopunctata*), *Santalum*, Sapotaceae and Trimeniaceae. Cryptogams are uncommon.

Conversely, cryptogams are common at Golden Grove and One Tree Hill where fern spores (Blechnaceae, *Calochlaena/Culcita*, *Cyathidites*, Gleicheniaceae, Osmundaceae, Polypodiaceae) comprise up to 52% of some assemblages. *Podocarpus-Prumnopitys* is frequent (up to 8%). Otherwise, pollen dominance and species composition is similar to the Noarlunga sandpit microfloras. Rare taxa not recorded at Noarlunga include Araucariaceae (*Araucaria*, *Agathis/Wollemia*), Podocarpaceae (*Halocarpus*), *Ascarina*, *Triorites magnificus* and a plethora of undescribed tricolporate types. *Triorites magnificus* is recorded at One Tree Hill and is present in other boreholes drilled ca. 3-4 km east of Maslin Bay (Harris 1964a, 1974) where it is associated with *Dicksonia*, Podocarpaceae (*Dacrycarpus*, *Dacrydium*, *Lagarostrobos*, *Podocarpus-Prumnopitys*) *Anacolosa* (*Anacolosidites acutullus*, *A. luteoides*), *Ascarina*, Cupanieae, Euphorbiaceae, *Ilex*, Loranthaceae, diverse Proteaceae, *Santalum* and Sapotaceae.

Correlative microfloras (with *Triorites magnificus*) from the northern Adelaide Plains are dominated by *Nothofagus* (*Brassospora*) and Proteaceae. Rare taxa include Cyatheaceae, *Anacolosa* (*Anacolosidites acutullus*), Cupanieae, Loranthaceae, Myrtaceae (including *Eucalyptus*), *Nothofagus* (*Fuscospora*, *Lophozonia*), Proteaceae (including *Banksia/Dryandra*, *Beauprea*, *Isopogon* and extinct species such as *Proteacidites reticulatus*) and *Santalum*.

Inferred Climate

The presence of both *Nypa* and *Nothofagus* (*Brassospora*)-*Lagarostrobos* rainforest in the Polda Basin is difficult to reconcile given the former imply very warm-hot (upper mesotherm-megatherm) conditions whilst the latter indicate mean annual temperatures were within the lower mesotherm range. Assuming that *Nypa* pollen are *in situ*, i.e. not reworked from Early Eocene deposits, the most likely explanation is that sea surface temperatures within sheltered embayments in the Bight were warm relative to air temperatures. The record is an important one as it supports other data for existence of a warm water gyre within the Bight during Late Eocene. Conversely, the high relative abundance of *Nothofagus* at Tarcoola implies relatively cool (lower mesotherm) and uniformly wet (perhumid) conditions on the margins of the Gawler Craton.

The Maslin Bay Sand microfloras closely resemble those found in the Eucla and Gippsland Basins during the Late Eocene and almost certainly represent similar relatively warm (mesotherm range) and uniformly wet (perhumid) climates. This may reflect the local influence of, for example, warm SSTs within the St. Vincents Gulf. Support for this is provided by the possibly early, widespread presence of thermophilous taxa such as *Anacolosidites sectus* and *Triorites magnificus*. If correct, then again the most probable

explanation is that a warm water gyre had developed in the shallow waters of the Great Australian Bight during the late Middle Eocene (cf. James and Bone 2000).

3.2.6 *South-East Australia*

1. <u>Southeastern Highlands of New South Wales</u>

Araucariaceae (chiefly *Agathis*/*Wollemia*) dominate a probable earliest possible Middle Eocene (Lower *Nothofagidites asperus* Zone Equivalent) microflora from Bungonia on the Southern Tablelands south of Sydney (Truswell and Owen 1998). Otherwise gymnosperms are uncommon, with the most frequently recorded genera being *Microcachrys* (2%) and *Podocarpus-Prumnopitys* (3%). The Podocarpaceae include *Dacrydium*, *Halocarpus*, *Phyllocladus* and two extinct genera: *Dacrycarpus* and *Lagarostrobos* are absent. Cryptogams are uncommon, with the only frequent taxa being Blechnaceae and Cyatheaceae. The angiosperm component, which comprises >70% of the count, is much more diverse with the dominance shared between unidentified tricolporates (11%), *Nothofagus* (*Brassospora*) spp. (11%) and Casuarinaceae (5%). Frequent (1-5%) types include Palmae (*Arecipites*), *Ascarina*, Cupanieae, *Ilex*, non-eucalypt Myrtaceae, *Nothofagus* (*Lophozonia*), Proteaceae (diverse), *Santalum* and Trimeniaceae. Rare taxa include *Sphagnum*, *Cyathea*, *Calochlaena*/*Culcita*, *Dicksonia*, *Hemitelia*, Osmundaceae, Polypodiaceae, *Ephedra*, *Anacolosa* (*Anacolosidites acutullus*, *A. luteoides*), Palmae (*Arecipites*, *Dicolpopollis*), Ericales, Euphorbiaceae (*Austrobuxus*-type), *Eucalyptus*? (*Myrtaceidites tenuis*), Loranthaceae, *Nothofagus* (*Fuscospora*, *Nothofagus*), Onagraceae, Pandanaceae (*Freycinetia*), Proteaceae (*Banksia*/*Dryandra*, *Beauprea*, Musgraveinae, *Telopea*, *Xylomelum occidentale*-type), Restionaceae and Tiliaceae.

Interpreting the parent vegetation in modern terms is difficult because of (1) the wide ecological tolerances of presumed dominants and (2) the presence of taxa that have not been recorded elsewhere. Some taxa that would be expected to occur, e.g. Sapotaceae, are absent. Others taxa have now mutually exclusive ecological distributions, e.g. Palmae and *Nothofagus* (*Lophozonia*), or have time distributions that do not overlap in the Gippsland Basin, e.g. *Myrtaceidites tenuis*, Onagraceae and Tiliaceae. On present indications the most likely interpretation is that palaeovegetation was a form of warm temperate rainforest that included now-extinct ecotypes of plants found in modern cool temperate and subtropical rainforests.

<u>Inferred Climate</u>

Climates are interpreted to have been seasonally wet to very wet (perhumid) with mean annual temperatures in the mesotherm range.

2. <u>Otway Basin</u>

Sediments deposited in the eastern Otway basin include the upper Wangerrip and lower Nirrandra Groups. However, little information is available regarding Lower or Middle *Nothofagidites asperus* Zone Equivalent microfloras that may be preserved in these formations.

Low diversity possible Middle-Late Eocene microfloras have been recovered from the Anglesea-1 and Nerita-1 wells drilled in the Torquay Sub-basin (M.K. Macphail unpubl. results). The dominant taxon usually is *Nothofagus* (*Brassospora*) although one or more of Araucariaceae (*Araucaria*), Podocarpaceae (including *Lagarostrobos*, *Podocarpus-Prumnopitys*), Casuarinaceae, Euphorbiaceae, *Nothofagus* (*Fuscospora*), Proteaceae and unidentified tricolporate types and fern spores (Cyatheaceae) may also be frequent to common. Rare taxa include *Sphagnum*, Araucariaceae (*Agathis/Wollemia*), Podocarpaceae

(*Dacrycarpus*, *Dacrydium*), Cupanieae, Droseraceae, Ericales, *Ilex*, Loranthaceae (*Tricolpites thomasii*), Meliaceae (*Dysoxylum*), *Nothofagus* (*Lophozonia*, *Nothofagus*), Proteaceae (including *Triorites magnificus*), Restionaceae (*Milfordia homeopunctata*), *Santalum* and Sapotaceae.

Much more diverse microfloras are preserved in precisely dated marine clays, greensands and marls at Browns Creek (Shafik and Idnurm 1997) but again few data are available.

Inferred Climate

The data confirm that climates were relatively cool (lower mesotherm range) and wet to very wet (perhumid), but rainfall may have been weakly seasonal given the frequent occurrence of *Nothofagus* (*Fuscospora*) and Araucariaceae.

3.   Murray Basin

Microfloras of possible Middle Eocene and confirmed Late Eocene (Middle *Nothofagidites asperus* Zone Equivalent) age are widely preserved at depth (Buccleugh and basal Olney Formations) throughout the basin and adjacent areas in inland New South Wales. Detailed reports or reviews of microfloras and pollen sequences, which illustrate changes in the relative abundance of commonly occurring taxa during the Late Eocene, have been published for the western (Truswell *et al*. 1985, McMinn 1986b), central (Macphail and Truswell 1989, 1993, Macphail 1999) and eastern (Harris and Morgan 1976, Martin 1987, 1993) sectors of the basin.

With few exceptions the Late Eocene assemblages are very diverse and usually dominated by *Nothofagus* (*Brassospora*) spp., with lesser amounts of Podocarpaceae (chiefly *Lagarostrobos* and Podocarpus-*Prumnopitys*), Casuarinaceae and other (unspecified) angiosperms (see Fig. 8 in Martin 1993). Araucariaceae, Myrtaceae, Proteaceae and cryptogams are relatively rare. *Lagarostrobos* and very diverse Proteaceae are more common in the south-east, Myrtaceae in the north-east, and Araucariaceae in the west of the basin. Cyperaceae and Sparganiaceae are consistently less frequent than in the Oligo-Miocene, including in the strongly marine-influenced south-west of the basin. Rare types include extinct taxa that appear to have required warm conditions (*Triorites magnificus*) as well as taxa with mesotherm NLRs, e.g. *Anacolosa* (*Anacolosidites acutullus*, *A. luteoides*, *A. sectus*), Apocynaceae (*Alyxia*), Palmae, (*Arecipites*, *Dicolpopollis*), Caesalpinaceae, Malpighiaceae, Rubiaceae (*Canthium*), *Santalum* and Sapotaceae.

Inferred Climate

Martin (1993) has proposed that systematic variation in the these groups of ecologically related taxa reflect both climatic gradients and edaphic effects related to topography, with *Nothofagus* occupying the drier sites and gymnosperms such as *Lagarostrobos* occupying areas that were periodically inundated by freshwater. More generally, the data point to a heterogeneous mosaic of floristically complex evergreen rainforest types growing under year round high (perhumid) rainfall and cool to warm (mesotherm range) temperatures.

4.   Gippsland Basin

Lower-Middle *Nothofagidites asperus* Zone sediments are routinely intersected in exploration wells drilled in the offshore Gippsland (upper Latrobe Group) Basin. These range from marginal marine facies to thick coal measures. Correlatives of the latter include the Traralgon-2 Seam, Yallourn, in the onshore Gippsland Basin. In excess of 100 taxa have been identified in the Gippsland Basin and many species have been described using specimens from this basin (Cookson and Pike 1954, Stover and Partridge 1973). However,

several taxa, which first appear in the Middle *N. asperus* Zone in the Gippsland Basin, are recorded in early Eocene (*Malvacipollis diversus* Zone Equivalent) and Middle Eocene (Lower *N. asperus* Zone Equivalent) microfloras in basins in south-west and central Australia, e.g. *Anacolosidites luteoides* and *Tricolpites thomasii*.

In general terms, angiosperms are more prevalent than gymnosperms (av. 60-75% versus 15-30%) throughout the Middle-Late Eocene, with the most common types being *Nothofagus* (*Brassospora*) spp. and Podocarpaceae (*Dacrydium*, *Lagarostrobos*, *Podocarpus-Prumnopitys*), respectively. Values of *Nothofagus* (*Brassospora*) increase from ~25% in the early Middle Eocene to >50% in the late Late Eocene whilst Casuarinaceae and Proteaceae decline from ~20% to less than 1-10% over the same interval (Partridge 1999). Coal microfloras are often dominated by *Lagarostrobos* whilst Araucariaceae (*Araucaria*, *Agathis/Wollemia*) tend to be more abundant in marine facies (Neves Effect). *Proteacidites asperopolus* is often common in Lower *N. asperus* Zone assemblages whilst high values of *P. pachypolus* are confined to the Middle *N. asperus* Zone.

Unlike other Australian basins, the Gippsland Basin database is sufficiently comprehensive to use both quantitative data and the first and last appearances of rare taxa as reliable proxy evidence for bioclimatic change *within* the Middle-Late Eocene. For example geological and sequence stratigraphic evidence support palynostratigraphic evidence that *Nothofagus* (*Brassospora*) spp., including one newly evolved canopy species (*Nothofagidites falcatus*), expanded very rapidly across the basin during the early Middle Eocene. Late Eocene rainforest appears to have been more diverse than Middle Eocene rainforest, due to the immigration of herbaceous and woody taxa, e.g. Sparganiaceae (*Aglaoreidia qualumis*), *Anacolosa* (*Anacolosidites sectus*), Loranthaceae (*Tricolpites thomasii*) and a range of extinct and extant Proteaceae. The latter includes *Isopogon* (*Proteacidites truncatus*); the former include *Proteacidites confragosus*, *P. reticulatus* and *Triorites magnificus*. The same diversification is reflected in the greater proportion of pollen taxa with complex ornamentation.

Inferred Climate

Conditions in the Gippsland Basin cooled markedly (to lower mesotherm values) during the Early-Middle Eocene transition although conditions remained wet to very wet (perhumid). Temporary warming, indicated by the appearance of *Triorites magnificus* during the Late Eocene, may correlate with transient warming of sea surface temperatures recorded elsewhere along the southern margin (B. McGowran pers. comm.).

3.2.7 *Tasmania*

Middle-Late Eocene facies (upper Eastern View Group) are intersected in the majority of wells drilled in the Bass Basin and onshore sub-basins in northern Tasmania but few data are available in well completion reports. It is unclear whether the plants producing Middle *N. asperus* Zone index species e.g. *Anacolosidites sectus, Tricolpites thomasii* and *Triorites magnificus* ever extended southwards into northeastern, central or southeastern Tasmania.

1.   Bass Basin

Morgan (1986b) indicates Lower and Middle *Nothofagidites asperus* Zone Equivalent microfloras are dominated by *Nothofagus* (*Brassospora*) with lesser amounts of Casuarinaceae. The same dominance is observed in Squid-1, where two extinct Proteaceae (*Proteacidites asperopolus*, *P. leightonii*) are abundant in Lower *Nothofagidites asperus* Zone Equivalent (Martin 1985).

2.   South-east Tasmania

Data on Middle-Late Eocene microfloras are unavailable or the reports predate the development of the Gippsland zonation. For example, Harris (1965c) has proposed a microflora from Spring Bay near Triabunna on the east coast is Middle Eocene based on the high relative abundance of *Proteacidites pachypolus*. If a related morphotype in the same assemblage is *P. asperopolus*, then the sample will be Middle Eocene; if not, the sample could be Late Eocene. Other taxa listed as common are ferns (Cyatheaceae), *Ephedra* and *Nothofagus* (presumably *Nothofagidites emarcidus-heterus*). Comparable assemblages are said to occur in the Longford area, near Launceston (Harris *ibid*).

Inferred Climate

The absence of *Anacolosa* and *Triorites magnificus* in *Nothofagus* (*Brassospora*) microfloras is likely to indicate that conditions in the Bass basin and south-east Tasmania were as uniformly wet (perhumid) but cooler (microtherm to lower mesotherm range) than the Gippsland Basin during the Late Eocene.

3.3   Other Records

3.3.1 *North-West Australia*

1.   North-West Shelf

Apthorpe (1988) notes that Late Eocene warming proposed, e.g. by McGowran and Beecroft (1985) is consistent with the presence of 'larger' benthic foraminiferal faunas on the North West Shelf and the presence of warm temperate faunas in the northern Canning Basin.

2.   Carnarvon Basin

The progressive decline in clastic input to the northern Carnarvon Basin and enhanced carbonate sedimentation implies rainfall had decreased relative to the early Eocene (Apthorpe 1988).

3.3.2 *North-East Australia*

Feary *et al.* (1991) have proposed low latitude regions underwent slight cooling.

3.3.3 *South-West Australia*

Cenozoic brachiopod assemblages in the Eucla Basin indicate relatively stable conditions during the Late Eocene-Miocene or (preferred) that brachiopods are more influenced by substrate than other environmental parameters.

3.3.4 *South-East Australia*

Planktonic foraminifera indicate sea surface temperatures cooled rapidly during the early Middle Eocene (McGowran *et al.* 2000). An oxygen isotope stratigraphy based on planktonic foraminifera from Browns Creek and Castle Cove in southwestern Victoria, indicates SSTs at the eastern end of the Bight reached a maximum value of ~24^{0}C during the Late Eocene (cf. Kamp *et al.* 1990, Shafik 1996)

4.   TIME SLICE T-4

Age Range: Oligocene-Middle Miocene [33.7-11.2 Ma]

   Zones: Upper *Nothofagidites asperus* to *Canthiumidites bellus* Zones
                  Phthanoperidinium comatum and informal *Oligospheridium* Zones

4.1   Macrofloras

The Tasmanian and southern Victorian macrofossil floras are the more extensive than for any other interval of Cenozoic time. Many taxa can be assigned to extant families and genera but most specimens represent extinct species within these higher order taxa.   Many of the gymnosperms present in Tasmania during the Oligo-Miocene have become restricted to South America, Fiji and/or New Zealand.

4.1.1   *North-West Australia*

No known record.

4.1.2   *North-East Australia*

Macrofloras include (1) fruits of Proteaceae (*Wilkinsonia*) and Elaeocarpaceae (*Elaeocarpus peterii*) in Oligocene-Middle Miocene sediments at Glencoe (Rozefelds 1995) and (2) fruits and seeds of wire-reeds (Restionaceae) and bull rushes (Typhaceae) in a latest Eocene-Oligocene mudstone underlying oil shale deposits in the Casuarina Basin near Rockhampton (Dettmann and Clifford 2000b).   *Wilkinsonia* is closely related to *Athertonia*, a tree now confined to tropical rainforest on the Atherton Tableland. The NLR of *Elaeocarpus peterii* (*E. stellaris*) is endemic to rainforest in northeastern Queensland.

