FLORA OF AUSTRALIA

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Section 2: The Environment

Evolution of Australian Environments

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EVOLUTION OF AUSTRALIAN ENVIRONMENTS

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Australian environments of the past have been influenced by the geological evolution of the continent as a result of its changing position on the globe, the evolution of its landforms, and wide swings in the global climate. The Australian vegetation has, in its turn, been affected by these changes, and perhaps equally as profoundly by the nature of the ancestral vegetation before the continent separated from Gondwana, by the ways in which the endemic floras evolved, and by occasional immigrants. Here the controls on palaeoenvironments exerted by the evolution of the continent itself over Phanerozoic time, that is, roughly the last 540 million years, are addressed. The foundation for discussion of continental movements and attendant palaeogeographic connections to other landmasses is provided by the work of Veevers (1984, 1991a), which also elucidates some of the developments in landform transformations. Detailed examinations of the most recent landforms and of the climatic history are based on a range of important publications, notably Langford *et al*. (1995) and Hill (1994). Study of the deduced trends in these variables and their interactions can lead to an integrated picture of how a changing Australia contributed to a history of changing vegetation.

In any geological history it is imperative to specify the time scale used. There are many such scales, both those relating to a part of Phanerozoic time and others which cover the whole of this enormous span of time. Scales differ mainly in the numerical ages assigned to boundaries between named Periods, Epochs or Ages, three representations of geologic time corresponding to progressively shorter spans of time. In this study, I employ a slightly modified version of the Phanerozoic time scale of Harland *et al*. (1990) (Fig. 31), a recently published and comprehensive effort. The appropriate sedimentary basins of Australia, important because they contain the record of palaeo-environments over geological time, are shown in Fig. 32.

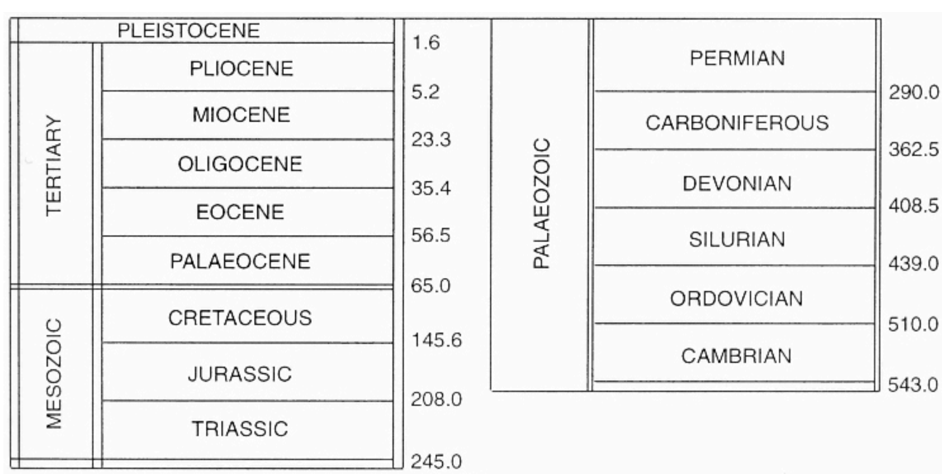

Figure 31. Geological Time Scale used in this chapter. Ages in millions of years (Ma) Modified from Harland *et al*., 1990.

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Australian palaeogeography

In considering the history of Australian vegetation, palaeogeography plays an important role. Location of the continent on the globe, particularly its latitudinal range and its spatial relationships to neighbouring seas, contributes strongly to the types and range of climates experienced by the continent, environmental factors of major significance for floras. Connections with adjacent or nearby landmasses determine the extent of migrations of exotic taxa, at least by land. Other aspects of palaeogeography – the topographic relief resulting from spasmodic tectonic activity and the configuration of seaways on the landmass – also influence the development and distribution of vegetation through time, by directing or restricting the dispersal of plant life. It is not intended here to present a detailed account of continental evolution but rather to provide a framework for consideration of the obvious changes in the Australian environments through time.

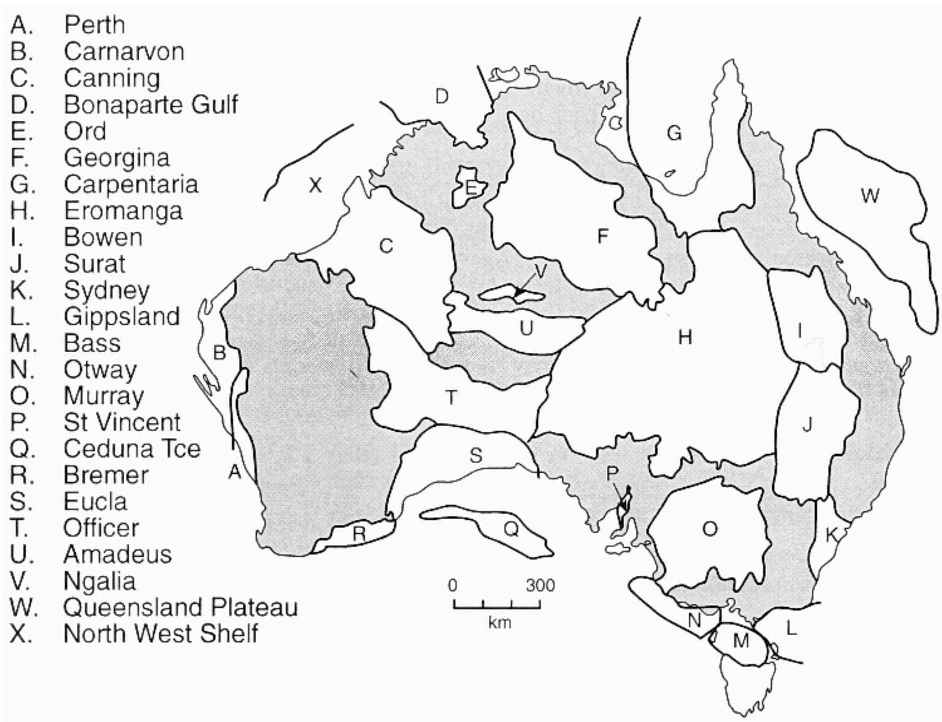

Figure 32. Phanerozoic sedimentary basins and other geological features of Australia.

Palaeolatitudes

The position of Australia on the globe has varied with motion of the continent through time (Fig. 33). The Phanerozoic saw the continent move from relatively low latitudes initially to very high latitudes in the Late Palaeozoic (Carboniferous to Permian, 363–245 million years ago (Ma)), then to mid-latitudes in the Early Mesozoic (Triassic to Jurassic, 245–145 Ma). In the early part of the Cretaceous Period (140–c. 95 Ma), the Australian landmass again occupied high latitudes, but thereafter it migrated, at first slowly but then more rapidly, to its present position in the low to mid-latitudes (Fig. 33; data from Embleton; in Veevers, 1984). This motion across lines of latitude is deduced from the inclination of the remnant magnetic field preserved in dated rocks, which is documented as a measure of latitude. The method thus determines the latitude and the orientation of latitude lines at the site from which the rock sample came; this permits the drawing of latitude lines on maps of the continent (Fig. 34). The data, however, convey no information relating to longitude of the sampling site, nor as to whether it was the magnetic/geographic pole, or the continent itself, which moved. Only relative motion between continent and pole can be specified.

Measurement errors for individual sets of samples can range from <5° for young samples to >15° of arc for older ones, and these values reflect the accuracy of the calculated latitudes. In the case of Australian positioning for the more recent past, the last 120 million years, the results from rock magnetism are supported by data from seafloor magnetic stripes in the Southern Ocean, which document the progressive northward movement of the continent. For more recent times, the location of Australia on the globe can be determined by reference to the seafloor magnetic anomalies to the south of the continent (Scotese *et al.*, 1988).

The south of Australia has not always been in the south (Fig. 33), because the direction of relative continental movement has often been oblique to both latitude and longitude. This was particularly true for intervals in earlier Phanerozoic time, when first the east and then the west instead occupied the southernmost position. Most of Australia resided in the Northern Hemisphere for much of the first 150 million years of the Phanerozoic; since about 390 Ma, the continent has been located in the Sorthern Hemisphere, twice moving to high latitudes. From its high latitude position about 110 Ma, the continent has travelled progressively northward, at first slowly but then at the present rate. The effects of these motions on climate will be discussed later, but for now it should be remembered that shifts through latitude zones presented both opportunities and limitations for the preservation and the dispersal of past floras.

