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Mike Macphail

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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 Cenozoicpalynostratigraphy 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 palaeonorthern Australia appear to have been relatively warm (upper mesotherm). Because of rotation of the continent about the geographic South Pole, these regions do not 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.