1.   North-east New South Wales

Holmes *et al*. (1982) have recorded the leaves and/or flowers of Cunoniaceae (*Ceratopetalum*), Lauraceae and Myrtaceae (including *Eucalyptus*) from the Middle Miocene Chalk Mountain Formation, Warrumbungle Mountains.   The 15 m thick deposit also preserves freshwater diatoms and the remains of fish and a bird.

Inferred climate

The Glencoe Flora indicates very warm (upper mesotherm) and seasonally very wet (perhumid) conditions during the possible Early Oligocene in central Queensland. The Chalk Mountain Flora is closely related to modern warm temperate rainforest and indicates cooler (lower mesotherm) but equally wet conditions during the Middle Miocene in northern New South Wales.

4.1.3   *Central Australia*

No known record.

4.1.4   *South-West Australia*

No known record unless the Myrtaceae-Proteaceae dominated West Dale macroflora is Oligocene or younger (cf. Barnes and Hill 1999b). Species assigned to extant families and

genera in this flora include *Agathis*, *Dacrycarpus*, Cunoniaceae, *Gymnostoma*, Cunoniaceae (*Codia*), Lauraceae, Myrtaceae, *Nothofagus* and Proteaceae (cf. *Banksieaephyllum*).

4.1.5 *Central southern Australia*

No known record

4.1.6 *South-East Australia*

1. Central west slopes of New South Wales

Wilkinsonia fruits occur in sediments underlying mid Miocene (13.8-14.8 Ma) basalts near Orange and Mudgee on the central west slopes of New South Wales (Rozefelds 1995). Rozefelds and Christophel (1996) note fossil Elaeocarpaceae (*Elaeocarpus clarkii*) is widespread in Oligocene-Middle Miocene deep lead deposits in southeastern Australia.

Inferred climate

The flora indicates warm (possible upper mesotherm) and very wet (perhumid) conditions based on the close morphological affinity of *Wilkinsonia* to *Athertonia*, a tree now confined to tropical rainforest on the Atherton Tableland, northeastern Queensland. The closest extant relatives of *Elaeocarpus clarkii* are also confined to northeastern Queensland (*Elaeocarpus bancroftii*, *E. linsmithii*).

2. Southeastern Highlands of New South Wales

Silicified wood occurs in association with Early Miocene basalts in the headwaters of the Lachlan River on the central west slopes (Bishop and Bamber 1985). Macrofossils, which have been transported down slope onto the site, are Mimosaceae (*Acacia*), and *Nothofagus*. An apparently *in situ* stump is identified as a possible *Eucalyptus*. The sites are located close to the Dalton silicified leaf flora described by Von Ettingshausen (1888). Selkirk (1975) has described epiphyllous fungi including Grade V germlings, associated with mummified leaves in a deep lead deposit from Kiandra at ~1400 m elevation. Leaf remains include Podocarpaceae (*Phyllocladus*, *Podocarpus*), Lauraceae and Myrtaceae. Hill and Whang (2000) have identified *Dacrycarpus* (Podocarpaceae) in a Miocene rainforest macroflora at the mid-elevation (530 m asl) Elands site on the Bulga Plateau inland of Taree on the Central Coast of New South Wales.

Inferred climate

The data point to very wet and cool (microtherm-lower mesotherm) conditions at mid elevations on the Eastern Highlands during the Early Miocene. The paucity of *Nothofagus* implies conditions at Elands were equally wet but warmer (mesotherm range).

3. Central South Coast of New South Wales

A leaf of the subtropical mangrove *Bruguiera* (Rhizophoraceae) is preserved in late Early to early Late Miocene (*Canthiumidites bellus* Zone Equivalent) estuarine sediments at Little Bay, near Sydney (Pickett *et al.* 1997). Other taxa represented by macrofossils include Araucariaceae (*Araucaria*/*Agathis*), Cupressaceae (*Libocedrus*), Podocarpaceae (*Dacrycarpus*, *Dacrydium*), Casuarinaceae (*Gymnostoma*), Cunoniaceae, Fabaceae, Lauraceae, Myrtaceae (*Acmena*, *Eucalyptus*, cf. *Eugenia*), Proteaceae (*Lomatia*) and, possibly, Sapindaceae.

Inferred climate

The southern limit of latitude of *Bruguiera* is in northern New South Wales, ~4^0 latitude north of Little Bay. If the northward drift of Australia is taken into account, this implies a shift in mean temperatures equivalent to about 11^0 latitude in present day terms. Accordingly the macroflora indicates very warm (upper mesotherm) and wet (humid) conditions. Since the sediments were deposited under a relative sea level some 30 m higher than present, it is reasonable to conclude the Little Bay sequence represented conditions at sea level during the mid Miocene thermal optimum although conditions before and after this optimum may have been cooler (lower mesotherm).

4.   Gippsland Basin

Oligocene-Middle Miocene macrofloras from the Berwick Quarry site near Melbourne and the Latrobe Valley, onshore Gippsland Basin have been described in great detail by Pole *et al.* (1993), and Kershaw *et al.* (1991) and Blackburn and Sluiter (1994), respectively. Additional palaeobotanical records are provided by Rozefelds (1995), Rozefelds and Christophel (1996) and Jordan and Hill (1996).

The Berwick Quarry Flora is dated as Late Oligocene to possibly earliest Early Miocene, based on a K/Ar date of 22 Ma for the overlying basalts. The assemblage preserves some of the earliest known *Eucalyptus* leaf remains as well as the remains of Araucariaceae (*Agathis*), Podocarpus (*Dacrycarpus*), Casuarinaceae (*Gymnostoma*), Lauraceae, *Nothofagus* and Proteaceae. The flora appears to represent a mosaic of rainforest and open forest communities growing under relatively cool (lower mesotherm) and wet (perhumid) conditions with a pronounced dry season.

Reconstruction of floras and vegetation occupying the Latrobe Valley are centred around brown coal measures forming the Early Oligocene-late Early Miocene (*Proteacidites tuberculatus* Zone) Morwell Formation and much thicker late Early-early Late Miocene (*Canthiumidites bellus* Zone) Yallourn Formation. Both sequences are believed to be ombrogenous (rain-fed) peat bogs whose development was periodically interrupted by marine flooding of the basin (Holdgate and Sluiter 1991) and dominance is strongly correlated with depositional environment due to local sourcing of the plant remains. Close sampling and good exposures mean that it is possible to trace lateral as well as vertical changes in plant community composition.

Floras at the base of the Morwell Formation are dominated by Proteaceae (*Banksieaephyllum*, *Orites*/*Darlingia*) and Myrtaceae (*Acmena*, *Baeckea*, *Melaleuca*, *Neomyrtus*, *Tristania*): Elaeocarpaceae are uncommon. Higher in the section, the dominants are Podocarpaceae (*Dacrycarpus*, *Dacrydium*) and Proteaceae (*Banksieaephyllum*), associated with frequent to common Araucariaceae (*Agathis*, *Araucaria*), Cunoniaceae? (*Phyllites*), Escalloniaceae (*Quintinia*), Myrtaceae (*Acmena*, *Eugenia*, *Tristania*), Oleaceae, Blechnaceae and Gleicheniaceae. The low fusinite content indicates wildfires were rare.

Sediments at the base of the overlying Miocene Yallourn Formation have a very high (up to 56%) fusinite content, indicative of frequent wildfires. The wetland macrofloras are dominated by Hepaticae, Blechnaceae, Gleicheniaceae, Podocarpaceae (*Phyllocladus*), Casuarinaceae (*Allocasuarina*, *Gymnostoma*), Cyperaceae, Elaeocarpaceae (*Elaeocarpus*), Epacridaceae (Styphelieae), Myrtaceae (*Baeckea*, *Leptospermum*, *Melaleuca*), Proteaceae (*Banksieaephyllum*, *Xylomelum*), Restionaceae, Sparganiaceae and/or Typhaceae. More recently, *Wilkinsonia* (cf. *Athertonia*) and an extinct *Elaeocarpus* sp. with close links to an undescribed living tree in montane northeastern Queensland have been found at the same stratigraphic level. Higher in the same section, the floras are dominated by Podocarpaceae

(*Dacrycarpus*, *Dacrydium* with locally common *Phyllocladus*), Araucariaceae (*Agathis* with locally common *Araucaria*), Casuarinaceae (*Gymnostoma*), Elaeocarpaceae, Lauraceae and Oleaceae. Myrtaceae (*Acmena*, *Syzygium*, *Tristania*) are widely distributed and cycads (Zamiaceae) are an uncommon but persistent element.

The Oligo-Miocene associations are suggested to represent swamp rainforests with emergent Araucariaceae and Myrtaceae and a shrubby understorey of ferns, Podocarpaceae, Proteaceae, Oleaceae and other small trees and shrubs. Major controls on plant community composition included variations in the water-table, saltwater incursions and fire.

Inferred climate

Increases in Araucariaceae and Myrtaceae genera with warm temperate to subtropical rainforest NLRs is consistent with warm (mesotherm range) temperatures and/or low soil nutrient levels associated with seasonally high humidity. The increased wildfire frequency may reflect increasingly dry summers during the Middle Miocene but are just as likely to be a consequence of higher fuel loads accumulating under sclerophyll-dominated communities.

4.1.7 *Tasmania*

1. Northern Tasmania

Fern pinnules which are identical to living South American fern *Lophosoria quadrapinnata* and bearing intact sporangia containing *Cyatheacidites annulatus* spores are preserved in Oligo-Miocene lignites at Balfour on the north-west coast (R.S. Hill pers. comm.). A probable Oligocene (*Proteacidites tuberculatus* Zone) macroflora is preserved at Pioneer at about 90 m elevation in northeastern Tasmania. This flora is dominated by the leaves of an extinct *Nothofagus* (*Lophozonia*) species and an unidentified angiosperm characterized by entire-margined notophylls (Hill and Macphail 1983). Less common taxa include Cupressaceae (*Athrotaxis*), Podocarpaceae (*Dacrydium*, *Phyllocladus*), Myrtaceae and Proteaceae (*Banksieaephyllum*).

Inferred climate

Lophosoria and high relative abundances of *Nothofagus* (*Lophozonia*) dominance indicate cool (upper microtherm) temperatures and uniform high humidity in northern Tasmania.

2. Central Plateau

Six Oligocene to possible late Early Miocene (*Proteacidites tuberculatus* Zone) macrofloras have been described from Bells Plains (~600 m elevation), Cethana (~300 m elevation), Lea River, (~800 m elevation), Lemonthyme Creek (~350 m elevation), Little Rapid River (~350 m elevation) and Monpeelyata (~920 m elevation) (Hill and Gibson 1986, Hill 1987, Carpenter and Hill 1988, Wells and Hill 1989, Hill and Carpenter 1989, Carpenter 1991b, Carpenter and Buchanan 1993, Hill *et al*. 1993, Carpenter *et al*. 1994a, Jordan 1995, Jordan and Hill 1996, Jordan *et al*. 1996, Hill and Whang 1996).

In most cases the focus is on the taxonomic relationships of fossil species rather than the source vegetation (inferred to be gymnosperm-*Nothofagus* temperate rainforest). For example, at least 20 conifer and up to 60 angiosperm species are present at Cethana and Little Rapid River. Mean leaf sizes fall within the microphyll and nanophyll classes. Unlike Oligo-Miocene sites on the mainland, foliage of the typically microtherm subgenus *Nothofagus Lophozonia* is common to abundant in most assemblages.

The lowest and possibly the oldest (possible Early Oligocene) Cethana flora is unique in including cycads (Zamiaceae). Other taxa assigned to living genera include Blechnaceae (cf. *Blechnum*), Gleicheniaceae (*Gleichenia*, *Sticherus*), Schizaeaceae (*Lygodium*), Araucariaceae (*Araucaria*, *Agathis*), Cupressaceae (*Papuacedrus*), Podocarpaceae (*Acmopyle*, *Dacrycarpus*, *Dacrydium*, *Lagarostrobos*, *Phyllocladus*, *Podocarpus*), Casuarinaceae (*Gymnostoma*), Cunoniaceae (*Callicoma*, *Cunonia-Weinmannia*), *Nothofagus* (*Brassospora*, *Fuscospora*, *Lophozonia*) and diverse Proteaceae (including *Banksieaephyllum* and *Lomatia*), Elaeocarpaceae, Epacridaceae, Lauraceae, Myrtaceae and Sterculiaceae (*Brachychiton*). The *Banksieaephyllum* specimens show scleromorphic and xeromorphic features.

The majority of these taxa are recorded at Lea River, Lemonthyme Creek and Little Rapid River. Additional species include an extinct *Dicksonia* with close affinities to extant subtropical and tropical species, and *Eucryphia* (Barnes and Jordan 2000). Conifers include *Libocedrus* and *Fitzroya* (Cupressaceae), now confined to the South-west Pacific and South America, respectively, and an extinct species of *Athrotaxis* (Taxodiaceae), now endemic to Tasmania. An extinct genus of Taxodiaceae (*Austrosequoia*), previously known only from the early Late Cretaceous Winton Formation, Queensland (Peters and Christophel 1978), occurs at Little Rapid River.

The highest and probably youngest macroflora (Early Miocene) at Monpeelyata includes a shrub podocarp that is virtually identical to the endemic species *Microstrobos niphophilus*, found in the upper subalpine-alpine zone in Tasmania. The same flora includes *Isoetes*, and Proteaceae whose leaves are similar to microphyll sclerophyll plants growing in the modern subalpine vegetation, and by association a cool-adapted Araucariaceae.

Inferred climate

Foliar physiognomic analysis (Carpenter *et al.* 1994a) indicates mean annual temperatures at moderate elevations (Cethana) were at the top of the upper microtherm range (~12^{0}C) during the Oligocene whilst temperatures at higher elevations (Monpeelyata) were much cooler (~7.5^{0}C) during the Early Miocene. High-grade (V) fungal germlings demonstrate conditions were uniformly wet to very wet (>1400-1500 mm pa) despite sclerophyllous adaptations to increasing seasonal stress.

4.2   Microfloras

Most of the macrofossil deposits also preserve diverse microfloras. Regions for which only microfossil data are available include northwestern, southwestern and central Australia. The index species of the *Proteacidites tuberculatus* Zone, *Cyatheacidites annulatus*, is found as far north as southern Queensland but has not been recorded in central, northern or western Australia (M.K. Macphail unpubl. observations). One Tasmanian site potentially preserves a world-class record of the impact of abrupt cooling during the Eocene-Oligocene transition on a high latitude flora (Macphail *et al.* 1993, Macphail and Hill 1994). However, the index species of the *Canthiumidites bellus* Zone, *C. bellus*, has not been recorded in Tasmania, making it difficult to distinguish between Early Oligocene-late Early Miocene and late Early-Middle Miocene floras. Martin (1990) has demonstrated that reports of extensive grasslands in central Australia during the Miocene (cf. Truswell and Harris 1982) are based on a misidentification of fossil graminoid Restionaceae pollen (*Milfordia homeopunctata*) as Poaceae (*Graminidites*).

4.2.1 *North-West Australia*

1. North-West Shelf

Middle Miocene turbidites accumulating at water depths of >4000 m on the Argo Abyssal Plain, north of Port Hedland, preserve trace numbers of Casuarinaceae, Chenopodiaceae and Restionaceae pollen (Martin and McMinn 1994).

Inferred climate

It is unclear whether these pollen represent coastal wetland and (Chenopodiaceae) salt-marsh communities or whether the regional dryland vegetation was dominated by Casuarinaceae and Chenopodiaceae-Amaranthaceae. If the latter, then the regional climate is likely to have been seasonally dry (subhumid to semiarid). The absence of Poaceae is against climates being very dry (arid).

2. Pilbara region

Possible Early-Middle Miocene (maximum age Late Oligocene) microfloras are preserved at depth below the western Fortescue Plains (Truswell 1987b). These are dominated by Gleicheniaceae (14-37%), Casuarinaceae (11-24%), *Eucalyptus* (22-31%) and *Nothofagus*. Species belonging to the subgenus *Fuscospora* are more common (5-13%) than *Brassospora* spp. (5-9%). Gymnosperm pollen are sporadically frequent, e.g. *Dacrydium* (up to 3%) and *Podocarpus-Prumnopitys* (1-2%). Apart from *Nothofagus*, the only other frequent (1-6%) angiosperm types are Restionaceae (*Milfordia hypolaenoides*) and unidentified Proteaceae and tricolporates. Rare taxa include *Acacia*, *Isopogon* and *Xylomelum occidentale*-type. The mix of sclerophyll, rainforest and wetland taxa may represent gallery forest or scrub communities growing along the banks of streams draining the Hamersley Ranges.

Inferred climate

Local humidity on the Fortescue Plain may have been augmented due to stream flow or groundwater discharge. Conditions on the Fortescue Plain are likely to have been sub-humid, and/or characterised by a pronounced dry season, although *Nothofagus* values imply wetter or more uniform condition, within gorges and higher valleys on the Hamersley Ranges. Mean annual temperatures are suggested to have been in the mesotherm rather than megatherm range.

4.2.2 *North-East Australia*

1. Central Queensland

Beeston (1994) has documented in great detail microfloras recovered from the Suttor Formation at Mt. Coolon and equivalent rock units at Riverside in central Queensland inland of Mackay. These lack age diagnostic species but are likely to be Early to Late Miocene based on occurrences of *Rugulatisporites cowrensis* (cited as *R. mallatus* and *R.* sp. cf. *R. micraulaxus*), *Acaciapollenites miocenicus* (cited as *A. myriosporites*) and a species (*Haloragacidites suttorensis*) that may be related to *H. haloragoides*. The maximum ages are Late Eocene (Middle *Nothofagidites asperus* Zone Equivalent), based on *Perfotricolpites digitatus*, or early Early Oligocene (Upper *Nothofagidites asperus* Zone Equivalent), based on *Striasyncolpites laxus* (cited as *Cupanieidites* sp. A) and *Malvacearumpollis mannanensis*. The minimum age may be early Miocene, based on the last occurrence of *Tricolpites retequetrus* in the Gippsland Basin.