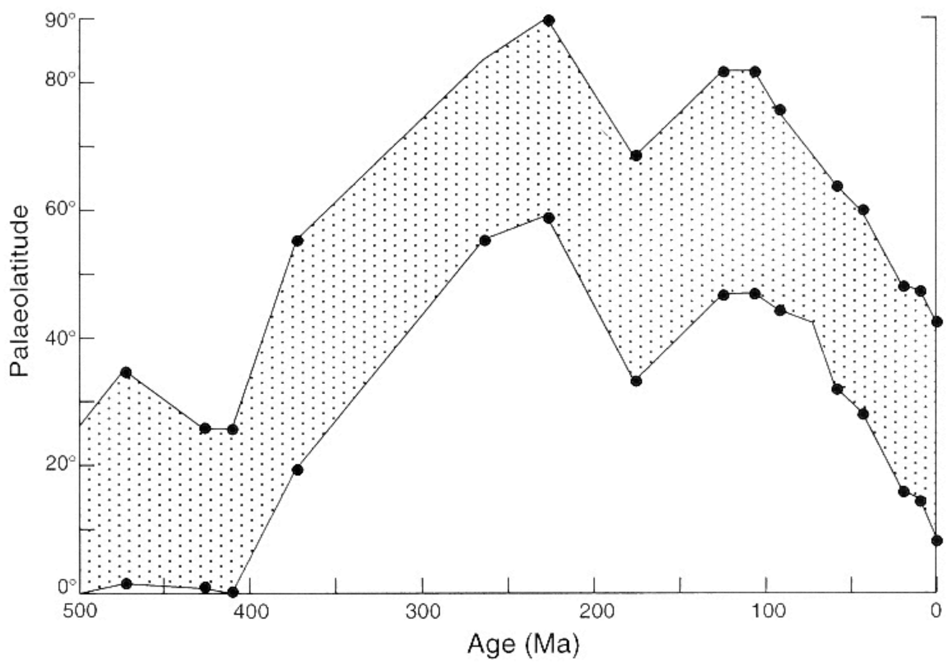

Figure 33. The latitudinal track of Australia through Phanerozoic time. Note that during rotation of the continent, various parts assume the most poleward and equatorial positions at various times. (Based on the summary of Embleton, 1984).

Relations with other landmasses

Amalgamations and drift

Australia has not travelled alone through its history. Just before the beginning of Phanerozoic time, the continent came together with all the major landmasses to form a supercontinent roughly centred on the equator and extending to the south pole. The Australian segment was located in the low to middle northern latitudes and maintained approximately the same position until the beginning of the Phanerozoic. The neighbouring continental masses consisted of Antarctica off the present southern margin, New Zealand to the east, and the Indian subcontinent and other parts of present Asia off the western margin. It has been suggested that North America lay in the region beyond and to the north of New Zealand (Fig. 35) (Moores, 1991; Dalziel, 1991). At some time in the Early Palaeozoic, the supercontinent divided into two major parts separated by the Tethys Sea – Laurasia, encompassing most of the present northern continents, and Gondwana comprising the southern continents, including Australia. Dalziel *et al.* (1994) suggest a different history: Australia as part of Gondwana was joined to North America until final separation by rifting at about 750 Ma.

The present north of our continent was situated near the border of the Tethys Sea, separated from it by part of present southern China and slivers of SE Asia. This collection of relatively small continental fragments is sometimes referred to as Cimmeria. The distance to Cimmeria may have been slight, and the gap may have been temporarily closed in the Late Devonian (Scotese *et al.*, 1985). It was not until much later, in the Jurassic and Cretaceous, that Australia left its neighbours and began to move independently.

Amalgamation of continental blocks to Australia in the Early Phanerozoic is marked by the Cambrian greenstone belts of Victoria and the deformed Early Palaeozoic rocks of eastern Australia; these can be taken to represent collision of both marine and continental fragments with what is now central Australia (Fig. 35). Later, beginning in the Devonian, accumulated blocks in the north-east included volcanic arcs related to subduction of Pacific oceanic crust (Fig. 36). This interpretation is based on evidence that much of eastern Australia, including the Lachlan Fold Belt, consists of displaced terranes exotic to the continent (Fergusson *et al.*, 1986). The distance of transport of these terranes from offshore may not have been much greater than about 100 km, judging from the age of their contained sedimentation versus the age of their deformation against the old continental margin. Overall, amalgamation and associated mountain building in this eastern sector of the continent may have ranged from Late Cambrian to Middle Devonian. Many of the data sites for Palaeozoic palaeolatitude determinations are located in the Lachlan Fold Belt, but the postulated short transport distances of these exotic blocks would suggest the measurements are valid for determining the position of the continent proper.

We now have a picture of Early Palaeozoic Australia (Fig. 36: c. 410–380 Ma), which included an adjoined large eastern block made up of much of Victoria, Tasmania, New South Wales and Queensland, as well as the possible north-western extremity consisting of part of southern China and the Himalayan fragments. The latter, now found as tectonic terranes caught up in deformed trends in Malaysia, Thailand and Burma, remained as part of Gondwanan Australia until at least the end of the Permian, judging from their faunal and lithological (e.g. Late Palaeozoic tillites) affinities.

From a palaeobiogeographical point of view, the obvious pathways for new landbased immigration in the Early Palaeozoic, that is, after the advent of landplants, were from the east and north-east via the adjoined eastern block, and possibly from the north (Cimmeria). Earlier avenues had been open from Gondwana via Antarctica and the Indian subcontinent and these continued as routes of access. However, any taxa gained through these pathways also may have originated from yet farther afield but still from within Gondwana. Because of the uncertain configuration of any join with North America, the degree of access from the Laurasian quarter is unknown. Migration routes within the continent were enhanced for marine organisms, owing to the presence of a major seaway which spanned much of the centre.