Dominants include fresh to brackish water algae and *Nothofagus* (*Brassospora*) spp. including frequent *Nothofagidites falcatus* (up to 42%), Casuarinaceae (up to 20%) and Myrtaceae (up to 18%). Less common to rare taxa include Blechnaceae, *Calochlaena/Culcita*, Gleicheniaceae, *Lygodium*, *Pteris*, *Araucaria*, *Agathis/Wollemia*, Cupressaceae, *Dacrycarpus*, *Dacrydium*, *Ephedra*, *Anacolosa* (*Anacolosidites* cf. *sectus*), *Archidendron*-type, Palmae (*Arecipites*), *Beauprea*, Caesalpinaceae, Caryophyllaceae (*Polyporina* sp.), *Cissus*, Convolvulaceae, *Coprosma*-type (*Palaeocoprosmadites*), Cupanieae, Euphorbiaceae (Austrobuxus-type), *Ilex*, Loranthaceae (*Gothanipollis*), Myrtaceae (including *Austromyrtus*-type but not *Eucalyptus*), *Nothofagus* (*Fuscospora, Lophozonia)*, Malvaceae, Musgraveinae, Polygalaceae, Sapotaceae, *Villarsia*-type and a diverse array of described and undescribed Proteaceae. Many of the former had warm temperate to tropical NLRs and many Proteaceae types are recorded in the possible Late Eocene Yaamba Basin. Given the location of the two sites, the source vegetation almost certainly represent an altitudinal sequence of subtropical to cool temperate rainforest types growing on the western slopes of the Eastern Highlands (Leichhardt Ranges-Redcliffe Tableland).

Inferred climate

Conditions are likely to have been wet to very wet (perhumid) with temperatures decreasing from warm (upper mesotherm) in the lowlands to cool (lower mesotherm) on the summit of adjacent ranges. The paucity of Araucariaceae is against rainfall being strongly seasonal.

2. South-east Queensland

a. Casuarina Basin

A latest Eocene-Oligocene swamp microflora is preserved in the Casuarina Basin near Rockhampton (Dettmann and Clifford 2000b). Riparian and dryland taxa include *Lygodium*, Cyatheaceae, Anacardiaceae (*Ailanthipites*), Palmae (*Arecipites*), Casuarinaceae, Convolvulaceae (*Perfotricolpites digitatus*), Cupanieae, *Ilex*, Liliaceae, Malvaceae, non-eucalyptoid Myrtaceae, Proteaceae (including *Proteacidites pachypolus*) and Sapotaceae. Rare gymnosperms include *Agathis/Wollemia*, *Dacrydium* and *Podocarpus-Prumnopitys*. Aquatic taxa include fresh- to brackishwater algae (*Botryococcus*, *Pediastrum*), Restionaceae, Sparganiaceae and Typhaceae.

b. Capricorn Basin

Microfossil evidence of the Oligocene-Middle Miocene flora and vegetation in northeastern Australia primarily comes from two offshore wells, Aquarius-1 and Capricorn-1A (Hekel 1972). Independent age control consists of 30 year old foraminiferal dates for Aquarius-1 (Palmieri 1971). However, the broad age determinations proposed for this well and Aquarius-1 are consistent with time distribution data from the Murray-Darling Basin (cf. Macphail 1999). If correctly dated, the combined data imply *Nothofagus*-dominated communities first became prominent in southern Queensland during the possible Late Oligocene and remained common throughout the Early Miocene (Foram Zones N4-N7).

Values of non-eucalypt Myrtaceae (characteristic of wet sclerophyll forest and some forms of subtropical rainforest) increase in relative abundance over the same period. Since presumed correlative assemblages from the Duaringa and Hillborough Basins on the central Queensland coast (and Mt. Coolon in central Queensland) also are *Nothofagus*-dominated but include a diverse Myrtaceae component, the trend appears to have been a regional one in eastern Queensland. *Nypa* is last recorded during the Early Miocene (N5-N7) in Aquarius-1 but is absent in correlative sections in Capricorn-1A.

The diversity of *Nothofagus* spp. remained high in Capricorn-1A but data from Aquarius-1, located further offshore, indicate regional *Nothofagus* and Myrtaceae populations collapsed during late Early Miocene time (N8). Both taxa are represented by trace pollen values only throughout the Middle Miocene (~N8-N14). The relative abundances of other commonly occurring taxa were relatively unaffected, e.g. Podocarpaceae and Casuarinaceae, or appear to increase, e.g. *Agathis*. Otherwise the Middle Miocene assemblages are characterised by abundant fern spores, including a possible aquatic species of Polypodiaceae (*Polypodiisporites usmensis*), associated with lesser numbers of Euphorbiaceae (*Austrobuxus*-type). Rare taxa include *Nothofagus* (*Lophozonia*) and three taxa that are now typical of low/open and salt-influenced coastal communities in eastern Australia, e.g. Asteraceae, Chenopodiaceae, Convolvulaceae (*Wilsonia*-type).

c.   Brisbane district

Oligo-Miocene microfloras are preserved in the GSQ Sandy Cape 1-3R drill hole at the northern tip of Fraser Island and several boreholes near Brisbane (Harris 1965d, Wood 1986). Independent age control from indirect K/Ar evidence (Grimes 1982) indicates that the Sandy Cape 1-3R sequence is no older than 30 Ma.

Sandy Cape 1-3R includes a lower (Late Oligocene-late Early Miocene) fluvio-deltaic section in which the associated microfloras are dominated by Casuarinaceae (35%) and *Nothofagus* (*Brassospora*) spp. (14%). Cryptogams are less common (11%), with *Cyathea* being the most abundant type. The only frequent gymnosperms are Araucariaceae (3%) and *Dacrydium* (5%). Cupanieae, Malvaceae and unidentified tricolporate angiosperms comprise between 3-12% of the total count. The upper marine-influenced (late Early-Middle Miocene) section in Sandy Cape-1 is dominated by cryptogams (total 27-60%) with occasionally high values of Araucariaceae (*Agathis/Wollemia*), *Nothofagus* (*Brassospora*) and non-eucalypt Myrtaceae. Casuarinaceae becomes relatively rare (<5%). Rare to uncommon taxa include *Lygodium*, Podocarpaceae (*Dacrycarpus*, *Dacrydium*, *Microcachrys*), Alangiaceae, Convolvulaceae (*Merremia*-type), Caesalpinaceae, Cupanieae, Ericales, Euphorbiaceae (*Mallotus*-type), *Ilex*, Mimosaceae (*Archidendron*-type), Myrtaceae (including *Austromyrtus*-type), *Nothofagus* (*Lophozonia*), diverse Proteaceae (including Musgraveinae), Rubiaceae (*Guettarda*, cf. *Randia*) and Sapotaceae.

As in the Capricorn Basin, the pollen data imply that *Nothofagus* and Myrtaceae rainforest communities expanded in southern Queensland/northern New South Wales sometime during the Oligocene and were replaced, at least at low elevations, by other angiosperm-dominated rainforest types during the late Early and Middle Miocene. Sporadically high values of Araucariaceae imply the coastal vegetation included stands of (possible *Agathis*-dominated) dry rainforest.

Inferred climate

Assuming the paucity of *Nothofagus* and other temperate rainforest elements in the Casuarina Basin microflora is not due to delayed migration into northeastern Australia, the combined data suggests that climates on the mid and northeastern coasts of Queensland were seasonally cool (possible lower mesotherm), and uniformly wet (perhumid) during the latest Eocene-possible Early Oligocene. Subsequent trends may reflect rising global sea levels during the possible Late Oligocene-Miocene, for example the increase in cryptogam spores and appearance of Asteraceae and Chenopodiaceae. Nevertheless the evidence strongly points to uniformly wet and relatively cool climates giving way to warmer (upper mesotherm range) and seasonally drier climates during the late Early Miocene. The Mt. Coolon flora and presence of *Lophosoria* in the Warrumbungle Mountains in far northern New South Wales is evidence that cooler (lower mesotherm) climates persisted at higher elevations and/or within deep, shaded gullies (cf. Dettmann 1986b, Beeston 1994).

Based on the relative abundance of Euphorbiaceae (*Malvacipollis* spp.) mean annual temperatures appear to have peaked in the late Early to Middle Miocene (Zone N8-N9) although by this time sea surface temperatures were inadequate to support *Nypa*.

3.   North-west slopes and plains of New South Wales

Probable Oligocene-Middle Miocene microfloras are preserved in palaeochannels of the Castlereagh, Macquarie and Darling River systems on the north-west slopes and plains (Morgan 1977, Martin 1980, 1981, 1988, 1999a, 1999b, McMinn 1981b, Macphail 1999, unpubl. results). The record is blurred by reworked (Late Eocene) and probable down-hole caved (Plio-Pleistocene) specimens in the (mostly) cuttings samples. The microfloras mostly represent cool to warm temperate rainforest communities growing on riverbanks near to or upstream of the site.

a.   North-west plains

Moderately diverse Oligo-Miocene (*Proteacidites tuberculatus* Zone Equivalent) microfloras from the 'Glen Villa' Bore (DWR 36937) near Bourke in western New South Wales, are dominated by Casuarinaceae (38%) and unidentified tricolpate/tricolporate types (20%), with lesser amounts of Myrtaceae (14%, including 4% *Eucalyptus*), *Nothofagus* (*Brassospora*) spp. (10%) and Onagraceae (3%). Cryptogams are uncommon (4%) and the most frequently recorded gymnosperms (~1%) are *Araucaria*, *Dacrycarpus* and *Podocarpus-Prumnopitys*. Rare taxa include *Cyathea*, *Lophosoria*, Cupressaceae, *Phyllocladus*, Chenopodiaceae, Convolvulaceae (*Merremia*-type) and Cyperaceae.

A possibly contaminated Oligocene-Early Miocene (*Proteacidites tuberculatus* Zone Equivalent) microflora from Darling River Bore DWR 36839 is dominated by a previously unrecorded Euphorbiaceae type resembling *Austrobuxus* (31%), *Nothofagus* (*Brassospora*) spp. (23%) and Casuarinaceae (11%) with common *Nothofagus* (*Fuscospora*) spp. (6%), Myrtaceae (6%) and *Nothofagus* (*Lophozonia*) spp. (2%). Araucariaceae (*Araucaria*) and Podocarpaceae (*Dacrydium*, *Lagarostrobos*, *Podocarpus-Prumnopitys*) are present but rare. In contrast, probable early Late to late Miocene (*Canthiumidites bellus* Zone Equivalent) microfloras from the same region (Jandra Bore DWR 36853) are dominated by Casuarinaceae (20-24%), *Podocarpus-Prumnopitys* (11-14%), *Nothofagus* (*Brassospora*) spp. (10-18%) and unidentified tricolpate/tricolporate types (11-15%). Less common taxa are *Cyathea* (4-6%), *Araucaria* (6-7%), *Eucalyptus* (up to 4%) and Cupanieae, Liliaceae, *Nothofagus* (*Lophozonia*) spp. and Sparganiaceae. Rare taxa include several species that are not found in the *P. tuberculatus* Zone Equivalent section, e.g. Podocarpaceae (*Halocarpus*), Euphorbiaceae (*Amperea*, *Mallotus*-type), Proteaceae (*Banksia*/*Dryandra*), Rubiaceae (*Canthium*) and Sapindaceae (*Dodonaea triquetra*-type). Similarly, a sparse possible Miocene microflora from Darling River Bore DWR 36839 is dominated by *Nothofagus*, (including 7% *Lophozonia* and 4% *Fuscospora* spp.), *Araucaria* (9%) and trace numbers of Podocarpaceae (*Dacrycarpus*, *Dacrydium*, *Phyllocladus*).

Correlative (*Canthiumidites bellus* Zone Equivalent) microfloras in the Glenmore-1 drillhole near Broken Hill (McMinn 1981a) are dominated by Myrtaceae (45-60%) with lesser amounts of Casuarinaceae (7-19%) and *Nothofagus* (*Brassospora*) (5-8%). Sporadically frequent taxa include cryptogams (3%), *Araucaria* (5%), *Podocarpus-Prumnopitys* (2%) and *Dacrydium* (1%). Rare taxa include *Dacrycarpus*, *Dacrydium*, Asteraceae (Tubuliflorae), Cupanieae, Cyperaceae, Euphorbiaceae (*Austrobuxus*-type), Mimosaceae (*Acacia*), non-graminoid Restionaceae, Sapotaceae and Sparganiaceae (*Aglaoreidia qualumis*). The flora appears to represent a gallery sclerophyll forest with a minor but persistent rainforest component.

<u>Inferred climate</u>

Assuming the microfloras in the Broken Hill district are correctly dated, the pollen data indicate climates along the upper reaches of the Darling River and tributaries became temporarily cooler and wetter and/or less seasonal (humid) during the Oligocene to Early Miocene, allowing temperate rainforest species to survive along rivers as far west as Broken Hill. Since the gallery flora also included warm temperate-subtropical species, e.g. Araucariaceae, *Austrobuxus*-type, Cupanieae and *Mallotus*-type, as well as cool temperate rainforest taxa such as *Lophosoria* and *Nothofagus* (*Lophozonia*) spp., a reasonable estimate is that mean annual temperatures remained within the mesotherm range. Subsequent climates became either warmer or seasonally drier in the late Early to Late Miocene, resulting in the expansion of sclerophyll taxa such as Casuarinaceae and Myrtaceae (including *Eucalyptus*) in drier sites. The same trend seems to have allowed Asteraceae to migrate into western New South Wales.

b.　　　North-west slopes

Martin (1999b) has identified *Proteacidites tuberculatus* and *Canthiumidites bellus* Zone Equivalent microfloras in Boreholes GW 096000, and GS-A and GW 069003, respectively, in the Macquarie River Valley near Narromine. Few details are provided beyond noting the younger (possible mid-Late Miocene) assemblages include *Calochlaena*/*Culcita*, Haloragaceae (*Gonocarpus*/*Haloragis*), Mimosaceae (*Acacia*) and occasionally significant amounts of *Nothofagus* (subgenus not specified). *Canthiumidites bellus* Zone Equivalent microfloras from the Namoi, Gwydir and Castlereagh Valley in far northeastern New South Wales (Martin, 1980, 1981) are dominated by Blechnaceae (2-6%), *Cyathea* (5-20%), *Dicksonia* (1-8%), *Dacrydium* (up to 4%), *Podocarpus-Prumnopitys* (1-7%), Casuarinaceae (2-10%), non-eucalypt Myrtaceae (2-36%), *Nothofagus* (*Brassospora*) spp. (7-19%) *Nothofagus* (*Lophozonia*) spp. (4-12%), Proteaceae (up to 6%) and unidentified tricolpate/tricolporate types (7-38%).

Less common (1-5%) taxa in the Castlereagh microfloras are Araucariaceae (*Araucaria*), Podocarpaceae (*Dacrycarpus*), Cupanieae, Euphorbiaceae (*Mallotus*-type, *Micrantheum*), Escalloniaceae (*Quintinia*), Mimosaceae (*Acacia*), Proteaceae, Rubiaceae (*Randia*), *Symplocos* and Winteraceae. Maximum relative abundance values of *Dacrydium* (4%), *Phyllocladus* (2%), *Mallotus*-type (11%), *Nothofagus* (*Brassospora*) spp. (19%) and *N.* (*Lophozonia*) spp. (8%) are significantly higher in the Namoi-Gwydir Valleys than in the Castlereagh Valley to the south-west. Rare taxa (both areas) include *Sphagnum, Pteris*, *Calochlaena*/*Culcita*, Ericales, Loranthaceae, non-eucalypt Myrtaceae, Poaceae, Proteaceae, Restionaceae, Rubiaceae (*Randia*) and Winteraceae.

<u>Inferred climate</u>

Mean annual rainfall appears to have been sub-optimal (seasonally humid) for *Nothofagus* except near the ranges (perhumid). Geographic gradients in the relative abundance of *Nothofagus* (*Lophozonia*) and other cool temperate rainforest taxa imply mean annual temperatures were within the lower mesotherm range on the lower slopes, decreasing to upper microtherm values within deeper valley and on the ranges.

4.2.3 *Central Australia*

Probable Oligocene-Middle Miocene microfloras are preserved in the Namba Formation in the Callabonna Sub-basin (Martin 1990), the Burt Plain, Santa Teresa, Tempe Downs and Ti-tree Basins in the Alice Springs District, DH Glenmore-1 drilled 160 km north of Broken Hill and an unnamed borehole (RN 16861) drilled near Mt. Wedge in western New South Wales

(Morgan 1977, McMinn 1981a, Martin 1988, 1991b, 1997b, Macphail 1996c, 1997a). The age determinations are based on floristically impoverished *Nothofagidites* assemblages that lack index species found in younger (Late Miocene-Pliocene) or older (Eocene) microfloras. None of the zone index species used to subdivide Oligocene-Middle Miocene time in southern Australia have been recorded to date in central Australia and the age determinations remain provisional.

1.   Callabonna Sub-basin

The one known assemblage from the Namba Formation is moderately diverse, with dominance shared between *Cyathea* (10%), gymnosperms (total 21%) and Restionaceae (39%). Frequent to common types are *Podocarpus-Prumnopitys* (9%), *Dacrydium* (5%), *Lagarostrobos* (3%), *Phyllocladus* (3%), *Nothofagus* (*Brassospora*) spp. (4%), Sparganiaceae (5%) and Cyperaceae (2%). Rare taxa include Araucariaceae (*Agathis*/*Wollemia*), Anacardiaceae, Caesalpinaceae and *Eucalyptus*. Proteaceae are absent.

2.   Alice Springs District

Pollen dominance is shared between Gleicheniaceae, Podocarpaceae (*Podocarpus-Prumnopitys*), Casuarinaceae and *Nothofagidites* (*Brassospora*) spp. For example the Borehole RN 16861 is wholly dominated by *Nothofagus* (*Brassospora*) spp. (59%) with lesser amounts of Casuarinaceae (27%), *Podocarpus-Prumnopitys* (7%) and *Dacrydium* (4%). Low numbers of *Botryococcus* cysts imply the depositional environment was an ephemeral, brackishwater lake.