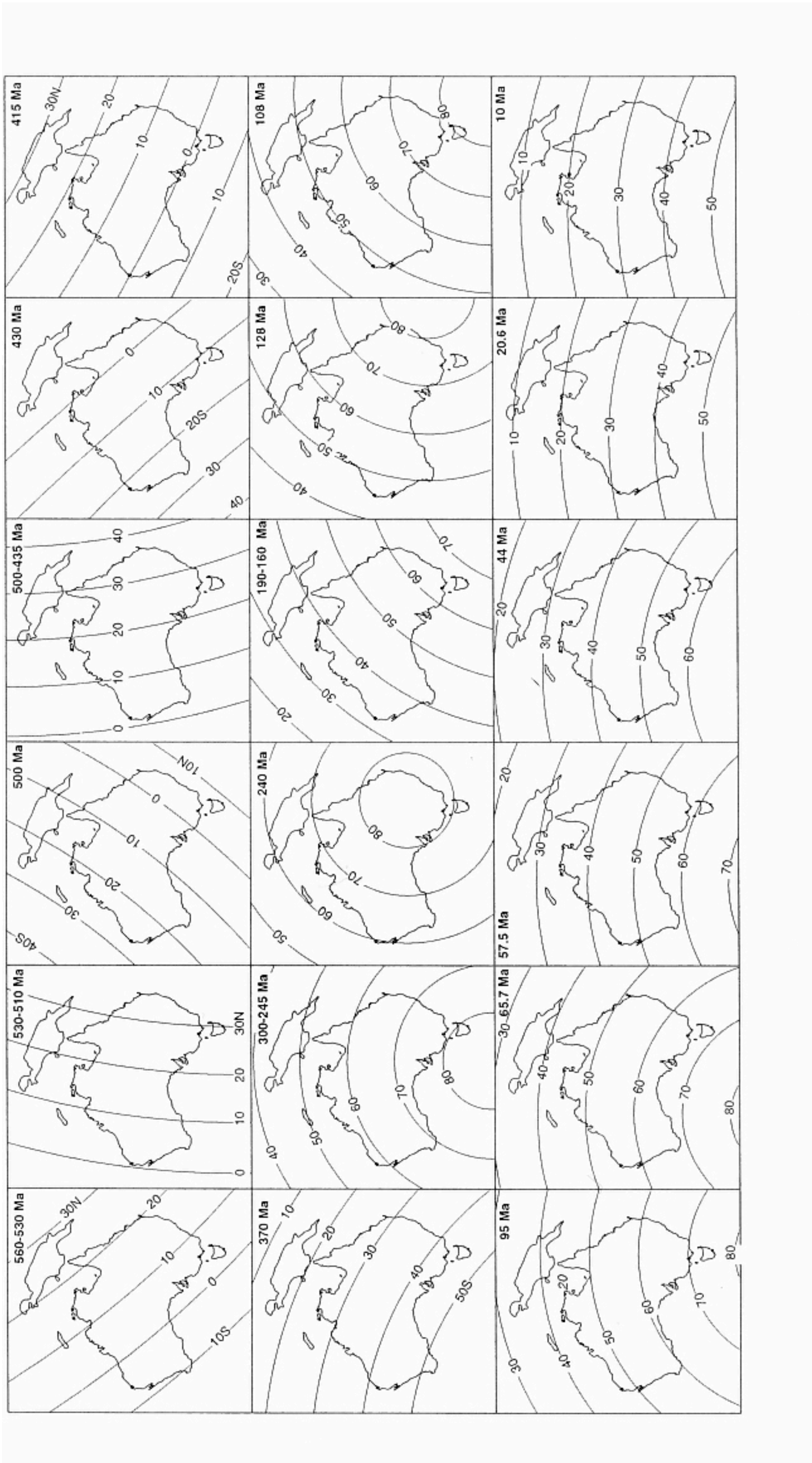

Figure 34. Palaeogeographic reconstructions showing the palaeolatitudes of Australia through the Phanerozoic (modified from Embleton, 1984).

As summarised by Veevers (1991a), the supercontinent Pangea was formed by the joining together of Gondwana and Laurasia along a suture between northern Africa and southern Europe at about 320 Ma (Carboniferous). Thus the supercontinent would have extended from pole to pole (Fig. 37). This idea radically alters the concept of Gondwana as a separate landmass on which accumulated the distinctive Gondwana sequence of sedimentary and volcanic rocks (Carboniferous to Jurassic), and the Gondwana biota. New palaeomagnetic data precisely locating the various elements are required to substantiate the temporal and geographical extent of this rejoining before judgements can be made about the efficiency or possibility of floral and faunal migrations into the Australian sector.

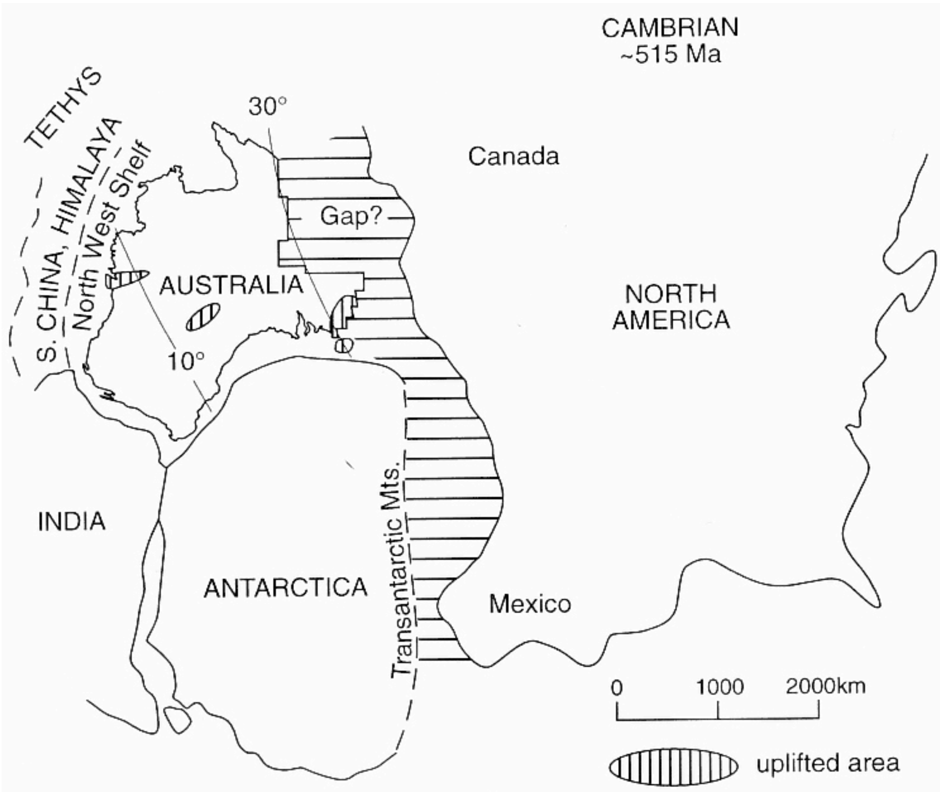

Figure 35. Palaeogeographic reconstruction of the Pacific region at about 515 Ma during the Cambrian Period. Note that there may have been a substantial gap between Australia and North America. Modified from Moores (1991). Palaeolatitudes after Embleton (1984).

Separations and drift

For our purposes, Gondwana can be considered as having existed as a continental entity during a long period, perhaps 160 million years, from about 360 Ma until sometime in the Jurassic, when a series of events began which eventually led to the isolation of Australia as a continent in its own right. The first separations took place along the northern and north-western Australian margins, with the displacement of southern China and the soon-to-be Himalayan fragments (Metcalfe, 1995). The timing of these movements is uncertain because the appropriate palaeomagnetic data is lacking. The fragments probably departed at about the same time as Gondwana began to split, with initiation of seafloor spreading in the north-eastern Indian Ocean (c. 155 Ma; Fig. 38). Within less than 10 million years, the whole of these northern terranes were separated from Australia/New Zealand/Antarctica by the northern arm of the new Indian Ocean, and all appear to have docked against various parts of Asia by about 50 Ma. Rifting, presaging spreading, created the non-marine Otway and Bight Basins along southern Australia at this time (Fig. 38). Long-established migration routes for Gondwanan floras and faunas to and from the Australian segment thus were disrupted at this time, with any direct land connections to Africa/South America severed as a consequence of the northward movement of India.

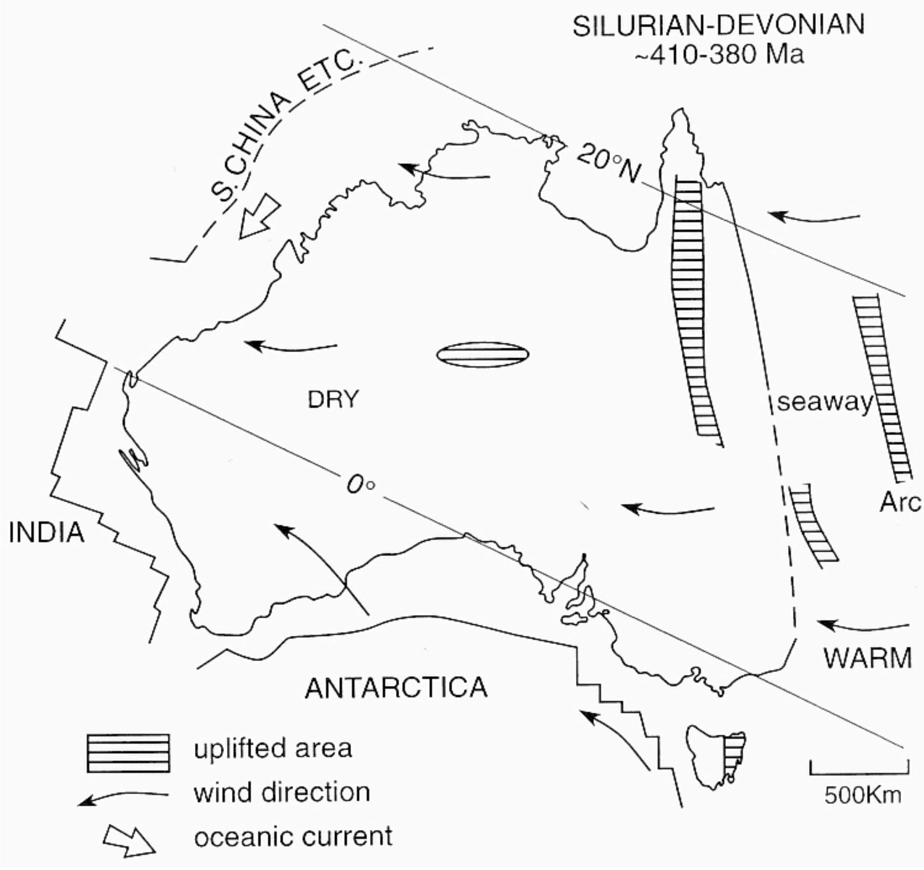

Figure 36. Tectonic uplifts and climatic elements of Australia, Silurian-Devonian (410–380 Ma). (Structures from Veevers *et al.*, 1991, and palaeolatitudes from Embleton, 1984).