Correlative *Nothofagus* (*Brassospora*) microfloras from the Burt Plain Basin occasionally include frequent to common numbers of Blechnaceae, Araucariaceae (*Araucaria*), Malvaceae (*Malvacearumpollis*) and unidentified tricolporate types. Rare taxa include *Pteris*, Araucariaceae (*Agathis*/*Wollemia*-type), early records of *Sprengelia*-type (Epacridaceae) and *Grevillea-Hakea* (Proteaceae), Menyanthaceae (cf. *Villarsia*), Onagraceae (cf. *Epilobium*) and an unidentified Sparganiaceae. Cyperaceae, Myrtaceae (including *Eucalyptus*) and Restionaceae are very rare or absent.

Assuming that the Namba and Alice Springs sequences are broadly contemporary, relative abundances appear to have been shaped by the depositional environment and regional topography. For example, the prominence of *Nothofagus* (*Brassospora*) spp. in the Alice Springs district compared to the Lake Eyre Basin almost certainly is due to the proximity of uplands such as the McDonnell Ranges. Conversely sedges and other swamp taxa are better represented in the low-lying Lake Eyre Basin. Apart from Casuarinaceae, which may include the dry sclerophyll genera *Allocasuarina*/*Casuarina* as well as *Gymnostoma*, it is unclear which taxa occupied dry interfluve sites. Halophyte taxa such as Chenopodiaceae-Amaranthaceae (*Chenopodipollis chenopodiaceoides*) or *Wilsonia* (*Tricolpites trioblatus*) appear to be absent although both occur in saline-influenced deposits in the Murray Basin by this time.

Inferred climate

The floristically and ecologically heterogeneous composition of the microfloras in central Australia point to relatively cool (lower mesotherm) and seasonally wet (humid) conditions in which mean summer rainfall was inadequate to support rainforest trees away from stream banks or sheltered gullies. The ephemeral nature of depositional environments also point to dry summers during which rivers fragmented into brackishwater swamps.

4.2.4 *South-West Australia*

1. <u>Yilgarn Craton</u>

A depauperate Oligo-Miocene (*Proteacidites tuberculatus* Zone Equivalent) microflora is preserved at ca. 50 m depth in Rollo's Bore near Norseman in south-west Western Australia (M.K. Macphail unpubl. results). Some reworking is evident in that the assemblage also includes the Early Jurassic species *Exesipollnites tumulus*. Otherwise the assemblage is wholly dominated by *Nothofagus* (*Brassospora*) spp. (74%) and Casuarinaceae (15%). Uncommon (< 3%) to rare taxa include lycopods (*Foveotriletes balteus*, *Latrobosporites marginis*), Gleicheniaceae (cf. *Sticherus*), *Cyathea* and related trilete spores (*Cyathidites minor*), Araucariaceae (cf. *Agathis*), *Dacrydium*, *Lagarostrobos*, *Podocarpus-Prumnopitys*, *Microcachrys* (*Microcachrydites antarcticus*, *Podosporites microsaccatus*), Ericales, Sparganiaceae (*Aglaoreidia qualumis*), Strasburgeriaceae, Trimeniaceae (*Periporopollenites demarcatus*), two *Beauprea* spp. (*Beaupreaidites elegansiformis*, *B. verrucosus*) and a distinctive but as yet unidentified tetracolporoidate species.

The closest recorded analogues are Oligo-Miocene microfloras preserved in the Alice Springs District (Macphail 1997a). Frequent *Nothofagidites falcatus* demonstrates the microflora is no older than Middle Eocene. The minimum age is more difficult to determine since all species are long-ranging or (*B. verrucosus*) possibly have extended time distributions in south-west Western Australia. However, geological data (P. de Broekert, pers. comm.) indicate the unit is younger than palaeochannel deposits that preserve diverse Late Eocene, Middle *N. asperus* Zone Equivalent microfloras.

<u>Inferred climate</u>

The microflora appears to represent floristically impoverished *Nothofagus* rainforest or scrub growing around a freshwater reed swamp. Such a community is ecologically consistent with relatively cool (lower mesotherm) but uniformly wet (humid) conditions during the Eocene-Oligocene transition although similar conditions may have persisted into Early Miocene time.

4.2.5 *Central southern Australia*

1. <u>St. Vincent Basin</u>

Probable *Proteacidites tuberculatus* Zone Equivalent and *Canthiumidites bellus* Zone Equivalent microfloras occur in marine facies in the Barossa Valley (Alley 1989) and St. Vincent Basin (Rowett 1993b), respectively. In both cases, the age determination is based on the absence or presence of species that first appear in the late Early Miocene in the Gippsland Basin, e.g. *Canthiumidites bellus*.

Pollen dominance in the older (Barossa) microfloras is shared between Blechnaceae (7-13%), *Lagarostrobos* (4-36%), Casuarinaceae (5-27%) and *Nothofagus* (11-29%) associated with occasionally frequent to common *Dacrydium* (4-6%), *Halocarpus* (up to 13%), Proteaceae (up to 13%) and a possible Meliaceae (8%). A short sequence of three microfloras provide a broad-brush record of floristic and vegetation change during the late Early-Middle Miocene in the St. Vincents Basin. The lowermost assemblage is characterised by *Lagarostrobos* (9%), *Podocarpus-Prumnopitys* (6%), Casuarinaceae (13%) and *Nothofagus* (13%) associated with rare occurrences of Asteraceae (Tubuliflorae) and Sparganiaceae. The higher microfloras are characterised by higher values of Cyatheaceae, Podocarpaceae (*Dacrydium*, *Podocarpus-Prumnopitys*), Casuarinaceae, Myrtaceae (5-9%) and Restionaceae (*Milfordia homeopunctata*). Araucariaceae (*Araucaria*, *Agathis*/*Wollemia*) and *Phyllocladus* are

common (up to 5-6%) in the middle sample only. Rare taxa in this sample include Mimosaceae (*Acacia*) and Asteraceae (Tubuliflorae). *Nothofagus* (*Brassospora*) decreases from being common (~10%) to uncommon (1-5%) in the uppermost microflora, which also includes Cupanieae and *Eucalyptus*.

Inferred climate

The floristic succession implies relatively cool (lower mesotherm) and uniformly wet (humid) conditions in the Oligocene were succeeded by warmer (mesotherm range) conditions with a dry season.

4.2.6 *South-East Australia*

The epicontinental Murray Basin preserves the only geographically extensive and detailed record of Oligo-Miocene floras and vegetation in Australia (Truswell *et al*. 1985, Macphail and Truswell 1989, 1993, Macphail and Kellett 1993, Macphail *et al*. 1993, Martin 1994, Macphail 1999). Thick carbonates accumulating in the offshore Gippsland Basin during Oligo-Miocene time form the seal for hydrocarbons accumulating in the underlying Latrobe Group. As such they are seldom sampled for palynology. Exceptions are (1) a thin sequence of earliest Oligocene (Foram Zone J-2) marls in the south-west of the basin and (2) geotechnical cores obtained during construction of the Flounder-5 and Hapuku-1 production platforms (Rexilius 1985, Macphail 1997b, A.D. Partridge and M.K. Macphail unpubl. results).

Palaeobotanical studies of the Morwell-Yallourn brown coal deposits in the onshore Gippsland Basin are complemented by analyses of the associated microfloras (Luly *et al*. 1980, Sluiter and Kershaw 1982, Bolger 1991, Holdgate and Sluiter 1991, Kershaw *et al*. 1991, Blackburn and Sluiter 1994, Holdgate *et al*. 2000). Other sites occur on the central and south-west slopes, Southeastern Highlands and South Coast of New South Wales.

1.   Northern Tableland of New South Wales

Sediments near Inverell on the New England Tableland are associated with Early Oligocene and Early Miocene basalts (Wellman and McDougall 1967, McMinn 1987, 1988, 1989f, Pickett *et al*. 1990). The associated Oligo-Miocene microfloras (some of which include *Canthiumidites bellus*) are wholly dominated by *Nothofagus* (*Brassospora*) spp. (37-89%). Other commonly occurring taxa are Blechnaceae, Cyatheaceae, Podocarpaceae (*Podocarpus-Prumnopitys*), Casuarinaceae, Ericales and Myrtaceae. Rare taxa include the fern *Lophosoria* (*Cyatheacidites annulatus*).

Inferred climate

The data indicate cool (microtherm range) and uniformly wet conditions. These conditions are likely to have been created by cloudy conditions or frequent mists due to uplift of moist air from the Tasman Sea.

2.   Central slopes of New South Wales

McMinn (1981b) has described a probable *Canthiumidites bellus* Zone equivalent microflora from the Home Rule Kaolin Pit near Dubbo. Commonly occurring taxa are *Nothofagus* (*Brassospora*) spp. (18-63%), Proteaceae (up to 16%), non-eucalypt Myrtaceae (up to 5%), *Dacrydium* (4%), *Calochlaena* (up to 56%) and Blechnaceae (7-19%). Rare taxa include Araucariaceae (*Araucaria*) and *Symplocos*. Plant impressions are common in carbonaceous clay units. The source vegetation is likely to have been a gallery rainforest.

<u>Inferred climate</u>

The high relative abundance of *Nothofagus* (*Brassospora*) spp. and cryptogams imply relatively cool (lower mesotherm) and uniformly wet (perhumid) conditions within the palaeochannel.

3.   <u>Central Coast of New South Wales</u>

Canthiumidites bellus Zone Equivalent microfloras recovered from Little Bay, Sydney, provide a detailed record of estuarine communities growing in the Sydney region during the mid Miocene 'thermal maximum' (Pickett *et al.* 1990).

Assemblages are dominated by *Nothofagidites* (*Brassospora*) spp. (av. 80%) associated with low values of *Araucaria* (av. 3%), *Nothofagidites* (*Lophozonia*) spp. (av. 7%), non-eucalypt Myrtaceae (av. 6%), Casuarinaceae (3%), *Eucalyptus* (av. 2%) and unidentified tricolporates. Uncommon taxa (<1%) include *Cyathea*, *Dicksonia*, *Pteris*, Araucariaceae (*Agathis*/*Wollemia*), Cupressaceae, Podocarpaceae (*Dacrycarpus*, *Dacrydium*, *Lagarostrobos*, *Microcachrys*, *Phyllocladus*, *Podocarpus-Prumnopitys*) and Euphorbiaceae (*Mallotus*-type).

Rare taxa include: Blechnaceae (*Stenochlaena*), Anacardiaceae, Apocynaceae (*Alyxia*), Palmae (*Arecipites*, *Dicolpopollis*), Asteraceae (Tubuliflorae), Caesalpinaceae, Chenopodiaceae-Amaranthaceae, Chloranthaceae (*Ascarina*), Cunoniaceae (*Gillbeea*), Cupanieae, Escalloniaceae (*Quintinia*), Euphorbiaceae (*Austrobuxus*-type, *Beyeria*-type, *Croton*), *Ilex*, Loranthaceae, Meliaceae (*Dysoxylum*-type), Myrtaceae (*Austromyrtus*-type, *Eucalyptus*, *Eugenia*-type), Mimosaceae (*Acacia*, *Archidendron*-type), *Nothofagus* (*Fuscospora*, *Nothofagus*), Polygalaceae, Restionaceae (*Milfordia homeopunctata*), Rhizophoraceae, Rubiaceae (*Guettarda*, *Randia*), Sapotaceae, Sterculiaceae (*Ungeria*) and Vitaceae (*Cissus*).

<u>Inferred climate</u>

Unlike many sites, Little Bay is located on the edge of an extensive low-lying coastal plateau, well away from areas of high topographic relief. The sequence therefore is important as it demonstrates that some of the sources of *Nothofagus* producing *Brassospora* and *Lophozonia* pollen types were able to grow under relatively warm (upper mesotherm) conditions if other conditions such as year-round high humidity were met.

4.   <u>Southeastern Highlands of New South Wales</u>

Microfloras representing very short intervals during the Oligo-Miocene are preserved along the length of Southeastern Highlands. Many of the sediments accumulated in shallow to deep lakes dammed by basalt flows.

a.   Early Oligocene to late Early Miocene.

The oldest recorded (*Proteacidites tuberculatus* Zone Equivalent) microfloras accumulated in a 100 km long but narrow lake at 700 m elevation, formed when the upper Shoalhaven River Valley was dammed by basalts between about 29-32 Ma (Nott and Owen 1992). Pollen dominance is shared between 20 species of ferns (8-29%), 10 species of gymnosperms (12-47%) and 60 species of angiosperms (23-60%). Frequent to common taxa (maximum values in parentheses) include: Blechnaceae (9%), *Cyathea* (5%), Gleicheniaceae (8%), cycads (3%), *Araucaria* (4%), *Dacrydium* (3%), *Halocarpus* (5%), *Lagarostrobos* (13%), *Microcachrys* (8%), *Phyllocladus* (10%), *Podocarpus-Prumnopitys* (16%), Euphorbiaceae (5%), *Nothofagus* (*Brassospora*) spp. (44%), *N.* (*Fuscospora*) spp. (13%), *N.* (*Lophozonia*) spp. (3%) and Proteaceae (12%). Rare to sporadically frequent (<3%) types include

Polypodiaceae, Palmae (*Dicolpopollis*), Casuarinaceae, Cupanieae, Ericales, *Ilex*, Loranthaceae, Myrtaceae (including *Eucalyptus*), Proteaceae (*Banksia*/*Dryandra*, *Beauprea*, *Embothrium*, *Xylomelum occidentale*-type), *Quintinia*, Trimeniaceae and Winteraceae.

b.   Late Early to early Late Miocene

Canthiumidites bellus Zone Equivalent microfloras are more widespread on the Southeastern Highlands. Sites for which detailed microfloral information is available are Elands (M.K. Macphail unpubl. results), Kiandra at about 1400 m elevation (Owen 1988), and Palaeolake Bunyan, at about 780 m elevation near Cooma (Tulip *et al*. 1982). Dating of the last site is insecure due to lack of age-diagnostic taxa.

The Elands microflora is dominated by Casuarinaceae (29%), *Araucaria* (14%), *Dacrycarpus* (13%), with lesser amounts of *Nothofagus* (*Lophozonia*) spp. (5%) spp., *Podocarpus-Prumnopitys* (4%), Blechnaceae (8%) and *Cyathea* (7%). *Nothofagus* (*Brassospora*) spp. are uncommon (2%). The diversity is moderately high, with some 17 cryptogam, 6 gymnosperm and 40 angiosperm species being recorded. Modern affinities range from cool temperate, e.g. *Dicksonia*, *Lophosoria* and Winteraceae, to warm temperate-subtropical, e.g. *Pteris*, Palmae (*Dicolpopollis*), Caesalpinaceae, Cupanieae, Euphorbiaceae (*Mallotus*-type), Malpighiaceae, Mimosaceae (*Acaciapollenites miocenicus*) and Rubiaceae (*Guettarda*, *Randia*).

Microfloras preserved some 4 degrees to the south, at Palaeolake Bunyan and Kiandra, are dominated by *Nothofagus* (*Brassospora*) spp. (maximum values 65% and 80%, respectively). Sporadically common to abundant taxa are (maximum values in parentheses): Sparganiaceae (29%), *Nothofagus* (*Fuscospora*) spp. (17%), *Nothofagus* (*Lophozonia*) spp. (15%), Ericales (23%), *Podocarpus-Prumnopitys* (16%), an extinct form of *Microcachrys* (*Podosporites microsaccatus*) (55%), Blechnaceae (31%) and an unidentified inaperturate type (42%). Araucariaceae (*Araucaria*, *Wollemi*-type), *Phyllocladus* and Casuarinaceae are relatively uncommon (1-9%). Sporadically common taxa are Kiandra are Gleicheniaceae (47%), trilete types (16%), *Dicksonia* (7%) and non-eucalypt Myrtaceae (9%). Whilst the cryptogam and gymnosperm components are moderately diverse, 'thermophilous' taxa only occur in trace numbers and then only in one to few occasional sample, e.g. *Ilex* and (Kiandra) Cupanieae, *Mallotus*-type, *Randia* and Sapotaceae.

The data imply rainforest communities at high elevations remained dominated by *Nothofagus* (*Brassospora*) spp. throughout the Oligo-Miocene but it is uncertain whether these were forest or wet scrub.

Inferred climate

Climates at lower elevations in the north of the area (Elands) are likely to have been weakly seasonal whilst mean air temperatures were adequate (upper mesotherm range) to support a form of araucarian (dry) rainforest which included palms. Climates at higher elevations in the south of the area were relatively cool (lower mesotherm range) and uniformly wet to very wet (perhumid). Despite its lower elevation, the Palaeolake Bunyan microfloras are distinctly less temperate than those recovered at Kiandra. Possible reasons are that vegetation around the former (a very large deep lake) was shaped by cold air drainage or that the microfloras post-date the mid Miocene thermal maximum.

5.   South-west slopes of New South Wales

Microfossil evidence from the Southeastern Highlands is complemented by analyses of correlative sediments in broad river valleys draining the south-west slopes, e.g. the Lachlan Valley (Martin 1973, 1987, 1991b). *Nothofagus* (*Brassospora*) spp., which are abundant during *P. tuberculatus* Zone Equivalent time, are replaced by Myrtaceae as the dominant

pollen type during the *Canthiumidites bellus* Zone Equivalent. Rare taxa that are found only in the *P. tuberculatus* Zone Equivalent include: Cunoniaceae, Elaeocarpaceae, Ericales, Euphorbiaceae (*Mallotus*-type), *Ilex*, Geraniaceae (*Pelargonium*-type), Loranthaceae, Malvaceae, Polygalaceae, Restionaceae (*Milfordia homeopunctata*) and Sapotaceae. Rare taxa, which first appear at the top of the *P. tuberculatus* or within the *C. bellus* Zone Equivalents are Asteraceae (Tubuliflorae), Goodeniaceae, Haloragaceae (*Haloragodendron*-type, *Gonocarpus*/*Haloragis*), Mimosaceae (*Acacia*), Sapindaceae (*Dodonaea triquetra*-type), *Symplocos* and Winteraceae. Cupanieae, *Quintinia* and Poaceae are present in both zones.

Inferred climate

The data point to wet to very wet (humid-perhumid) conditions up to Middle Miocene time, after which climates appear to have become seasonally too dry to support *Nothofagus* (*Brassospora*) spp. Temperatures during the Middle Miocene remained within the (possibly lower) mesotherm range but appear to have been less equable than during the Late Oligocene-Early Miocene, resulting in effective 'cooling' during an interval marked by relatively warm temperatures elsewhere.

5.   South Coast of New South Wales

Nott *et al*. (1991) has reported possible *Proteacidites tuberculatus* Zone Equivalent microfloras in two samples from the Long Beach Formation on the far south coast of New South Wales. Revisions of the assemblages (Macphail *et al*. 1994) indicate these represent a wetland community dominated by Gleicheniaceae (42-48%). Frequent to commonly occurring types are, *Dacrydium* (5-7%), *Dacrycarpus* (up to 4%), Casuarinaceae (up to 18%), *Nothofagus* (*Brassospora*) spp. (13-16%), *N*. (*Lophozonia*) spp. (3-5%), *Rhoipites* sp. cf. Rutaceae (up to 10%), Sparganiaceae/Typhaceae (up to 3%) and unidentified tricolpates (11%). Rare taxa include Araucariaceae (*Araucaria*), Podocarpaceae (*Halocarpus*, *Lagarostrobos*), Cupanieae, Myrtaceae (including *Eucalyptus*), *Nothofagus* (*Fuscospora*, *Nothofagus*) spp., Meliaceae, Menyanthaceae, Proteaceae (including *Xylomelum occidentale*-type) and Sparganiaceae (*Sparganiaceaepollenites*). The source vegetation appears to have been a mosaic of rainforest and sclerophyll scrub-heath and fern communities analogous to coastal vegetation growing in sand dune swales in northern New South Wales.

Inferred climate

Soil fertility, drainage and fire may have been as important as climate in directing community development on the South Coast. The presence of *Dacrycarpus*, *Dacrydium* and *Nothofagus* is evidence that rainfall was sufficiently high (humid-perhumid) and reliable during summer months to maintain high water table levels. Low values of Araucariaceae make it unlikely mean annual temperatures ranges as high as upper mesotherm.

6.   Otway Basin

Pollen dominance during *Proteacidites tuberculatus* Zone time in the Otway Basin and other areas in southwestern Victoria is similar to the Gippsland Basin (see below) although the diversity of rare taxa appears to be higher. For example, microfloras from 'deep leads' north of Stawell, are dominated by *Nothofagus* (*Brassospora*) spp. (66-75%) associated with relatively low numbers of *Cyathea* (~2%), *Dacrydium* (2%), *Lagarostrobos* (1-2%), *Podocarpus-Prumnopitys* (3-4%), Casuarinaceae (4-5%), Myrtaceae (1-7%), *Nothofagus* (*Fuscospora*) spp. (1%), Proteaceae (~2%), Trimeniaceae (1-2%) and unidentified tricolporates (4-7%) (Partridge 1993, A.D. Partridge and M.K. Macphail unpubl. results). Rare types include Araucariaceae (*Araucaria*), Proteaceae (*Dacrycarpus*), Cunoniaceae (*Gillbeea*-type), Euphorbiaceae (*Austrobuxus*-type, *Micrantheum*), *Ilex*, Loranthaceae, Myrtaceae (*Austromyrtus*-type), *Nothofagus* (*Lophozonia*) spp., Polygalaceae, *Quintinia* and

Strasburgeriaceae. Proprietary information on *Canthiumidites bellus* Zone assemblages from the offshore Otway Basin was not available when this review was prepared.

Inferred climate

The limited data are consistent with relatively cool (lower mesotherm) and uniformly wet (perhumid) conditions.

7.   Murray Basin

Reliably dated *Proteacidites tuberculatus* and *Canthiumidites bellus* Zone Equivalent microfloras are preserved in over 175 boreholes. Because of the size of the basin, regional palaeobotanical trends during the Oligo-Miocene are often obscured by edaphic phenomena. Other complications are episodic marine transgression-regression sequences of the south-west and central west, and extension of saltwater 'wedges' along rivers into the north and east, of the basin. Reviews of the palynostratigraphic database (Macphail and Truswell 1989, Martin 1986, 1993, 1994, 1998a, Macphail 1999) indicate that taxa such as Araucariaceae, *Lagarostrobos* that now are confined to mesotherm and microtherm rainforest types, respectively, provide a reliable guide to the complex and evolving climatic gradients across the basin during the Oligo-Miocene. The relative abundance of *Nothofagus* (*Brassospora*) spp. varies in time and proximity of the site to the Southeastern Highlands of New South Wales.

a.   Western Murray Basin

Proteacidites tuberculatus Zone Equivalent microfloras are preserved in the fluvio-lacustrine Renmark Group and marginal marine 'lower' Geera Clay in the Oakvale-1 core hole, northwestern margin (Truswell *et al.* 1985) and in marginal to restricted marine correlatives (Ettrick Formation, Mannum-Morgan Limestone) in SADME MC63 bore in the central west of the region (Martin 1991a).

Pollen dominance in Oakvale-1 is shared between cryptogams, gymnosperms and angiosperms. Commonly occurring taxa are trilete ferns (2-7%), Gleicheniaceae (1-14%), *Araucaria* (1-35%; av. 7%), *Dacrycarpus* (1-5%), *Dacrydium* (1-7%), *Podocarpus-Prumnopitys* (2-14%), Casuarinaceae (5-21%), Cunoniaceae (up to 5%), Cyperaceae (up to 4%), Elaeocarpaceae (up to 4%), *Eucalyptus* (up to 13%), non-eucalypt Myrtaceae (up to 36%), *Nothofagus* (*Brassospora*) spp. (5-50%: av. 20%) and unidentified tricolporate types (4-12%). *Nothofagus* (*Brassospora*) values decrease from ~ 25% 5 to ~7% up section whilst Casuarinaceae and Araucariaceae show the reverse trend, decreasing to ~21% and 17%, respectively. Rare to uncommon (maximum values in parentheses) taxa include: *Sphagnum* (1%), *Dicksonia*, *Lophosoria*, *Lagarostrobos* (1%), *Microcachrys* (1%), *Agathis/Wollemi*, Palmae (*Arecipites*), Chenopodiaceae-Amaranthaceae, Cupanieae, Euphorbiaceae (1%), Gyrostemonaceae, *Ilex*, Loranthaceae, Malvaceae, Mimosaceae (*Acacia*), Myrtaceae (*Austromyrtus*-type), *Nothofagus* (*Fuscospora*) spp. (2%), *Nothofagus* (*Lophozonia*) spp., Poaceae (2%), *Quintinia*, Restionaceae, Sapindaceae (*Dodonaea triquetra*-type), Sapotaceae and Trimeniaceae. Microfloras from SADME MC63 are similar except that maximum values of gymnosperms and Casuarinaceae are lower, e.g. *Araucaria* (<9%), whilst *Nothofagus* (*Lophozonia*) spp. are slightly more common (up to 3%). Cupressaceae is frequent (up to 5%). *Acacia* (2%) and Asteraceae (Tubuliflorae) first appear at the top of the *P. tuberculatus* Zone Equivalent interval.

Pollen dominance in *Canthiumidites bellus* Zone Equivalent microfloras in Oakvale-1 and SADME MC63 are similar to those of the underlying *Proteacidites tuberculatus* Zone Equivalent. For example, the microfloras are dominated by Casuarinaceae (9-28%), non-eucalypt Myrtaceae (1-22%) and *Nothofagus* (*Brassospora*) spp. (3-17%). Values of

Araucaria (4-13%; av. 8%) and *Nothofagus* (*Lophozonia*) spp. (1-3%) are slightly higher. However the interval can be distinguished by consistent occurrences of mostly thermophilous taxa that were rare or absent in the *P. tuberculatus* Zone Equivalent, e.g. *Cyathea*, *Pteris*, *Acacia*, Aquifoliaceae (*Ilex*, *Sphenostemon*), Palmae (*Dicolpopollis*), Caesalpinaceae, Convolvulaceae (*Merremia*-type), Ericales, Haloragaceae (*Gonocarpus*/*Haloragis*), *Quintinia*, Rubiaceae (*Gardenia*, *Randia*) and Winteraceae. *Nothofagus* (*Lophozonia*) spp. and *Phyllocladus* become rare, and Trimeniaceae and *Lagarostrobos* are absent during the zone.

Inferred climate

The pollen data confirm that climates in western Murray Basin were sub-optimal (possibly seasonally too dry) for the extensive development of either *Nothofagus* or Araucariaceae-dominated rainforest although conditions were markedly wetter (humid) and overall warmer (mesotherm range) than at present. Trends in rare taxa suggest mean temperatures reached a maximum during the late Early to Middle Miocene. *Araucaria* and *Lagarostrobos* values imply climates became effectively drier/more strongly seasonal at about the same time. The prominence of Poaceae suggests marine flooding favoured the expansion of grasslands around the shoreline at a time when grasses were relatively rare in the interfluve vegetation.

b.   Central Murray Basin

Much of the detailed information comes from four fully cored drill holes, Hatfield-1, Manilla-1, Piangil West-2 and Woodlands-1 (Macphail and Truswell 1989), augmented by a much larger number of boreholes, which have been sampled by cuttings only (Macphail 1999). Unlike the western sector, the central (depocentre) region appears to preserve correlatives of the earliest Oligocene Upper *Nothofagidites asperus* Zone deposits of the Gippsland Basin, e.g. Hatfield-1, located near the present confluence of the Lachlan and Murrumbidgee Rivers. These are defined by the first appearance of cf. *Epilobium* (Onagraceae) and *Archidendron*-type (Mimosaceae) in *Nothofagus* (*Brassospora*) dominated microfloras, which lack *Lophosoria*.

Relative pollen abundance in these earliest Oligocene (Upper *Nothofagidites asperus* Zone Equivalent) microfloras show little change. Araucariaceae values are intermediate between values recorded in the Late Eocene and Middle *N. asperus* Zone Equivalent (see Figure 8 in Macphail and Truswell 1989). *Nothofagus* (*Brassospora*) values tend to be lower/more irregular than during the Late Eocene and commonly occurring types include Casuarinaceae and non-eucalypt Myrtaceae. Pollen dominance in Early Oligocene-early Late Miocene (*Proteacidites tuberculatus* Zone Equivalent) microfloras is similar but *Nothofagus* (*Brassospora*) values are even more variable whilst those of Araucariaceae, Casuarinaceae and Myrtaceae increase towards the top of the zone. These trends are variably maintained during the *Canthiumidites bellus* Zone Equivalent, leading to Casuarinaceae and/or Araucariaceae being as common as or more abundant than *Nothofagus* (*Brassospora*) at the top of the *Canthiumidites bellus* Zone Equivalent in the Manilla-1, Piangil West-2 and Woodlands-1 boreholes. Araucariaceae reaches maximum values within this zone.

Cyperaceae, Restionaceae and Sparganiaceae are more abundant in microfloras recovered from the marginal marine Geera Clay than in the underlying (fluvio-lacustrine) Renmark Formation. This implies these wetland taxa formed specialised shoreline and strand communities. Probable Early Miocene microfloras from marine sediments in the Balranald area (Pickett and McMinn 1983) are dominated by *Nothofagus* (*Brassospora*), Casuarinaceae and Myrtaceae (total ~90-95%). Rare taxa include *Araucaria, Dacrydium,* Cupanieae, and *Quintinia*.

Rare taxa which first appear in the Late Oligocene-Early Miocene in the central Murray Basin are Chenopodiaceae-Amarathaceae, Mimosaceae (*Acacia*) and Rubiaceae (*Randia*) and a plethora of taxa that have not been recorded, or are extremely rare in, correlative microfloras in the Gippsland Basin. Examples are: *Pteris* (*Asseretospora*), Podocarpaceae (*Microstrobos*), Alangiaceae (*Alangium*), Palmae (*Dicolpopollis*), *Callitriche* (*Retistephanocolpites* sp.), Convolvulaceae, *Fuchsia* (*Diporites aspis*), Malpighiaceae, Malvaceae, Mimosaceae (*Acacia*, *Archidendron*-type), Onagraceae (cf. *Epilobium*), Polygonaceae (*Glencopolis ornatus*), Portulacaceae, Sapindaceae (*Dodonaea triquetra*-type) and numerous Proteaceae including *Banksia serrata*-type and *Isopogon* (*Proteacidites isopogiformis*). Rhizophoraceae (*Zonocostites*) pollen are present in very low numbers, but otherwise it is not clear which plants occupied the salt-marsh or mangrove niche within the basin, or if tidal regimes within the basin allowed extensive halophytic vegetation types to develop.

Inferred climate

The high diversities almost certainly reflect the very large area and diversity of plant communities from which the fossil pollen and spore were sourced. Many of the taxa found in the Murray Basin, but not in the Gippsland Basin, have modern pan-tropical distributions, implying mean annual temperatures within the Murray Basin were relatively warm (possible upper mesotherm range). Rainfall was high to very high (perhumid) but the change from *Nothofagus* (*Brassospora*) spp.-dominated to Casuarinaceae/Myrtaceae-dominated microfloras via a transitional phase in which Araucariaceae were prominent is reliable evidence that precipitation became increasingly seasonal during the Oligo-Miocene.

c.   Eastern Murray Basin

Harris and Morgan (1976) have described a possible Early Oligocene Upper *Nothofagidites asperus-Proteacidites tuberculatus* Zone Equivalent microflora from the Jerilderie district on the southeastern margin of the Murray Basin. This includes a number of taxa with warm temperate to tropical NLRs, e.g. Cupanieae, *Ilex*, Proteaceae (including *Embothrium*), *Santalum* and Sapotaceae but lacks *Lophosoria*. Otherwise the bulk of the palynostratigraphic data from boreholes in the eastern Murray Basin is centred on changes in the relative abundance of five commonly occurring taxa (expressed in ratio form) *viz*. *Nothofagidites flemingii*/total *Nothofagidites*, total Myrtaceae/total *Nothofagidites* and, *Araucariacites*/total gymnosperms (Martin 1986).

Martin (*ibid*) suggests that the individual taxa form an ecological *continuum*, with *Nothofagus* occupying the driest and *Lagarostrobos* the wettest sites. These results are difficult to compare with other regions. Presentation of the same data in alternative formats (Martin 1993) indicates that the microfloras are dominated by either *Nothofagus* (*Brassospora*) spp. or Myrtaceae, with the latter becoming relatively more abundant during *C. bellus* Zone Equivalent time. *Lagarostrobos* and *Phyllocladus* were more common and persisted longer in the eastern Murray Basin than elsewhere, and this also appears to have been the case with *Lophosoria* (M.K. Macphail unpubl. results). *Lophozonia* spp. increases in abundance relative to other *Nothofagus* subgenera, especially in sites located close to the Southeastern Highlands of New South Wales.

Inferred climate

The data confirm that conditions were wet (perhumid) relative to the western Murray Basin and probably cooler (lower mesotherm range) than the central Murray Basin. Martin (1993) argues expansion of Myrtaceae and *Nothofagus* (*Lophozonia*) spp. indicates that climates became effectively drier (possibly more seasonal) during the mid Miocene. Whilst drier/more seasonal climates are supported by the diminishing relative abundance of riparian swamp taxa

such as *Lagarostrobos*, increases in the relative abundance of *Lophozonia* spp. are more likely to reflect increasing cool and cloudy conditions on the slopes and summit plateaux of the Southeastern Highlands.

8.   Gippsland Basin

a.   Earliest Oligocene

Earliest Oligocene, Upper *Nothofagidites asperus* Zone microfloras are transitional in that they are dominated by *Nothofagus* (*Brassospora*) spp. (>50%) and lack the index species of the Late Eocene Middle *N. asperus* Zone and Early Oligocene *Proteacidites tuberculatus* Zone (Stover and Partridge 1973).

Gymnosperms are more common during the Early Oligocene than in the late Eocene (~ 30%) and some coal microfloras are wholly dominated by *Lagarostrobos* (>80%). Sparganiaceae (*Aglaoreidia qualumis*) and Proteaceae are present although relative abundance is low (<1%). For some unknown possibly ecological reason, two previously rare *Proteacidites* spp., *P. rectomarginis* and *P. stipplatus*, replaced other species such as *P. pachypolus* as the most commonly recorded Proteaceae. A genus of waratahs (*Embothrium*), which is endemic to the central and southern Andes, reached Australia during the earliest Oligocene, and a *Sphagnum* species [*Stereisporites* (*Tripunctisporis*) sp.] that had been continuously present in the basin since the Late Maastrichtian, became extinct at about the same time.

Correlative Early Oligocene palynofloras from 9200-9221 ft. in the deep-water well Hapuku-1 (Macphail 1997b, M.K. Macphail and A.D. Partridge unpubl. data) are dominated by *Nothofagus* (*Brassospora*) spp. (33-59%) with lesser amounts of *Cyathea* (1-11%), *Araucaria* (4-19%), *Lagarostrobos* (4-6%), *Podocarpus-Prumnopitys* (4-7%), Casuarinaceae (6-7%), Myrtaceae (2%), *Nothofagus* (*Fuscospora*) spp. (2-4%) and *Nothofagus* (*Nothofagus*) spp. (2-4%). The diversity is high despite the remote offshore location and a number of the trace records represent first or early occurrences in the basin. Examples are Apocynaceae (*Alyxia*), Gyrostemonaceae (*Gyropollis psilatus*), Malvaceae (*Malvacearumpollis*), Rubiaceae (*Coprosma-Opercularia*) and Stylidiaceae (*Tricolpites stylidioides*). The only taxa that have NLRs with warm temperate to tropical affinities in Australasia are *Lygodium*, *Beauprea*, Didymelaceae and *Ilex*.