The final isolation of Australia came about through a further major event. Beginning about 83 Ma, rapid seafloor spreading opened up much of the Southern Ocean south of Australia, albeit in the shape of a narrow seaway, and New Zealand and the Lord Howe Rise were isolated by spreading in the Tasman Sea (Fig. 38). The final stage in this sector was the separation of southern Tasmania and the South Tasman Rise from Antarctica at about 35 Ma (Veevers, 1988). Subsequent to these events, the only significant route for dispersal of immigrant plants over land was via bridges created during periods of low sea-levels in the Quaternary, on northern shelves connected to Papua New Guinea. Introduction of new taxa from nearby landmasses was also possible by wind and sea dispersal, but in a less predictable manner and probably to a lesser extent.

Topography

Elevation due to collision

Significant alterations to Australian landscapes resulted from tectonic activity associated with both docking of terranes and continental fragmentation. Uplifts generating erosion and sedimentary deposition in concurrently subsiding basins have been both localised relative to the surrounding countryside and continent-wide with respect to sea-level. In many cases the most conclusive evidence for uplift is found in basinal sediments, which can yield information about the provenance of the sediment and the direction, type and strength of transporting agents.

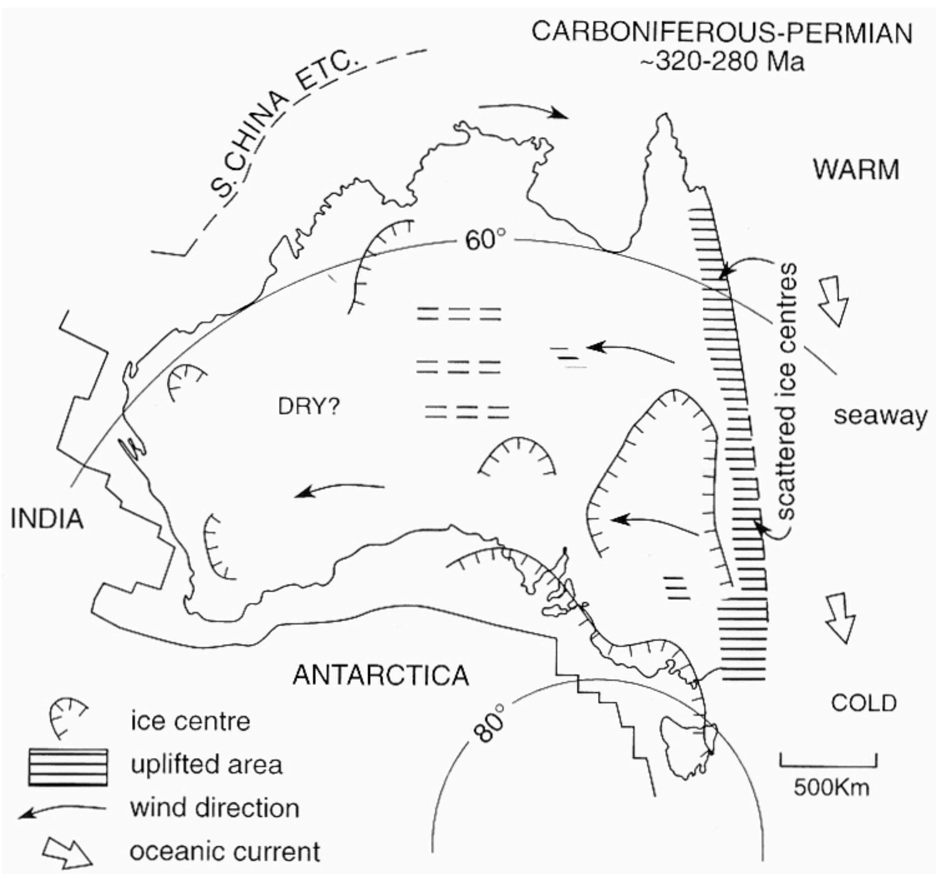

Figure 37. Palaeogeography and palaeoclimatic features of Australia at some time in the Carboniferous-Permian (320–280 Ma). (Structural framework modified from Veevers *et al.*, 1991, ice masses after Crowell & Frakes, 1975, and palaeolatitudes after Embleton 1984).

Little is known about the topography of Australia in the earliest Phanerozoic, but the Musgrave Block of central Australia underwent tectonic uplift in the Late Proterozoic and persisted as a mountainous area into the Cambrian. North-west marginal areas also demonstrate uplift in the Cambrian (Fig. 35). Cambrian docking of exotic terranes in the south-east no doubt raised mountains which only slightly later shed debris into newly created basins at their margins, as for example, the Melbourne Trough. Much of the remainder of the continent seems to have lain at a low elevation in this period.

The Late Cambrian Delamerian Orogeny (c. 495–515 Ma) raised highlands stretching from western Tasmania through the site of the present Flinders Ranges and on into north-eastern Queensland (Veevers & Powell, in Veevers, 1984). The Great Dividing Range of eastern Australia, on the other hand, owes much of its present elevation to the series of later collisional tectonic events as terranes attached themselves to the mainland during the Early Palaeozoic. The eastern highlands of Victoria and New South Wales and parts of Tasmania have undergone a series of denudations since about 365 Ma (Late Devonian), according to fission track dating by Foster & Gleadow (1993), Gleadow & Lovering (1978), Morley *et al*. (1981) and O'Sullivan *et al.* (1995). This dating is indicated by the length and density of fission tracks in apatite crystals in granitic rocks, which could only begin to form once the rock cooled to about 100°C. The cooling may have followed emplacement of the granite, or it may have resulted from intrusion-related uplift into cooler levels of the crust. Although uplift is implied in both cases, elevations cannot be specified. Throughout the first half of the Palaeozoic, mountain building/uplift in the eastern zone was accentuated by the construction of offshore magmatic (volcanic) arcs.

The Late Devonian–Early Carboniferous was a time of extensive vertical tectonics on the continent, and the effects lingered on into the latest Palaeozoic in the form of raised regional elevations (Fig. 37). In addition to the highlands raised in the eastern zone, uplifts also occurred in central Australia (Pertnjara Movement), where deformation continued at least to the end of the Early Carboniferous (Alice Springs Orogeny: c. 320 Ma). A substantial uplifted area thus reached from the central Northern Territory into north-eastern Western Australia, nearly to the Fitzroy Trough. Other smaller uplifts occurred adjacent to the Bonaparte Gulf Basin near the present coastline. Again, elevations of these uplifts cannot yet be specified, but it has been suggested that the region of the eastern margin was sufficiently high to initiate glaciation early in the Late Carboniferous (Crowell & Frakes, 1971; Powell & Veevers, 1987). A collisional episode of Palaeozoic uplift in north-eastern Australia carried over into the Early Triassic in the form of volcanic activity in east-central Queensland. Otherwise, the continent experienced a long interval of tectonic quiescence through most of the following Mesozoic Era.

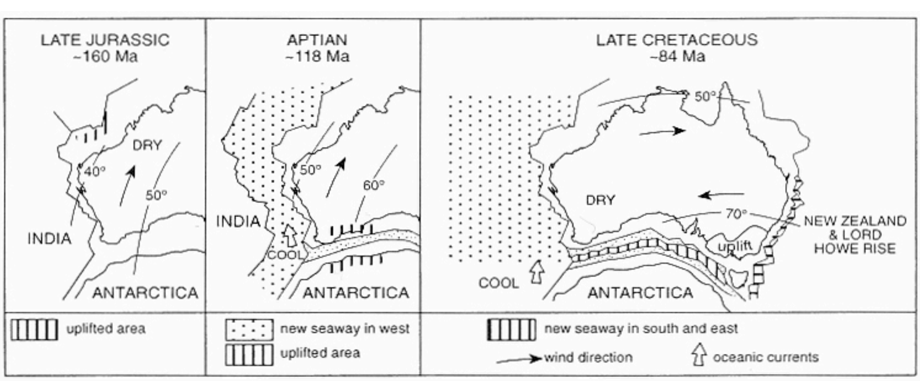

Figure 38. Palaeogeography, palaeoclimatic elements and the opening of the new ocean basins around Australia over the interval Late Jurassic to Late Cretaceous (160–84 Ma). (Modified from Veevers *et al*. (1991) with palaeolatitudes from Embleton, 1984).