Inferred climate

The palynostratigraphic record is complicated by a major fall in global sea levels during the Early Oligocene, but the data are emphatic that rainfall remained uniformly high (perhumid). Accordingly, the most ecologically convincing explanation for massive impoverishment of *Nothofagus* communities is that mean temperatures decreased catastrophically into the microtherm range during the Eocene-Oligocene transition. If correct, Upper *Nothofagidites asperus* Zone microfloras in the Gippsland Basin are contemporary with the Lemonthyme Glaciation of northwestern Tasmania (cf. Macphail *et al*. 1993), subsidence of the South Tasman Rise to abyssal depths, and formation of the Circumantarctic Current.

Proteacidites tuberculatus Zone microfloras are more diverse than Upper *Nothofagidites asperu*s Zone assemblages and are distinguished by the re-appearance of *Lophosoria* (*Cyatheacidites annulatus*: last recorded in the Maastrichtian). With few exceptions, these are dominated by *Nothofagus* (*Brassospora*) spp. with lesser amounts of Casuarinaceae, Podocarpaceae (*Podocarpus-Prumnopitys*) and Araucariaceae (*Araucaria*). Because of deep-water depositional environments, the offshore microfloras are biased towards riparian plants whose pollen or spores are transported by water or wind (Neves Effect).

Correlative microfloras in the onshore Latrobe Valley are dominated by pollen and spores derived from the peat-forming vegetation. Nevertheless, immigration of dryland taxa allows the zone to be informally subdivided into three zonules – the Lower, Middle and Upper *P. tuberculatus* Zones – provisionally correlated with Early Oligocene (Foram Zone J-2 to J-1) time, Oligocene (Foram Zone J-2 to J-1) time, Late Oligocene (Foram Zone I-2 to H-2) time, and Early Miocene (Foram Zone H-1 and G) time (A.D. Partridge, pers. comm.).

b.   Early Oligocene to late Early Miocene

Early Oligocene/Lower *P. tuberculatus* Zones assemblages have been recovered from the (offshore) Lakes Entrance Formation and (onshore) inter-seam clays below the Morwell 2A-C seam. The former are dominated by *Nothofagus* (*Brassospora*) spp. (~40%), *Podocarpus-Prumnopitys* (~12%), *Araucaria* (~9%), *Agathis*/*Wollemia* (~5%), *Lagarostrobos* (4%) and Casuarinaceae (~5%). Late Oligocene/Middle *P. tuberculatus* Zone assemblages preserved at the base of the Morwell 1B Seam are dominated by Myrtaceae and Elaeocarpaceae. Higher in the same section, the microfloras are dominated by *Nothofagus* (*Brassospora*) spp. with frequent to common Myrtaceae, Casuarinaceae and Elaeocarpaceae, and occasional high values of *Lagarostrobos* (Fig. 14.6 in Blackburn and Sluiter, 1994). Values of Myrtaceae and *Lagarostrobos* increase at the expense of *Nothofagus* (*Brassospora*) spp. in the Early Miocene/Upper *P. tuberculatus* Zone Morwell 1A Seam. *Acacia* and *Guettarda* (Rubiaceae) are recorded for the first time in this zonule. A correlative microflora from Hapuku-1 (9182 ft.) is dominated by *Nothofagus* (*Brassospora*) spp. with lesser amounts of *Lagarostrobos*, *Podocarpus-Prumnopitys* and Casuarinaceae. Rare taxa include *Lophosoria*, *Phyllocladus* and Winteraceae.

c.   Late Early to ~early Late Miocene

Nothofagus (*Brassospora*) continued to dominate (30 to >50%) offshore and (Yallourn Formation) onshore microfloras during late Early to Middle (or early Late) Miocene *Canthiumidites bellus* Zone time although values decline relative to some temperate gymnosperms and sclerophyll angiosperms.

For example, sporadically common taxa in the lower part of the Yallourn Formation include Gleicheniaceae (up to 10%), *Banksia*/*Dryandra* (up to 8%), Casuarinaceae (10-30%), Ericales (up to 12%), Myrtaceae and Proteaceae (2-10%), and Restionaceae (up to 35%). The only frequent to common gymnosperms are *Lagarostrobos* and *Podocarpus-Prumnopitys*. Uncommon to rare taxa include *Cyathea*, Podocarpaceae (*Dacrycarpus*, *Dacrydium*, *Phyllocladus*), Araliaceae, Cunoniaceae, Cupanieae, Elaeocarpaceae, Loranthaceae, Myrtaceae (*Austromyrtus*-type, *Syzygium*-type), *Nothofagus* (*Fuscospora*) spp., *N.* (*Lophozonia*) spp., *Quintinia*, Sapotaceae and probable members of the Rhamnaceae, Rosaceae, Rutaceae families.

Canthiumidites bellus Zone microfloras in Hapuku-1 encompass Foram Zone F to Foram Zone B-2 time (A.D. Partridge pers. comm.). Rare taxa which first appear in the interval include (modern equivalents in parentheses) the wet forest ferns *Rugulatisporites cowrensis* (*Calochlaena*/*Culcita*) and *Polypodiaceoisporites tumulatus* (possibly extinct *Pteris*), herbs such as *Tubulifloridites antipodica* (Asteraceae) and *Haloragacidites haloragoides* (*Gonocarpus*/*Haloragis*), and at least one small rainforest tree *Symplocoipollenites austellus* (*Symplocos*). *Nothofagus* (*Brassospora*) spp. values appear to be lower (8-11%) than in the *Proteacidites tuberculatus* Zone. Taxa that are consistently frequent to common are Blechnaceae (up to 4%), Dicksoniaceae spp. (up to 9%), Araucariaceae (23-34%), *Dacrydium* (up to 4%), *Lagarostrobos* (up to 8%), *Podocarpus-Prumnopitys* (7-10%), *Eucalyptus* (up to 2%) and *Nothofagus* (*Lophozonia*) spp. (up to 3%). Rare taxa include *Dicksonia* (*Matonisporites*, *Trilites tuberculiflormis*), *Phyllocladus*, Mimosaceae (*Acacia*), Sapindaceae (*Dodonaea*), *Symplocos* and Winteraceae. One sample included pollen of a possible *Nypa*

species (*Spinizonocolpites uvatus*) in association with unusually abundant *Lophosoria* (~12%).

Inferred climate

Oligo-Miocene climates were uniformly wet to very wet (perhumid) but characterised by marked variations in mean temperatures. For example, the extinction of thermophilous taxa at the Eocene-Oligocene boundary (Middle/Upper *Nothofagidites asperus* Zone boundary) is consistent with an abrupt drop in mean temperatures to microtherm values. Subsequent trends point to gradual warming during the Early Oligocene-Early Miocene with maximum warmth (mesotherm range) being achieved in the late Early or Middle Miocene.

Mean annual temperature values appear to have remained within the lower mesotherm range during the late Early to late Miocene but it is possible that warm SSTs allowed a relative of the tropical mangrove palm *Nypa* to migrate into the Gippsland Basin. The record is an interesting one given the sporadic appearance of warm water benthic foraminifera in southern Australia during the Middle Miocene (B. McGowran pers. comm.). The relative decline in *Nothofagus* (*Brassospora*) spp. (Fig. 2 in Sluiter and Kershaw 1982) and increasing representation of taxa typical of low/open community types suggests rainfall may have become more seasonal at about the same time. Nonetheless moisture levels remained adequate to support possibly extensive *Lagarostrobos* swamp forests into the early Late Miocene.

4.2.7 *Tasmania*

For reasons that remain unclear many of the Early Tertiary palaeochannels that preserve macrofossil deposits in Tasmania became infilled (and possibly buried) during Oligo-Miocene time. The combined macrofossil and microfossil record is unusually comprehensive, both in terms of geographic coverage relative to the size of the island and in numbers of taxa able to be identified to genus or species level. Only in exceptional cases are independent age control available and it remains uncertain if the taxa used to distinguish *Proteacidites tuberculatus* and *Canthiumidites bellus* Zone Equivalent time in the Gippsland were present in the flora of inland northern and southern Tasmania during the Oligo-Miocene. For example, the earliest known record of one important accessory species of the *Canthiumidites bellus* Zone (*Symplocoipollenites austellus*) is Late Pliocene. Consequently some floras and sites dated as Early Oligocene to late Early Miocene may prove to be late Early to early Late Miocene.

1.   Bass Basin

Martin (1985) has provisionally identified *Proteacidites tuberculatus* Zone Equivalent microfloras in Squid-1 (1400-1855 m) and Tasmanian Devil-1 (600-750 m), Bass Basin. Range chart data indicate the microfloras are wholly dominated by *Nothofagus* (*Brassospora*) spp. Rare taxa include *Araucaria*, *Dacrydium*, *Lagarostrobos*, Cupanieae, *Nothofagus* (*Lophozonia*), Polygalaceae and (diverse) Proteaceae. *Lophosoria* was not recorded.

Harris (1965c) has recorded *Lophosoria* in a probable *Proteacidites tuberculatus* Zone Equivalent microflora from Cape Barren Island off the northeastern coast of Tasmania. This assemblage is unusual in that it includes *Dacrycarpus*, *Dacrydium*, *Phyllocladus*, *Beauprea*, Cupanieae and *Nothofagus* (*Brassospora*) spp. but not *Lagarostrobos* or *Podocarpus-Prumnopitys*. Araucariaceae are absent.

Inferred climate

The assemblages are depauperate versions of correlative microfloras preserved in the Gippsland Basin. Without access to quantitative data, it is difficult to determine whether the

impression of floristic impoverishment is valid or merely due to cursory examination of the material. If the former then it is probable that conditions within the Bass Basin were as wet (perhumid) but cooler (upper microtherm) than in the Gippsland Basin.

2.   North-west Coast

Diverse microfloras are preserved in mudstones at Wilsons Creek in the lower Mersey Valley in northwestern Tasmania, and a rafted clast of estuarine mud deposited in offshore marls at Fossil Bluff at Wynyard (Macphail 1996a, M.K. Macphail unpubl. results).

The Wilsons Creek microfloras lack *Cyatheacidites annulatus* but include two rare taxa (*Mutisiaepollis patersonii*, *Tricolpites stylidioides*) that first appear in the earliest Oligocene/latest Eocene Lemonthyme Creek and Wilmot Dam sections (Macphail and Hill 1994) and are likely to be no older than Early Oligocene. Dominance is shared between *Lagarostrobos* (24%), *Podosporites-Prumnopitys* (21%) and *Nothofagus* (*Brassospora*) spp. (15%), with lower relative abundances of *Nothofagus* (*Nothofagus*) sp. (9%), *N.* (*Fuscospora*) spp. (3%), Osmundaceae (2%), *Araucaria* (3%), *Dacrycarpus* (3%), Casuarinaceae (4%), Proteaceae (3%), Trimeniaceae (3%) and unidentified tricolporates (2%). Rare taxa include *Sphagnum*, *Cyathea*, *Dicksonia*, a possible pteridosperm (*Alisporites simplis*), Araucariaceae (*Agathis/Wollemia*), Podocarpaceae (*Dacrydium*, *Microstrobos*, *Phyllocladus*), Cyperaceae, Droseraceae, Ericales, Euphorbiaceae (*Austrobuxus*-type, *Croton*-type), Loranthaceae, Menyanthaceae, Myrtaceae and Sapotaceae.

Foraminiferal evidence indicates that the *Proteacidites tuberculatus* Zone microflora from Fossil Bluff was deposited during the earliest Miocene Foram Zone N5. *Nothofagus* (*Brassospora*) spp. are abundant (34%). Frequent to common taxa are *Cyathea* (10%), Dicksoniaceae (10%), Osmundaceae (2%), *Araucaria* (9%), *Dacrydium* (5%), *Lagarostrobos* (3%), *Podocarpus-Prumnopitys* (7%), *Nothofagus* (*Lophozonia*) spp. (4%) and *N.* (*Fuscospora*) spp. (2%). Rare taxa include *Lophosoria*, Cupressaceae-Taxodiaceae, Podocarpaceae (*Dacrycarpus*, *Halocarpus*, *Microcachrys*, *Microstrobos*, *Phyllocladus*, *Podosporites*), Apocynaceae (*Alyxia*), Chenopodiaceae-Amarathaceae, *Ascarina*, Ericales, Euphorbiaceae (*Amperea*), *Ilex*, Myrtaceae (*Austromyrtus*-type, *Eucalyptus*), Proteaceae (*Agastachys*-type, *Beauprea*, *Embothrium*, *Xylomelum occidentale*-type), *Quintinia*, Sapindaceae (*Dodonaea ericifolia*-type, *D. triquetra*-type) and Winteraceae.

The microfloras represent floristically complex evergreen rainforest lining coastal rivers and possible strandline communities (Fossil Bluff). Although the cryptogam and gymnosperm components are relatively diverse, the number of angiosperms is lower than in co-eval rainforest stands in mainland south-east Australia.

Inferred climate

Conditions are likely to have been cool (microtherm range) and uniformly wet to very wet (perhumid).

3.   North-east

Proteacidites tuberculatus Zone lignites at Pioneer preserve rich microfossil assemblages as well as macrofossils including tree trunks (Harris 1964b, 1965c, Hill and Macphail 1983). Dominant taxa are *Nothofagus* (*Brassospora*) spp. (49-64%) associated with lower numbers of Blechnaceae (2-3%), trilete types (1-3%), *Dacrydium* (2-4%), *Nothofagus* (*Lophozonia*) spp. (up to 5%), *Nothofagus* (*Fuscospora*) spp. (up to 4%), Proteaceae (1-3%) and unidentified tricolporate types (2-3%). *Cyathea* (6%), *Quintinia* (2%) and Trimeniaceae (5%) are occasionally frequent. Osmundaceae, Casuarinaceae, Cunoniaceae, Myrtaceae and Restionaceae are present in low but significant numbers (~1%).   Rare taxa include:

Lophosoria, *Dicksonia*, Araucariaceae (*Araucaria*, *Agathis*/*Wollemia*), Podocarpaceae (*Dacrycarpus*, *Halocarpus*, *Microstrobos*, *Phyllocladus*), Anacardiaceae, Cupanieae, Elaeocarpaceae, Euphorbiaceae (*Austrobuxus*-type), *Ilex*, Loranthaceae, Myrtaceae (including *Austromyrtus*-type, *Eucalyptus*), Proteaceae (including *Agastachys*-type, *Beauprea*, *Xylomelum occidentale*-type), Sapotaceae and Winteraceae. The assemblages represent *Nothofagus*-gymnosperm temperate rainforest.

A comparison of the macrofossil and microfossil data shows that the canopy dominants were species within the *Nothofagus* subgenus *Lophozonia*, not the subgenus *Brassospora*, as indicated by relative pollen abundance. The corollary is that *Nothofagus* (*Brassospora*) spp. are over-represented by pollen.

Inferred climate

Climates were upper microtherm and uniformly very wet (perhumid).

4.   West Coast

Lignites preserved in Tertiary palaeochannels near Zeehan and Balfour provide 'snap shots' of the *Proteacidites tuberculatus* Zone vegetation on the west coast (M.K. Macphail unpubl. results). Both microfloras represent floristically simple *Nothofagus*-gymnosperm evergreen rainforest.

The possibly older Zeehan microflora is dominated by *Nothofagus* (*Brassospora*) spp., Proteaceae (especially *Agastachys*-type) and Casuarinaceae. *Lagarostrobos*, *Quintinia*, Trimeniaceae and a small *Ilex* grain are frequent. Rare taxa include *Microstrobos*, *Gunnera*, Lactoridaceae (now endemic to the Juan Fernandez Islands off Chile), Myrtaceae, *Nothofagus* (*Lophozonia*) and Strasburgeriaceae. Pollen dominance at the possibly younger Balfour site is shared between *Nothofagus* (*Brassospora*) spp. (30%), *Dacrydium* (10%), *Lagarostrobos* (15%), *Podocarpus-Prumnopitys* (11%), Casuarinaceae (6%) and *Nothofagus* (*Fuscospora*, *Nothofagus*) spp. (5%). Frequent types include *Araucaria* (2%), *Podosporites* (2%), Strasburgeriaceae (1%), Trimeniaceae (3%) and Ericales (2%). Rare taxa include *Lophosoria*, Cupressaceae, *Gunnera*, Polygalaceae, *Quintinia* and Winteraceae. Cupanieae are absent.

Inferred climate

Climates were cool (microtherm range) and uniformly wet (perhumid). Conditions do not appear to have been significantly cooler at Zeehan than at Balfour despite differences in elevation.

5.   Central Plateau

Sites preserving diverse Oligo-Miocene microfloras occur at Cethana, Lemonthyme Creek, Lea River, Link Road, Little Rapid River and Wilmot Dam in northwestern Tasmania (Macphail *et al.* 1993, Macphail and Hill 1994, M.K. Macphail unpubl. results) and at Monpeelyata, near Great Lake on the eastern margin of the Central Plateau (Macphail *et al.* 1991). In all cases the assemblages accumulated in palaeochannels incised into Jurassic or older rocks. The microfloras represent *Nothofagus*-gymnosperm rainforests, which were structurally less complex and floristically simpler than comparable rainforests growing in the south-east of the mainland.

The earliest microfloras (Lemonthyme Creek and Wilmot Dam) are associated with probable earliest Oligocene glacial deposits (Lemonthyme Glaciation). K/Ar dates of overlying basalts confirm the sections are older than 26.7 Ma. Although assigned to the *Proteacidites tuberculatus* Zone, based on *Cyatheacidites annulatus*, it is probable that this fern

(*Lophosoria*) reached Tasmania before southeastern Victoria. If correct, the Lemonthyme and Wilmot microfloras may be correlatives of the Upper *Nothofagidites asperus* Zone assemblages in the Gippsland Basin. Pollen dominance is variable, with the mostly commonly occurring taxa being Dicksoniaceae (up to 15%), *Lagarostrobos* (8-17%), *Podocarpus-Prumnopitys* (6-12%), *Podosporites* (1-3%), *Nothofagus* (*Brassospora*) spp. (24-37%), *Nothofagus* (*Fuscospora*) spp. (4-5%). *Nothofagus* (*Nothofagus*) spp. (1-6%), Casuarinaceae (1-4%), and Proteaceae (3-4%). The diversity of cool temperate cryptogams and gymnosperms is unusually high whilst species whose NLRs are confined to warm temperate or subtropical rainforest are very rare, e.g. *Ascarina*, Cupanieae, *Ilex*, *Quintinia* and Sapotaceae. Other rare taxa include species that are unique to the sites or are the earliest records to date for Tasmania, e.g. Droseraceae, Menyanthaceae, Sparganiaceae, Stylidiaceae and cf. Trimeniaceae (*Periporopollenites hexaporus*). Other species point to floristic interchange with South America, e.g. Asteraceae (Mutisieae) and Proteaceae (*Embothrium*).

Proteacidites tuberculatus Zone Equivalent microfloras from Cethana, Lea River and Little Rapid River are dominated by *Nothofagus* (*Brassospora*) spp. with lesser amounts of Podocarpaceae (*Lagarostrobos*, *Podocarpus-Prumnopitys*), Casuarinaceae and Proteaceae. Cryptogams such as Lycopodiaceae, Dicksoniaceae (*Trilites tuberculiformis*) and *Lophosoria*, and two angiosperms, *Ilex* and Liliaceae, are unusually frequent at Lea and Little Rapid Rivers relative to mainland assemblages of similar age. Taxa that are usually uncommon to rare include Araucariaceae (*Araucaria*, *Wollemia*-type), Cupressaceae, Podocarpaceae (*Dacrycarpus*, *Dacrydium*, *Halocarpus*, *Microcachrys*, *Microstrobos*, *Phyllocladus*, *Podosporites*), *Ascarina*, Casuarinaceae, Cunoniaceae, Cupanieae, Cyperaceae, Ericales (including *Sprengelia*-type), Euphorbiaceae (*Austrobuxus*-type, *Micrantheum*), Gyrostemonaceae, Meliaceae, Myrtaceae (including Eucalyptus), *Quintinia*, Proteaceae (including *Agastachys*-type, *Beauprea*, *Embothrium*, *Telopea*-type), Restionaceae, Sparganiaceae (*Aglaoreidia*, S*parganiaceaepollenites*), Strasburgeriaceae and Winteraceae. Unusual records include Asteraceae (Mutisieae), Droseraceae, Menyanthaceae, Stylidiaceae, and the youngest known records of the primitive angiosperm family Lactoridaceae (Macphail *et al*. 1999). A probable *Proteacidites tuberculatus* Zone assemblage from Moina, ca. 10 km west of Cethana, is reported to include diverse *Nothofagus* spp. and rare *Lophosoria*, Sparganiaceae and Winteraceae (Harris (1967).

A probable Early Miocene (late *P. tuberculatus* Zone Equivalent) microflora from Monpeelyata is wholly dominated by *Nothofagus* (*Brassospora*) spp. (43%) and *Lagarostrobos* (45%) but otherwise is similar in composition to Cethana, Lea River and Little Rapid River. The assemblage includes an early record of Mimosaceae (*Archidendron*-type), misidentified as *Acacia* in Macphail *et al*. (1991) and (macrofossil data) cool-adapted species of Araucariaceae, Proteaceae and Epacridaceae. *Lagarostrobos* macrofossils are not recorded despite the high relative abundance of the associated fossil pollen type (*Phyllocladidites mawsonii*).

Inferred climate

Holocene data (Macphail 1979) confirm that microfloras accumulating within the upper subalpine and alpine zones usually include a significant percentage of pollen transported upslope by wind from forests at lower elevation. Assuming the same phenomenon occurred during the Oligo-Miocene, then some of the taxa recorded at Monpeelyata may have been growing on the eastern escarpment of the Central Plateau or at lower elevations within the Midlands. Thermophilous taxa such as *Archidendron*-type and Cupanieae are one example; *Lagarostrobos* may be another.

If correct, then mean annual temperatures will have varied from cool (upper microtherm) at lower elevations such as Cethana, to cold (lower microtherm) on the Central Plateau at Monpeelyata. Rainfall was high to very high (perhumid) throughout the year.

4.3   Other Records

4.3.1 *North-West Australia*

The major regression at ~30 Ma (Early Oligocene) almost certainly reflects the development of continental ice sheets in Antarctica.   Subsequent eustatic events are overprinted with the effects of tectonic downwarping along the western margin due to collision of the Australian and Asian plates (Bradshaw *et al*. 1988, Apthorpe 1988).

4.3.2 *North-East Australia*

1.   Coral Sea

Feary *et al.* (1991) estimate surface water temperatures off the north-east coast of Queensland during the Oligo-Miocene time were between 9.5-13.0^{0}C in the Early Oligocene, rising to 14.5-19.5^{0}C and 17-20.5^{0}C during the Early and Middle Miocene, respectively.

2.   Riversleigh

Diverse vertebrate faunas preserved in freshwater limestones at Riversleigh are circumstantial evidence that complex tropical rainforests lined some streams in northwestern Queensland (Sige *et al*. 1982; Archer *et al*. 1989, Duncan *et al*. 1998, Hand 1998). This interpretation may be overly simplistic, based on the rare occurrence of *Allocasuarina*/*Casuarina* and Sapindaceae (Cupanieae) leaf impressions.

4.3.3 *Central Australia*

Faunal remains found at and near the surface in central Australia are difficult to date and/or correlate with microfloras recovered from below the weathering front. In exceptional cases, a combination of palaeomagnetic and palaeontological evidence allows local Land Mammal biostratigraphies to be established, for example the Tirari-Sub-basin (Woodburne *et al*. 1993). This schema potentially provides an independent record of evolving climates in the basin during the Late Oligocene.

More generally however, the palaeontological and geological evidence of climates are contradictory or reflect different local hydrologic regimes at different intervals within the Late Oligocene-Miocene. For example, the remains of turtles, freshwater crocodiles, aquatic birds and dolphins confirm that climates were sufficiently wet to support some permanent water bodies in central Australia. Terrestrial vertebrate faunas are dominated by browsing marsupials and include possums and a koala-like species that indicate sclerophyll trees (cf. Woodburne 1967, Archer *et al*. 1994). Geological evidence indicates climates were strongly seasonal with elevated (possible mesotherm) temperatures (Alley 1998).

4.4.4 *South-East Australia*

1.   Northern Tablelands of New South Wales

Geological and palaeomagnetic analyses of bauxites developed on, and overlain by, mafic volcanic flows indicate deep weathering over a significant period of time during mid Oligocene to Early Miocene time on the New England Plateau (Acton and Kettles 1996).

2.   <u>Otway Basin</u>

Oxygen isotope stratigraphies from Browns Creek and Castle Cove indicate sea surface temperatures (SSTs) decreased by up to 7^0C during the terminal Eocene event, reaching a minimum value of $\sim13^0C$ during the earliest Oligocene (Kamp *et al*. 1990). A rapid rise in SSTs during the Early Oligocene is explained by local warming within the Bight, where local circulation was effectively decoupled from the effects of the Circumantarctic Current. Foraminifera and mollusc faunas indicate significant warming across southern Australia during the Early Oligocene and Miocene, with maximum warmth reached in the early Middle Miocene (Li and McGowran 1997, McGowran and Li 1997, Li *et al*. 2000). On present indications, sea surface temperatures in the Otway Basin (and Murray, Bass and Gippsland Basins) were cooler than in the Eucla and St. Vincent Basins to the west.

5. TIME SLICE T-5

Age Range: Late Miocene-Pliocene [11.2-1.78 Ma]

Zones: *Monotocidites galeatus* (Murray Basin)/*Cingulatisporites bifurcatus* (Gippsland Basin) to *Tubulifloridites pleistocenicus* Zones. Informal *Oligospheridium* Zones

5.1   Macrofloras

5.1.1   *South-East Australia*

1.   Central Highlands of Victoria

Foliage of *Callitris* (Cupressaceae) is preserved in probable Plio-Pleistocene lacustrine clays at Daylesford in the central highlands (K. Sneiderman pers. comm.).

Inferred climate

With the exception of *C. macleayana*, which occurs on rainforest margins, all Australian *Callitris* are canopy species in open (dry sclerophyll) forests and woodlands (Boland *et al.* 1994). Most occur at lower elevations although one species, *Callitris endlicheri*, dominates low open forest at higher elevations on the granite massif of Mt. Burrowa (1277 m) in southeastern Victoria (Foreman and Walsh 1993). The Daylesford population may indicate seasonally dry (possibly humid) and relatively warm (possible lower mesotherm) conditions.

5.1.2   *Tasmania*

1.   West Coast

Phyllocladus stumps, which have been radiocarbon-dated as 26 ka, are preserved *in situ* occur in a Late Pliocene palaeosol in the Linda Valley, western Tasmania (Macphail *et al.* 1993).

Inferred climate

Cool (microtherm) and wet (humid-perhumid) conditions are indicated.

5.2   Microfloras

Palaeobotanical evidence for Late Neogene climates in Australia up to 1991 are reviewed by Kershaw *et al*. (1994) and Macphail (1997b). Climatic reconstructions are based on circular reasoning to the extent that the inferred age of the assemblage is based on the presence or absence of Tertiary rainforest species. The palaeoclimatic implications of a world class mid Pliocene sequence at Yallalie in south-west Western Australia (Macphail 1994b) are discussed in Dodson and Macphail (in press).

5.2.1   *North-West Australia*

1.   North West Shelf

Turbidites, which have been deposited at depths of ~4000 m on the Argo abyssal plain, preserve a highly generalised pollen record of the Late Miocene-Pleistocene vegetation growing in the Kimberley region 600 km to the south (Martin and McMinn 1994). The Late

Miocene microfloras are dominated initially by Casuarinaceae (presumed to be *Allocasuarina/Casuarina*), Gyrostemonaceae and Restionaceae with minor values of Mimosaceae (*Acacia*). Poaceae values increase abruptly towards the end of this interval. The Pliocene microfloras are dominated by Poaceae, Chenopodiaceae-Amaranthaceae and Asteraceae (Tubuliflorae), with minor *Acacia* and Myrtaceae. On present indications, Late Neogene vegetation in northern Australia seems to have been similar to the mosaic of rainforest, sclerophyll and grass-dominated formations found in present-day northwestern Australia. Assuming changes in pollen dominance are not due to erosion or non-deposition, data from the Argo abyssal plain imply rapid replacement of relatively closed, possibly tall sclerophyll vegetation types by lower, more open communities in which herbs were prominent (possibly savannah woodland) during the Late Neogene.

A very sparse microflora, dominated by grass but including pollen of a vine found in semi-deciduous (monsoonal) rainforest, is preserved in semi-lithified sediments at the base of a palaeochannel of the Victoria River, Arnhem Land (M.K. Macphail unpubl. data). The assemblage is presumed to be of Late Neogene-Early Pleistocene age.

Inferred climate

Macphail (1997b) suggests mean annual rainfall decreased from about 600-1500 mm to below 600 mm and/or became strongly seasonal during the latest Miocene. This drying trend was maintained during the Pleistocene (Hope 1994).

5.2.2 *North-East Australia*

1.   North-East Queensland

Evidence for Late Neogene climates in northeastern Queensland mostly comes from offshore sites on the Great Barrier Reef or from the deepwater (>1000 m) Queensland Trough (Hekel 1972, Martin and McMinn 1993). Deposition appears to have been continuous, but the microfloras will be strongly biased towards wind-pollinated gymnosperms (Neves Effect) and riparian ferns. The only onshore Pliocene sediment known to preserve microfossils is a sub-basaltic deposit at Butchers Creek at 720m elevation on the Atherton Tableland (Kershaw and Sluiter 1982). The combined data indicate the coastal vegetation was a mosaic of Araucariaceae and angiosperm-dominated rainforest and sclerophyll types on the coast. Possibly small stands of *Nothofagus* temperate rainforest survive in at higher elevations on the Atherton Tableland.

2.   Queensland Trough

Late Miocene to Late Pliocene microfloras recovered from ODP Site 815 at the southern end of the Queensland Trough are dominated by Araucariaceae (*Agathis*) and Casuarinaceae with lower amounts of *Podocarpus-Prumnopitys*, Cyperaceae and *Cyathea*. Frequent taxa include *Pteris*, *Dacrycarpus*, *Dacrydium*, Gyrostemonaceae, *Acacia*, Asteraceae, Chenopodiaceae, *Dodonaea* and Poaceae. Uncommon to rare taxa include *Phyllocladus*, *Eucalyptus* and *Nothofagus* (*Brassospora*, *Lophozonia*). The site records a progressive decline in the relative abundance of *Podocarpus-Prumnopitys* during the Late Miocene and Araucariaceae during the late Early to Late Pliocene. The relative abundance of Asteraceae, Chenopodiaceae-Amaranthaceae and Gyrostemonaceae increases over this period.

3.   Atherton Tableland

Probable Late Pliocene microfloras from Butchers Creek are dominated by *Nothofagus* (*Brassospora*) with more variable but high representation of *Podocarpus-Prumnopitys,*

Casuarinaceae, Cunoniaceae, Elaeocarpaceae and *Symplocos*. The only 'frequent' Proteaceae is an extinct species, *Proteacidites pachypolus* (M.K. Macphail unpubl. data).

4.   Capricorn Basin

Late Miocene to Early Pleistocene microfloras are co-dominated by *Podocarpus-Prumnopitys*, Araucariaceae (*Agathis*), Casuarinaceae, Myrtaceae, Casuarinaceae and trilete ferns including *Cyathea*. Palmae and/or Liliaceae occur in trace numbers: *Nothofagus* is not recorded the Late Miocene or Pliocene sections.

5.   Northern New South Wales

Palaeovalleys incised into the north-west slopes in New South Wales are filled with Late Cenozoic colluvium. Independent age control is lacking, although a number of assemblages include rare taxa that become extinct during the Late Neogene, e.g. *Lophosoria*. Martin (1973, 1980, 1981) has proposed that the associated microfloras can be dated as Mid-Late Miocene, Pliocene and Pleistocene, based on the abundance of *Nothofagus* (*Brassospora*) spp. relative to Asteraceae, Chenopodiaceae-Amarathaceae and Poaceae. For example, *Nothofagus* (*Brassospora*) spp. had become rare or extinct although gymnosperms (Araucariaceae, Podocarpaceae) continued to dominate stands of gallery rainforest during the Early Pliocene. By the Late Pliocene, the regional vegetation was dominated by sclerophyll taxa, Asteraceae and (at one site) Poaceae.

Inferred climate

Climates on the northeastern Queensland coast were very warm (upper mesotherm) and very wet (perhumid) with a possibly pronounced dry season. Climates at higher elevations on the Eastern Highlands were cooler (lower mesotherm) and wetter during summer months. Macphail (1997b) has proposed that the increase in sclerophyll taxa is evidence that regional climates became increasingly seasonal (possibly monsoonal) during the Late Neogene.

In inland northwestern New South Wales, summer rainfall first fell below the threshold (~200 mm per month) to support *Nothofagus* during the mid to Late Miocene, possibly earlier in the north than in the south of the region. Conditions were warm (upper mesotherm) and relatively wet (humid) during the Early Pliocene but had became cooler (lower mesotherm) and much drier (subhumid) and/or strongly seasonal during the Late Pliocene.

5.2.3   *Central Australia*

A probable Late Neogene microflora is preserved in the Tempe Downs T1A borehole, drilled ca. 160 km north-east of Uluru (Macphail 1996c). This is dominated by Casuarinaceae (70%) but includes a significant representation of mesophytic taxa, e.g. *Araucaria* (2%), *Dacrydium* (2%), *Podocarpus-Prumnopitys* (10%) and Cyperaceae (12%). *Nothofagus* is not recorded but *Lagarostrobos*, *Eucalyptus*, *Dodonaea*, Epacridaceae and Restionaceae (*Milfordia homeopunctata*) occur in trace (<1%) numbers.

Further to the south, possible Late Miocene-Pliocene microfloras have been identified in samples from the top of the Namba Formation in the Callabonna Sub-basin (Martin 1990) and in the Wipajiri and Tirari Formation in the Tirari Sub-basin of the Eyre Basin (Callen *et al.* 1995). The probable older of the two microfloras (Namba Formation) is dominated by Casuarinaceae (54%) and Restionaceae with lesser amounts of *Eucalyptus* (10%), *Dodonaea* (5%) and *Grevillea-Hakea* (3%). Unequivocal rainforest elements are absent. Conversely the younger (Tirari Formation) microfloras included trace numbers of *Nothofagus* (*Brassospora*) and Podocarpaceae (*Lagarostrobos*, *Podocarpus-Prumnopitys*).

The regional vegetation appears to have been sclerophyll woodlands, with relict populations of rainforest species in the uplands or (gallery forest) on the banks of streams flowing into the Eyre Basin.

Inferred climate

Climates are likely to have been relatively cool (mesotherm range) and seasonally dry (subhumid-humid), although rainfall (or groundwater discharge) was adequate to support the wetlands in the Callabonna Sub-basin.

5.2.4 *South-West Australia*

Late Neogene microfloras are preserved at Yallalie north of Perth and in fragmented lake systems on the Yilgarn Plateau (Bint 1981, Clarke 1994).

1.   Yallalie Basin

A 110 m thick sequence of Late Neogene (Macphail 1994b, Dodson and Macphail in press) lacustrine silts and clays is sealed under Quaternary cover beds in a probable Early Cretaceous meteor crater (Dentith *et al*. 1999) at Yallalie, about 200 km north of Perth (Yallalie Basin).   Palaeomagnetic dating (J. Dodson pers. comm.) confirms that these sediments accumulated between ~2.5 to 3.6 Ma – a period that coincides with pronounced warming in the mid to high latitudes of both hemispheres (Macphail 1997b).   Charcoal is abundant in all samples.