At what stage New Zealand and the Lord Howe Rise attached themselves to Australia is not known precisely, but the event may be recorded in Late Jurassic magmatic activity along the New South Wales-Queensland margin. It is likely that this sector consisted of a series of blocks which were detached from the Antarctic landmass and moved northward along transcurrent faults.

Elevation due to marginal rifting

To this point, discussion has centred on Early to Mid-Palaeozoic land elevations created as a result of collisional tectonics, that is, by thickening of the crust due to opposed motions of 'core Australia' and other major blocks. Another principal means by which elevated topography is formed, doming of incipient continental margins by extensional forces, would also have been in operation over a long period of Australian history. The earliest such phase involved large scale extension and doming preceding the separation of the Himalayan and southern China blocks from the north-west margin (assuming that they actually were attached to the mainland in the manner suggested by Sengor (1987) and Veevers (1988); Fig. 38). As noted above, the precise timing of this event is uncertain but a post-Permian age is firm because the peripatetic fragments contain Permian stratigraphic sequences and fossil assemblages analogous to those of western Australia. The split-up probably took place in the Late Jurassic (post-Callovian, as suggested by Audley-Charles *et al*., 1988) concurrent with the earliest seafloor spreading, and may have occurred in two closely spaced stages, first southern China and then the Himalayan fragments. Preceding separation, it is likely there was doming in the region centred on the North West Shelf, followed by subsidence of elongate central segments (rifting). Eventually, the separated block moved laterally away from the new continental margin. Elongate domes, some also developing subsidiary rim basins, characterised the sites from which the now displaced Himalayan fragments departed. Similar uplifts of moderate altitude are likely to have occurred where later separations (i.e. of the Indian subcontinent, New Zealand-Lord Howe Rise, and Antarctica) were to take place (Fig. 38).

Fragmentation of the Australian sector of Gondwana thus led to the development of narrow and lengthy highlands which bordered a series of newborn rift structures around the periphery of the continent. Rifts and various associated rim basins vary in age from Callovian (Late Middle Jurassic; c. 160 Ma) in north-western Australia to probably about 55 Ma, when the Tasman/Coral Sea ceased spreading (Falvey & Mutter, 1981; Veevers, 1991b). Those bordering on the Indian Ocean proper propagated from the region of the North West Shelf and down the western margin in an anticlockwise fashion. Around the newly forming south-eastern margin, elevated rift shoulders and/or volcanic edifices were generated progressively from south to north as the locus of Tasman spreading shifted in the same direction into the Coral Sea. Elevated rift shoulders would have attained their highest relief at somewhat earlier times than those cited above. Elevations attained on rift shoulders are unknown, but the maximum might have been about 2 km, analogous to those reached in modern rift areas (east Africa, western North America). It is unlikely that such great heights were achieved in Australia, except possibly in the south-eastern highlands. However, elevations of about 1 km (Veevers & Cotterill, 1976) are considered reasonable estimates for many Australian rift shoulders.

The first rending of the Australian Gondwanan sector was at about 160 Ma, along the north-west coast of the continent (Fig. 38). According to Veevers (1984), uplifted blocks formed adjacent to the new ocean floor, but these lay well off the present coastline (200–300 km) and the continent was largely unaffected. Separation of the Indian subcontinent continued the process, with later rifting and drifting extending steadily southwards and then along the present southern continental margin. The Indian subcontinent was entirely freed from the west coast of Australia by c. 130 Ma. Uplift involving volcanism may have occurred near the south-western corner of the continent slightly before or during initial seafloor spreading there, at about 130 Ma. All such uplifts had subsided by the beginning of Tertiary time at 65 Ma.

Separation of Antarctica was preceded by a long interval of southern margin doming and rifting (Fig. 38) which finally culminated in the initial seafloor spreading and incursion of the sea into the Otway Basin at about 97 Ma. Volcanic activity accompanied rifting, as seen in volcanogenic sediments of the Otway Basin. However, the lack of volcanic centres of approximately this age along the margin suggests the sediments were derived either from horst blocks within the rift system or from the Antarctic side of the rift. Southern margin uplifts related to the south-eastern highlands are apparent in the fission track data cited above. These appear not to extend westward into the region of the Great Australian Bight, but do indicate that the highlands reached northward into central coastal New South Wales. It is probable that isolated uplifts existed along that section of eastern seaboard intersected by Tasman Sea/Coral Sea magnetic anomalies, that is, to latitudes matching that of the tip of Cape York. It is suggested that these uplifts were geographically distinct and were slightly older than the anomalies (again, beginning about 97 Ma and through to about 55 Ma); they were related to the series of rift structures that developed in marginal positions. The Tasman Sea/Coral Sea opening effectively removed New Zealand and the Lord Howe Rise from positions adjoining Australia and ended the extensional phase.

The lifespan for rifted domes, arches and other types of uplifts associated with extensional tectonics around the continental margins is speculative. The uncertainty is apparent from a variety of conceptual models which allow a duration of up to 50 million years for the interval from initiation of uplift to collapse, as signalled by the beginning of seafloor spreading. For our purposes, 30 million years is the span assumed in construction of Fig. 38. This is probably a sufficiently long time to allow migration of plants into elevated zones, for stabilisation of floras, and perhaps even for development of endemic taxa. The much more extensive lowlands, on the other hand, would have had a more diverse flora occupying a great variety of habitats across the continent. These are the taxa we can expect to be most common among fossil flora assemblages. However, vegetation in the lowlands, as in the highlands, was periodically exposed to influxes of plant taxa from adjoining landmasses and to marked changes in climatic conditions.

Evidence for past climates

Climate in Australia has varied over the last 570 million years. Changes have come about because of two main factors. Firstly, the continent has passed through climatic zones ranging from tropical to polar and sub-polar as a result of the motions of the Australian tectonic plate. Secondly, from an abundance of information it is known that the general thermal state of the Earth has undergone changes attributed to a variety of causes. At times, one or the other of these influences has been in the ascendancy, but the widest swings in the continental climate have resulted when the effects have been additive towards either warming or cooling.

Indicators of palaeotemperature

Most information on the history of Australian climates comes from studies on the biological content of ancient sedimentary rocks. These studies encompass all the modern techniques of palaeoclimatic analysis but unfortunately are concentrated in largely qualitative methods and on the materials formed in more recent times. As a result we presently have rather sketchy information on climates across the time spectrum and an abundance of data of somewhat limited scope concerning the last few million years. Perhaps it is because we have a relatively small ratio of scientists per km^2 of geology that the number of controversies is minimal.

Oxygen isotopes

The most powerful tool for the study of palaeoclimate is the oxygen isotope method, which uses the ratio of two isotopes to calculate the temperature of formation of carbonate minerals. These are frequently the product of shell formation by marine organisms and hence the past temperature of the marine waters in a basin can be determined. It can also be used on carbonates of non-marine origin, on the remains of fossil vertebrates such as reptiles and fish, and on other minerals, including clays. Surprisingly, given the presence of the necessary mass spectrometers and expertise at several institutions in Australia, the palaeoclimatic data gained by the oxygen isotope method are meagre when compared with those for most other continents.

Biological extrapolations

Other techniques, familiar to biologists, include determination of environmental parameters through studies of organic diversity and by estimation of past conditions through comparison of a fossil with a close living relative whose tolerances are known. Both methods, of course, have their limitations, in most cases related to uncertainties as to whether relationships between the organism and the environment have remained constant over time. Another commonly used procedure allows estimation of past climate parameters by statistical analysis of foliar physiognomy in fossil floras. The method relates the proportion of entire-margined leaves to the temperature and/or rainfall during growth of the plants by comparison with the leaf litter from modern floras (Wolfe, 1979). For Australian Tertiary floras, this type of analysis has some justification, as Australasian plants were considered in establishing the proportions among modern plant assemblages.

The first objective in many studies of fossil plants is to determine the environmental conditions of growth. Since few sites yield more than a few assemblages, it is not often that a record of any climate change at the site can be obtained. The situation then results in a scattering of sites of varying ages, not the best scenario for rigorous interpretation of climate history at a single site or of climate on a regional or continental scale. Ideally, a large amount of data from contemporaneous sites is required before meaningful interpretations of the variability of climate can be made for any sizeable area. Similarly, documentation of major climate change over time requires sequential data closely spaced in time and preferably from widely separated sites.

Rock types

The occurrence of certain rock types also is used to specify particular aspects of past climates. Particular strata are considered to have developed under similar conditions to those which developed their modern counterparts. Ancient climates are identified by making an analogy between rock type and modern environment; for example, the humid regimes of modern peat formation, the aridity of evaporite environments, the warm regimes of modern reefs and rainforests, or the frigid conditions which today feature in the formation of glacial deposits. Providing we know the full range of conditions under which distinctive sediments are formed, this is a valuable approach. Examples of past misconceptions include the idea that red non-marine sediments are restricted to arid conditions, and the notion that all limestones record warm water. Basinal conditions can be deduced from the distribution of some rock types, but the value of lithological indicators in palaeoclimatology is greatest when attempting to estimate the state of the climate on a global scale.

Indicators of humidity and aridity

Thus far, we have considered the means by which temperature can be measured or estimated. Temperature is an important parameter of the climate system and the one for which evidence is most easily obtained. Other aspects of past climate, such as precipitation and evaporation rates and wind speed and direction are more difficult to appraise, and atmospheric pressure of course is not recorded in sedimentary rocks.

Biological indicators

As mentioned, leaf proportions in foliar physiognomy studies can be used as a measure of humidity/aridity as well as for temperature estimation, but in some cases this can complicate the interpretation of temperature (Wolfe, 1977). The total composition of a flora or the presence of individual plant taxa having modern relatives of restricted tolerance can serve as guides to the annual or seasonal abundance of rainfall, particularly in Cenozoic assemblages. The width and character of growth rings in fossil wood is another important line of evidence from fossil plants (Chaloner & Creber, 1973).

Palaeosols

The type and thickness of palaeosols are reliable (although qualitative) indicators of past climate conditions and have been used extensively in Australia. Silcretes, calcretes, kaolinitic soils and lateritic profiles are abundant, and each carries its own significance as to mean annual rainfall and/or its distribution through the year. Palaeosols of Late Cenozoic age especially have been the subject of investigations, but their relative scarcity in older sequences limits their usefulness. Evidence for prevailing wind directions comes from the transport directions measured in rare occurrences of aeolian cross-bedded sandstones.

In summary, sedimentary rocks, including biogenic reef and other carbonate materials, are useful though not infallible indicators of warm climatic conditions. Tillites are the best indicator for polar/sub-polar climates, when identified by their association with other glacial facies. Between these extremes the assignment of palaeotemperatures on the basis of rock types is difficult indeed. Nonetheless, at times in the geologic record the distribution of variable lithologies provides a framework for palaeotemperature estimation. With regard to estimating precipitation, the chief indicators are the several ranks of coal deposits and their opposite numbers, the evaporitic minerals. Most studies of rock types for their palaeoclimatic significance have necessarily been limited to qualitative rather than quantitative results.

The sum of palaeoclimate data for the Australian Phanerozoic is disappointingly small. This limited information is summarised in the following sections and an effort is made to supplement it by projecting what is known of the history of the global climate state onto the map of the continent. Although most of what we know is concentrated in the later part of the geological record, the discussion follows the course of history, beginning at the opening of Phanerozoic time and proceeding through to the most recent past.

Chronology of Australian climate change

From the foregoing it is evident that there are many ways to estimate ancient climatic conditions. Such information, most of which is necessarily qualitative or semi-quantitative, can then be assembled into a history of climate. However, to summarise continent-wide data is to also generalise regional differences, thus blurring what might be significant variations from one place to another. A climatic chronology from the Cambrian to the end of the Cretaceous is presented in Fig. 39. In constructing the curves, trends in both temperature and precipitation are estimated for a point roughly located at the centre of the continent. The scales for both parameters are arbitrary and are meant to show only relative conditions.

Australia in the Early Palaeozoic: low latitude climates

Extensive Late Proterozoic glaciation of Australia (Adelaide and Flinders Ranges, Amadeus, Ngalia, Georgina and Officer Basins, plus the Kimberley region) ended a few tens of million years before the dawn of Phanerozoic time. In stark contrast, the initial Period of the Phanerozoic, the Cambrian, displays evidence of generally warm climates in the form of widespread carbonate strata deposited in a broad seaway spanning central Australia (Fig. 35). Many of these occurrences contain carbonate oolites or pisolites, which in modern environments are restricted to warm shallow seas. Structures resembling reefs and consisting almost entirely of archaeocyathids also occur in this region. Whether these grew in tropical environments typical of modern reefs, however, is uncertain owing to their great antiquity and lack of modern relatives. Attempts at oxygen isotope analysis of archaeocyathids have thus far proved unsuccessful, possibly because of internal variations in shell composition and diagenetic effects, whereby the isotopic composition can be altered by post-burial waters

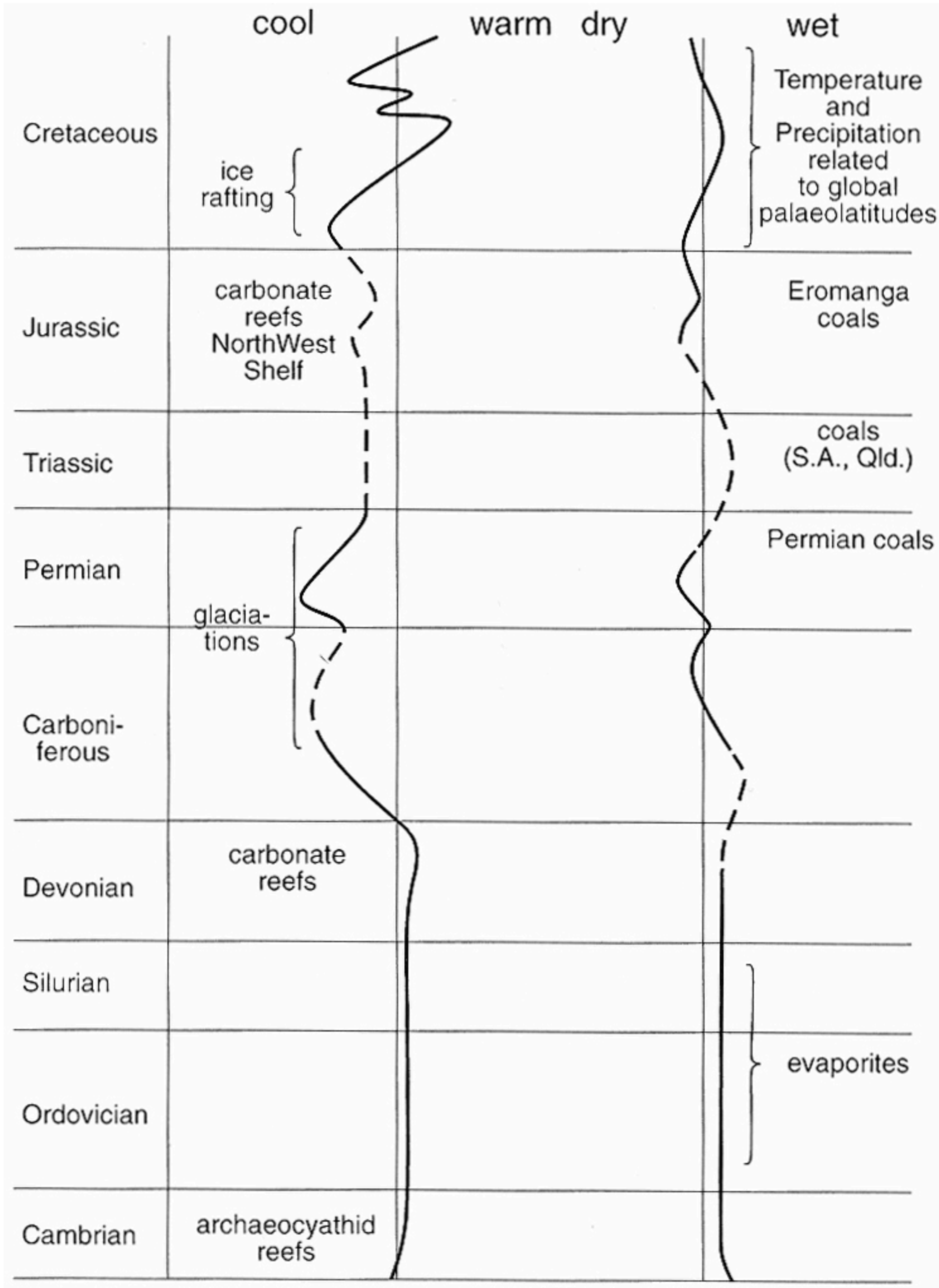

Figure 39. Estimated trends in palaeotemperature and precipitation for the centre of Australia. Note that the reference lines represent modern conditions. Arbitrary scales.

having different compositions. The available evidence, and the position of the continent, between about 5° and 40°N latitude suggests that Australia experienced a warm climate in the Cambrian. South-eastern regions, where extensional (South Australia) or collisional (mainly Victoria) tectonics were taking place, lay at the highest latitudes (Fig. 35) and may have experienced even cooler temperatures as a result of uplift, but direct evidence for this is lacking.