At least 100 distinctive fossil pollen and spore types are present (M.K. Macphail unpubl. data).   The number of plants forming the source vegetation is likely to be much greater since many types represent more than one species or genus and several distinctive fossil types cannot be assigned to any living family or genus.   Dominants are Restionaceae and sclerophyll taxa, in particular non-eucalypt Myrtaceae such as *Melaleuca* and *Leptospermum*: Chenopodiaceae-Amarathaceae are common to abundant in three intervals with estimated ages of 2.56 Ma, 2.59 Ma and 2.90 Ma but otherwise are uncommon to rare (< 1%). Araucariaceae are sporadically frequent to common over the same period.   Rare taxa represent a number of rainforest species that no longer occur in south-west Australia, such as *Cyathea*, *Calochlaena*, *Lygodium*, *Pteris* and *Phyllocladus*, or Australia as a whole, such as. *Dacrycarpus*, *Dacrydium*, *Nothofagus* (*Brassospora*) spp. and *Ungeria*.   Some other taxa no longer occur in the local area, such as Caesalpinaceae, *Podocarpus* and *Eucalyptus spathulata*. *Aglaoreidia qualumis* represents an extinct clade of Sparganiaceae.

2.   Yilgarn Craton

Pliocene microfloras appear to be widely preserved in relict drainage lines in south-west Western Australia (Bint 1981, Clarke 1994, Partridge 1997).   These are dominated by Casuarinaceae and Restionaceae but also include trace numbers of Araucariaceae (chiefly *Araucaria* with occasional *Agathis*/*Wollemia*), Podocarpaceae (including *Lagarostrobos*), *Nothofagus* (*Brassospora*) spp. and Sapotaceae.

Inferred climate

The presence of Araucariaceae hints that mean temperatures in south-west Western Australia were warmer (upper mesotherm) than at present during the mid Pliocene. If Pliocene *Agathis* spp. at Yallalie possessed similar temperature requirements to the most southerly occurring species (*A. bidwillii*) then mean minimum and maximum temperature will have been ~16^{0}C and ~26^{0}C based on 1995 *Bureau of Meteorology* climatic averages for Brisbane. The mean minimum temperature of the coldest month will have been between 5-10 ^{0}C and mean

maximum temperature of the hottest month between 28-32^{0}C (Boland *et al.*, 1994). Lower values are obtained if modern distribution data for *Araucaria* is used.

Rainfall is less easily estimated since soil drainage, salt accumulation and fire are major controls on plant community composition in drier regions of south-west Australia at present. Deep fracturing due to the meteor impact raises the possibility that groundwater discharge has contributed to the survival of rainforest taxa at Yallalie (Dodson and Macphail in press). This is not the case on the Yilgarn Plateau where the survival of *Nothofagus* (*Brassospora*) spp. and *Lagarostrobos* almost certainly will have been determined by summer rainfall. If correct, then the combined data point to sub-humid climates characterised by relatively dry summers and wet winters in the Yallalie district, and wetter (humid) and/or less strongly seasonal conditions on the southern margin of the Yilgarn Craton. Spikes in the relative abundance of semi-arid zone taxa, in particular Chenopodiaceae-Amaranthaceae and halophytic diatoms, demonstrate that locally warm and seasonally wet conditions were interrupted by three distinct episodes of aridification around 2.56, 2.59 and 2.90 Ma. The same data hint that the frequency of phases of relative aridity increased around 2.6 Ma. How closely the Yallalie sequence mirrors trends in continental climates elsewhere in southern Australia is unclear. The vegetation response appears to be similar to that seen in southeastern Australia during Late Pleistocene glacial arid maxima, and suggests that alternating cycles of high humidity and aridity analogous to Late Pleistocene glacial-interglacial conditions were in evidence by 2.5 Ma. This observation ties in well with oxygen isotope data from marine cores. More generally the period of record overlaps with initiation of continental glaciation and an increase in the frequency and intensity of climatic fluctuations between 2.6-2.8 Ma in the middle latitudes of the Northern Hemisphere.

5.2.5 *Central southern Australia*

As in southwestern Australia, the only microfloral evidence for Late Neogene climates comes from palaeochannel fill deposits.

1.   Eucla Basin

Benbow *et al*. (1995) have recorded Cupressaceae (frequent), Mimosaceae (*Acacia*) and Euphorbiaceae (*Micrantheum*) in a palaeochannel deposit from the eastern side of Eucla Basin, south-west South Australia. The absence of *Nothofagus* and other rainforest spp. implies that the deposit is Late Pliocene or younger.

2.   Eyre Peninsula

Truswell and Harris (1982) report trace numbers of *Nothofagus* (*Brassospora*) and Podocarpaceae (*Dacrydium*, *Lagarostrobos*, *Phyllocladus*, *Podocarpus-Prumnopitys*) in a possible Late Miocene-Early Pliocene deposit on the northern Eyre Peninsula. The microfloras are co-dominated by Myrtaceae (including frequent to common *Eucalyptus*), Asteraceae, Chenopodiaceae-Amarathaceae, Poaceae and Cyperaceae.

Alley (1983b) has reported a Late Pliocene or younger microflora at Tarcoola located ca. 200 km inland from Streaky Bay on the western side of Eyre Peninsula. Dominants are Poaceae, Chenopodiaceae-Amaranthaceae and Asteraceae (Tubuliflorae). Rare taxa include *Acacia* and rainforest elements are absent.

Inferred climate

Assuming the inferred ages are broadly correct, Late Neogene climates were strongly seasonal with mean annual rainfall falling to semi-arid to arid values (below ~400 mm) during the Pliocene.

5.2.6 *South-East Australia*

Late Neogene microfloras come from a diverse spectrum of localities and depositional environments in southeastern Australia. End-member examples are Lake George at 673 m elevation on the Southeastern Highlands and a bioclastic carbonate sequence (Hapuku-1) located about 50 km off the present-day coast of southeastern Victoria (offshore Gippsland Basin).

1.   Southeastern Highlands of New South Wales

Sediments infilling Lake George provide snap-shot records of Late Neogene climates at moderate (~650 m) elevations on the Southeastern Highlands near Canberra (Kershaw *et al*. 1991). Episodes of deep weathering have destroyed most of the organic record, including plant microfossils. Exceptions are thin intervals dated by palaeomagnetism as late Early Pliocene and late Late Pliocene.

Microfloras recovered from the earlier interval are dominated by *Podocarpus-Prumnopitys*, Casuarinaceae, Myrtaceae (including *Eucalyptus*) and *Nothofagus*. The last is dominated by *Brassospora* spp. but includes significant numbers of *Fuscospora* and *Lophozonia* types. *Nothofagus* is absent in the younger interval where the microfloras are dominated by Asteraceae, Casuarinaceae, Chenopodiaceae and Poaceae. Araucariaceae pollen is not recorded in either section and podocarps only range as high as the basal microflora in the younger interval.

McMinn (1981c) has recorded a gymnosperm-dominated microflora of possible Pliocene age from Wingecarribee Swamp near Bowral.

Inferred climate

The presence of *Nothofagus* (*Brassospora*) and *N*. (*Lophozonia*) spp. but not Araucariaceae is reliable evidence that local conditions were uniformly very wet (perhumid), and mean temperatures cool-cold (microtherm range) during the early Late Pliocene. If the steep dissected fault scarp forming the western margin of Lake George provided a refugia for rainforest taxa, then regional climates could have been much drier (subhumid) or more strongly seasonal than is indicated by the fossil pollen data. The first appearance of Asteraceae-Poaceae dominated communities may reflect the onset of seasonally very cold (lower microtherm) and winter-wet climates during the Plio-Pleistocene transition (cf. Truswell 1993).

2.   South-west slopes of New South Wales

Microfloras preserved in the Upper Lachlan Valley appear to represent plant communities growing at relatively low (90-120 m) elevations on the south-west slopes of the Southeastern Highlands.

Martin (1973, 1991b) has proposed that microfloras preserved in the major alluvial formations infilling these valleys (Lachlan and Cowra Formations) were deposited during the Pliocene and Pleistocene, respectively. Microfloras 'assigned' to the Late Miocene and Late Pliocene ages are wholly dominated by Casuarinaceae and Myrtaceae but recounts of microfloras recovered from the Lachlan Formation (Macphail 1997b) support the Late Miocene-Early Pliocene age and confirm the survival of *Nothofagus* (*Brassospora*) spp. in rainforest communities co-dominated by *N*. (*Fuscospora*) and *N*. (*Lophozonia*) spp., podocarps and Myrtaceae. By this time Araucariaceae are rare or absent. Martin (1991b) has proposed that trends in pollen dominance reflect the transient expansion (Early Pliocene) of

Nothofagus-gymnosperm temperate rainforest within (Late Miocene, Late Pliocene) predominantly wet sclerophyll forest types.

Inferred climate

The expansion of *Nothofagus* (*Lophozonia*) spp. is likely to be due to uniformly wet (perhumid) and cool (upper microtherm) conditions on the upper slopes of the Southern Highlands during an interval (Early Pliocene) when other sites in southern Australia experienced increasing warmth. The most plausible explanation is that warm sea surface temperatures and high relative sea levels resulted in increased orographic cloudiness, and therefore effectively cooler wetter conditions, over the Southeastern Highlands.

3.   Otway Basin

Grange Burn, at 180 m elevation, near Hamilton in south-western Victoria is located close to the limits of marine transgression in the Otway Basin during Late Neogene time. The site provides a record of an Early Pliocene environment that is unique in Australia for two reasons. A regressive non-marine alluvium is preserved between a late Miocene-Early Pliocene marine silt and a K/AR-dated 4.46 Ma old basalt. Fossils preserved in the alluvium include the remains of plants and mammals animals whose NLRs are confined to coastal northeastern Queensland (Flannery *et al*. 1992, Macphail 1996b). Commonly occurring microfossils include *Cyathea*, Araucariaceae (*Araucaria*), Podocarpaceae (*Dacrycarpus*, *Podocarpus-Prumnopitys*), Casuarinaceae and Myrtaceae (including *Eucalyptus*). Less common or rare taxa are *Dacrydium*, Asteraceae, *Eucalyptus spathulata*-type, *Nothofagus* (*Brassospora*, *Fuscospora*, *Lophozonia*) spp. and Poaceae.

Inferred climate

The combined microfloral and palaeontological evidence point to a mosaic vegetation of Araucariaceae (dry) rainforest and open-canopy sclerophyll communities, which may have been confined to the stream banks. There is no evidence that *Nothofagus* spp. were part of these communities or present elsewhere in the district. Poaceae are suggested to have colonised drier (interfluve) areas but there is no evidence that grasslands *per se* were part of the regional dryland vegetation. Macphail (1996b) has proposed that climates were wet (humid) and weakly seasonal. Mean annual temperatures are likely to have been very warm (upper mesotherm).

4.   Murray Basin

Marine transgressions during the Late Miocene and Early Pliocene resulted in the deposition of marginal marine facies in the south-west sector of the basin. Examples are the Bookpurnong Beds and basal Loxton-Parilla sands (Brown and Stephenson 1991).

Microfloras from restricted marine and estuarine facies are dominated by Araucariaceae, Casuarinaceae and/or Myrtaceae, with relatively low and diminishing relative abundances of *Nothofagus* (*Brassospora*) spp. Microfloras from paralic facies where the marine influence was weak or absent are dominated by *Nothofagus* (*Brassospora*), Araucariaceae and Casuarinaceae, with lower abundances of Myrtaceae. These facies are difficult to correlate using plant microfossils and it is uncertain whether differences in pollen dominance are due to the Neves Effect, edaphic-forcing or evidence that *Nothofagus*-dominated rainforest was succeeded by drier, Araucariaceae-dominated, types of rainforest.

Inferred climate

If the data merely reflect spatially heterogeneous rainforest communities, then climates in the central west Murray Basin were warm (mesotherm range) and wet to very wet (perhumid) during the Early Pliocene. Conversely if the data represent successional trends within the rainforest vegetation, then climates became increasing seasonal (effectively drier) and possibly warmer (upper mesotherm) during the same period.

5.   Central Highlands of Victoria

A probable Plio-Pleistocene sequence is preserved in a volcanic crater (Stony Creek Basin) at Daylesford in central highlands. Preliminary data (M.K. Macphail pers. observation, based on material supplied by K. Sneiderman) indicate plant communities surrounding the crater lake were a mosaic of sclerophyll and temperate rainforest taxa. The latter included taxa that were last recorded in the Gippsland Basin during the Late Miocene or Early Pliocene, e.g. *Lophosoria*, *Dacrycarpus*, *Dacrydium*, an extinct relative of *Microcachrys* (*Podosporites microsaccatus*), *Nothofagus* (*Brassospora*) spp. and *Symplocos*, rainforest taxa with subtropical to tropical NLRs that are typical of mid Pliocene sites in southern Australia, e.g. *Araucaria* and *Agathis*/*Wollemia*, and sclerophyll shrubs that are not part of the present-day vegetation in central Victoria, e.g. *Stirlingia*.

Inferred climate

The Stony Creek Basin appears to have been a refuge for Tertiary rainforest taxa, possibly due to highly fertile basaltic soils mitigating the effects of any wildfires (Jackson 1968). Conditions are likely to have been relatively warm (mesotherm range) and wetter than at present but by how much is unclear (see Section 5.1.1).

6.   Gippsland Basin

Microfloras recovered from deepwater carbonates (Seaspray Group) in Hapuku-1 provide a quasi-continuous record of plant communities occupying the Gippsland coastal plain throughout the Neogene. Relative abundance values reflect a strong Neves Effect due to the offshore/deepwater location of the well.

Key events (Macphail 1997b) are: (1) the expansion of *Araucaria* and *Podocarpus-Prumnopitys* at the expense of *Nothofagus* (*Brassospora*) spp. during the latest early Miocene; (2) a marked increase in *Cyathea*, associated with a decrease in rainforest gymnosperms to low (<5%) values during the late Late Miocene; (3) a return to high values of *Araucaria* and *Podocarpus-Prumnopitys*, associated with an equally marked increase in Casuarinaceae (presumed to be *Allocasuarina*/*Casuarina*) and *Eucalyptus* during the Early Pliocene; and (4) a marked increase in Asteraceae and Poaceae during the Late Pliocene.

Inferred climate

The Hapuku succession is suggested to represent the onset of weakly seasonal conditions (as early as 16 Ma ago) and strongly seasonal conditions by about 3 Ma ago. Mean annual precipitation is estimated to have fallen from perhumid to humid levels over this period. Changes in the relative abundance of *Araucaria* imply mean temperatures during the Miocene and Early Pliocene were warmer (possible median mesotherm) than in the Late Pliocene (possible upper microtherm).

5.2.7 *Tasmania*

Late Neogene sediments are extremely rare in Tasmania due to glacial erosion and periglacial activity during the Pleistocene. The one exception is a thin unit of carbonaceous silts and sands preserved below glacial outwash at ~300 m elevation in the Linda Valley, near Queenstown (Macphail *et al.* 1995). The associated microfloras are dominated by one or more of *Dacrydium*, *Lagarostrobos*, *Microstrobos*, *Nothofagus* (*Brassospora*) spp., and Restionaceae. *Nothofagidites asperus*, the fossil equivalent of pollen produced by the dominant temperate rainforest tree in western Tasmania (*Nothofagus cunninghamii*), is uncommon relative to fossil types representing *N.* (*Brassospora*) spp. Rare taxa also include genera that are extinct in Tasmania but survive in mainland Australia or landmasses to the north, e.g. *Austromyrtus*-type, *Beauprea*, *Cassinia arcuata*-type (*Tubulifloridites pleistocenicus*) and *Eucalyptus spathulata*-type (*Myrtaceidites lipsis*). Cyclic changes in pollen dominance, which appear to represent depositional rather than climatic events, imply the vegetation was altitudinally zoned, with *Microstrobos*-Restionaceae wet heath occupying the upper slopes and *Nothofagus-Lagarostrobos-Dacrydium* rainforest the lower (possibly swampy) ground.

Inferred climate

Local climates were seasonally cold (lower microtherm) and uniformly wet to very wet (perhumid).

5.3   Other Records

1.   *North-West Australia*

An impoverished Pliocene fauna is preserved at Quanbun in the Kimberley region (Flannery 1984). Conditions were sufficiently wet to support crocodiles.

2.   *North-East Australia*

A Pliocene vertebrate fauna is preserved at Bluff Downs in northern Queensland (Archer and Wade 1968, Archer *et al.* 1994). The high percentage of extant mammalian genera indicates that essentially modern conditions were in existence at the time of deposition. Wroe and Mackness (2000) suggest that the presence of dasyurids in the mid Pliocene Chinchilla Fauna imply conditions in south-eastern Queensland were relatively dry (subhumid) and strongly seasonal.

3.   *Central Australia*

Late Miocene vertebrate remains in the Alcoota Local Fauna (Waite Basin, Alice Springs district) are dominated by browsing herbivores and lacks arboreal and grazing mammals (Woodburne 1967). The vegetation is likely to have been open sclerophyll woodland or shrubland which lacked a ground cover of abrasive grasses such as *Spinifex* and *Triodia*. Lacustrine gastropods and crocodile gastroliths are evidence that climates in this now arid region were sufficiently wet (possibly subhumid) to maintain freshwater ponds.

4.   *South-East Australia*

Lacustrine sediments infilling Palaeolake Bunyan, in the Murrumbidgee River Valley between Bredbo and Cooma on the Southeastern Highlands, are capped by a diatomite unit which is provisionally dated as Late Miocene (Taylor *et al.* 1990). Cyclic bedding within the diatomite is interpreted as evidence for (1) strong seasonal variation in air water temperatures and photoperiod and (2) on a longer time scale, climatic instability with a periodicity less than or equal to 8000 years.