Northern Australia (Queensland, the Northern Territory and adjoining parts of Western Australia), located between about 10° and 30°N latitude and oriented so that it occupied a west-coast position at this time, was the site of non-marine evaporite and redbed deposition. As the precise longitudes of the southern China block are not known, the extent of any connection with Australia cannot be estimated, but we can speculate that there was a gap between the two landmasses possibly large enough at times for trade winds driving off the continent to create arid conditions similar to those which characterise modern west-coast deserts. In this scenario, the only source of atmospheric moisture was from marine basins in the interior; this, apparently, was not abundantly tapped and aridity prevailed in what is now the north.

In summary, the land area of the Cambrian continent was bisected by warm marine seaways and at least the northern one third of the continent suffered an excess of evaporation over precipitation. Most of the landmass experienced warm climates.

Climatic conditions during the Ordovician Period appear to have differed little from those of the Cambrian, judging from the deposition of carbonates and evaporites in the centre and north-west respectively (Fig. 36). Carbonates include coral reef structures that originated in docked terranes from the Pacific. Coarse clastic deposits in much of eastern Australia document the collisions of these fragments with the mainland and Tasmania and the elevation of highlands in the eastern quarter of the continent. As would be expected from its low latitude position, there is no evidence in Australia of the cooling and glaciation that affected the higher latitudes – northern Africa, central South America and parts of Europe – in the Late Ordovician and Early Silurian. Rather, essentially unchanged conditions since the Cambrian are in keeping with relatively slight changes in latitude (to within the band 20°N to 20°S in the Ordovician).

The Silurian and Devonian Periods, encompassing the initiation of significant terrestrial plant life, saw the passage of Australia out of the Northern Hemisphere and the early stages of a long journey to the polar zone. For most of this time, the continent remained between about 5° and 35°S latitude (Fig. 36) and, as before, with north-western Australia in a west coast orientation, trade winds passing over the mass of the continent would be expected to have led to aridity in northern and western areas.

Along with the disappearance of interior seas, regional changes in climate are well-documented for this time. For the Silurian, carbonate rocks containing reefal structures suggest warmth as might be expected from the east-west orientation of the continent. The reefs are found within the now-docked terranes constituting parts of Queensland, New South Wales and Victoria and thus lay facing the warm equatorial currents of the Pacific. In contrast, thick and extensive evaporite deposits of the Carnarvon Basin in Western Australia were deposited in a west coast position, adjacent to cool surface waters moving from higher latitudes. The Cambrian to Silurian saw a shift of evaporite environments from the north-east and north to the north-west of the continent in response to a clockwise rotation of some 90°.

It has been suggested that marked increases in the root mass (and biomass) of land plants in the Late Devonian led to a sequence of events as follows:

1) increased pedogenesis and stabilisation of landforms,

2) increased delivery of nutrients to the world's oceans,

3) increased marine fertility and burial of organic matter,

4) enhanced silicate weathering over the Earth, drawdown of atmospheric carbon dioxide, and consequent global cooling (Algeo *et al*., 1995).

The first Australian land plants appeared in Early Devonian time. The fossils are found in reddish sandstones suggestive of arid conditions in central and eastern Victoria.

Australia did not significantly change its position until late in the Devonian Period, when the Gondwana supercontinent began to accelerate its motion across the south pole. Although the clockwise rotation continued at a reduced rate, there was a perhaps unexpected shift in the distribution and a marked increase in the abundance of evaporite deposits. Evaporites formed in northern and central parts of the continent (Canning and Bonaparte Gulf Basins, Arckaringa Basin) and also expanded into the eastern regions (Adavale Trough of central Queensland). The latter possibly formed in a rain shadow of tectonically uplifted areas to the east, which sheltered the Adavale Trough from the moist Pacific trade winds. It is uncertain whether these deposits are all of the same age but most would fall in the Middle Devonian, a time of extensive evaporite formation on a global scale, perhaps because of major transgressions of the sea throughout the Period. Bauxites and other products of deep weathering did not develop in Australia during the Devonian, further supporting the idea that widespread aridity prevailed.

Carbonate strata also developed widely during the Devonian and carbonate reefs are found from Victoria to Queensland. The most spectacular occurrence is the Late Devonian structure at Bugle Gap in the Canning Basin, Western Australia. Reports of Devonian oolites are restricted to the Canberra region. However, the abundance of limestones is in keeping with the low latitude position of the continent and the global warmth of the Devonian. A cooling episode near the end of the Devonian led to short term glaciation in Brazil, but no indication of this cooling has been reported in Australia despite the motion of the continent towards higher latitudes. In summary, it appears that the low latitude warmth and aridity which characterised the Early Palaeozoic continued without significant interruption through into the Carboniferous. Aridity seems in fact have been more extensive in the Devonian than earlier.

Australia in the Late Palaeozoic: high latitude cooling and glaciation

Australia continued a rapid transit into the high latitudes in Carboniferous time, where it remained through the Permian Period, and as a result of its latitudinal position glaciation affected much of the continent (Fig. 37). In the Late Carboniferous and Permian, massive glaciation spread throughout much of the Gondwana supercontinent, but the earliest ice masses, as recorded by their deposits (tillites and associated strata), are located in eastern Australia and western South America. The oldest Australian occurrences, Namurian A in age (c. 330 Ma), are found in the Tamworth Trough and also near the coast east of the New England Highlands. They indicate the presence of glacial ice at sea-level, and thus extremely cold climates for this part of the continent. However, it is thought that the glaciers originated in elevated terranes and flowed downslope to form piedmont types adjacent to the sea (Crowell & Frakes, 1971). The remainder of the continent apparently was not affected by glaciation in these early stages.

It has been suggested that the Tamworth region and the elevated regions bordering on the Pedirka, Arckaringa and Cooper Basins of central Australia were glaciated as a result of contemporaneous mountain building known to have affected both the east and the centre at this time (Powell & Veevers, 1987). A difficulty with this idea is that the maximum age of the glacial deposits of central Australia has not been established and, although they may extend back well into Carboniferous time, they are dated only as 'Early Permian (Sakmarian) and older'. There is thus a gap of at least 45 million years between the timing of tectonic activity in the centre and the earliest dated glacial deposits in these basins. However, it is certain that glaciation and attendant cold climates were factors in the environments of central Australia by Early Permian time.

During the whole of the Late Palaeozoic (c. 360–245 Ma), Australia lay in latitudes higher than 25°S, but as a result of prolonged poleward motion, the whole of the landmass was positioned in the mid- to high latitudes (50–80°S) by the middle part of the Carboniferous. The near polar location of Australia and its neighbouring continents in Gondwana, thus provided seats for the growth of ice sheets, and no doubt made a major contribution to the most severe cooling recorded in Earth history. At no other time in the Phanerozoic was there such a congregation of landmasses in the polar zones and the coincidence in the Late Palaeozoic of polar landmasses and global cooling must be more than an accident of history. However, the development of large-scale glaciation seems to have taken a considerable time, as the deposits of the first Australian ice sheet (Late Westphalian, c. 300 Ma) post-date those of the mountain and piedmont glaciers of eastern Australia by at least 20 million years. Dating for an ice sheet which covered much of the east, from Tasmania to Queensland, is uncertain, as it is derived from the apparently long-ranging *Potonieisporites* palynoflora (Late Carboniferous to Early Permian). A second ice sheet occupying parts of South Australia originated from adjacent Antarctica. Tillites there record glaciation near sea-level, but the timing (Latest Carboniferous to Early Permian) is similarly obscure. Considering the global range of ages cited for the Late Palaeozoic glaciations, Frakes *et al*. (1992) suggested that the relatively few citations for the Latest Carboniferous is evidence that there was a warming within the major Late Palaeozoic glacial interval, a possibility supported by Crowley & Baum (1992), despite calculated low atmospheric carbon dioxide levels.

The Early Permian (Asselian-Sakmarian (290–269 Ma)) saw the greatest expansion of ice on the continent, with glacial deposits laid down as far north as 60°S latitude (Fig. 37). An amalgamated ice sheet spread over the present east coast from southern Tasmania to as far north as central Queensland and stretched to the basins of central Australia. Separated centres for the growth of ice also existed in the west, next to the Perth, Carnarvon, Canning and possibly the Bonaparte Gulf Basins. For these, the geographic extent of the ice cannot be determined due to subsequent erosion or deep burial of the deposits, but ice masses do seem to have been limited geographically. Judging from the nature of the deposits, the intensity of cooling may have been substantially less than in the eastern centres. The central basins lay in a broad belt of high latitude westerly winds which, after their long passage over the continent, were relatively dry. There was also a shortage of moisture sources for ice growth within the centre, as the few marine basins there would have been frozen over for much of the year. The restricted growth of the ice masses of the Australian centre was probably regionally related to elevated terranes raised during Early Palaeozoic tectonism. Over this time interval, while the continent lay in roughly the same orientation as now (i.e. with its long axis roughly parallel to lines of latitude) only the far north of the continent experienced moderate temperatures. Migration of those land plants requiring a land connection was severely constrained in the Early Permian because of the ice, and only hardy immigrants (*Glossopteris*? etc.) would have arrived, probably from the Indian subcontinent to the west.

Vegetation patterns during the Sakmarian (c. 275 Ma) were reduced to biomes by Ziegler (1990), who interpreted them to indicate a variety of climate conditions:

far north	temperate evergreen forests	warm temperate, humid
north-west	tropical deciduous forests	tropical, humid summers
south-east	(boreal) coniferous forests	cold temperate
south	–	ice-covered, polar

In the Late Permian, the gradients in temperature south to north across the continent averaged about 20°C, according to the modelling results of Fawcett *et al*. (1994). There were strong seasonal variations with winters averaging between -10°C and +10°C and summers between +10°C and +30°C. The coolest region was located in the south-east.

The frigid landscape of Australia, along with the remainder of Gondwana, warmed greatly toward the end of the Permian Period. This took the form of increased seasonality, as seen in computer climate modelling and comparisons with the vegetation biomes of this time (Kazanian, see Kutzbach & Ziegler, 1994). From inferred vegetation biomes, Ziegler (1990) predicted that most of Australia was covered by cool temperate broadleaf (nemoral deciduous) forest during the Kazanian. Temperatures in the centre in mid-summer reached 35°C and in winter -15°C. The geological evidence tells us that most continental ice had melted abruptly by about 269 Ma (end Sakmarian). Tasmania appears, quite understandably considering its southern position, to have been the last region to come out of the cold spell. The evidence, however, does not support the presence of a late ice cap there, but instead signals the final decay of the ice masses during a time of strongly seasonal climates, which included winter freezing to form river and marine shore ice at basin margins. Ice floes carried stones northward into marine environments in Tasmania and along the southern New South Wales coast and deposited them during summer melting. The same process began and ended in eastern Queensland somewhat earlier. As a result of general global warming ice rafting had ended in Australia (and in conjugate Siberia, the only Northern Hemisphere locality where the process has been identified), and in Gondwana, by about 250 Ma.

A major problem is posed by the termination of both the extensive glaciation of Australia and the subsequent seasonal ice rafting while the continent maintained a polar to subpolar position. At this key time there is a lack of climate indicators to support the climatic conditions suggested by the latitudinal position of the continent. It appears that a major shift in the state of the global climate led to substantial warming at all latitudes in the Late Permian. The forcing function for warming probably lay in the geochemical cycle of carbon. A geochemical model relating the consumption of carbon during the weathering of silicate rocks to global tectonic events and sea-level (Berner, 1994) reveals that the drawdown of atmospheric carbon dioxide was very strong from the Early Carboniferous until the middle Jurassic. This can satisfactorily explain the cool Earth of the Late Palaeozoic mainly as a consequence of tectonic activity, but not the termination of glaciation nor the warm and wet conditions, characterised by the deposition of the later Permian coals in New South Wales, Queensland and Western Australia, which followed. One hypothesis to address this warming suggests the release of carbon dioxide from ocean waters and seafloor sediments to the atmosphere near the end of the Permian (Frakes *et al.*, 1992).

Some climate modelling also suggests the initiation of monsoonal conditions in Late Permian Australia (Kutzbach & Ziegler, 1994). These monsoons were felt most strongly in eastern Australia, where rainfall varied from more than 2000 mm/yr in summer to about 1000 mm/yr in winter. Monsoonal conditions originating at this time extended into the Triassic, when they dominated the climate over a large part of Gondwana. However, modelling by Fawcett *et al*. (1994) suggests high summer rainfall in the west and south-east but only moderate rainfall (c. 1000 mm/yr) for most of the continent.

The cooling of Gondwana during the Palaeozoic was a major event in the evolution of Australian environments. However, the long transition from tropical to sub-polar regimes, reflecting the drift to high latitudes, brought about gradual rather than sudden change. Consequently, the stepwise impacts on the fauna and flora of the continent, although dramatic in the long term, were subdued over short periods. In this sense, Australia, particularly the western part, may have acted at times as a refuge for life forms of Gondwana but it was not the sole location from where re-establishment of stocks throughout the supercontinent could occur. Although northern parts of Africa and South America, possibly cooled, they were not subjected to glacial conditions, and other regions underwent only sporadic spells of glaciation. As long as intercontinental connections survived beyond the ice sheets, so too could the Gondwanan biota.

Australia in the Mesozoic – a totally different picture

During the Mesozoic Era (the Triassic, Jurassic and Cretaceous Periods), Australia remained in the high latitudes (Fig. 38), yet the only indication of cool climates is found in Early Cretaceous strata of the centre (Fig. 39). The abnormal warmth which began late in the Cretaceous is documented in all continents and signals a global warming which is unprecedented in Earth history.

Triassic

The Triassic Period saw a concentration of the world's landmasses across the equatorial zone and the consequent development of widespread monsoonal conditions (Robinson, 1973; Parrish *et al*., 1982; Frakes *et al*., 1992). Australia, however, was positioned too far south to be affected by tropical monsoons. Rises in global sea-level were associated with the melting of the ice in the Late Permian but, paradoxically, during the Triassic interval of warmth there was a withdrawal of the sea from all around Australia. This latter observation seems a contradiction in itself, as an Earth without polar ice caps would be expected to experience rising sea-levels as water from melting polar ice returned to the oceans. The alternative mechanism for global lowering of sea-level may resolve the difficulty. Decreased tectonic activity in the ocean will lead to increased volume of the ocean basins and hence, regression of the sea from continents. There is no model of continental evolution which would permit the opposite mechanism, a comprehensive rise of the continents. In the Triassic Period, the only slight encroachments of the sea onto the land were in southern coastal Queensland and the Perth and Canning Basins, where previously formed basins already existed. In general the landmass appears to have been without large scale relief, except perhaps in near-coastal zones of northern New South Wales and Queensland where tectonism and associated volcanism took place in the Early Triassic (c. 245–241 Ma).

Paradoxically, at the time Australia lost its glaciers, the continent moved into yet higher latitudes. During the Triassic the pole appears to have moved into south-eastern Australia (Fig. 33) and at no time in the period did the continent extend to lower latitudes than about 55°S. Did the pole move or the continent? The fact that Triassic polar Australia underwent significant warming and lacks any evidence of glaciation whatsoever is but a part of the bigger problem – the total lack of any glacial evidence on the globe at this time, the only Period in the Phanerozoic for which glaciation is not documented.

Quantitative estimates of Triassic temperatures (from oxygen isotope studies) are few in number and restricted to the Tethyan low latitudes (Hudson & Anderson, 1989). As a result, the Triassic thermal state of Australia is poorly known. Some suggestion of aridity in the Early Triassic is offered by red shales and sandstones that occur in small patches around Australia, but further studies are required to substantiate the idea that the coloration represents oxidation during deposition, as seen in some modern deserts. The best indications of Triassic climate come from the coals of small basins within the Flinders Ranges of South Australia, in Tasmania, and also from the coastal regions of New South Wales and Queensland previously affected by volcanism. During the Middle and Late Triassic (about 241–208 Ma) these regions became centres for humid climates, which may have been of much greater extent. The east coast deposits can be explained by their location: as in previous glacial times, warm currents moving southwards from the equatorial Pacific would have provided these areas with abundant precipitation (Fig. 37). Retallack (1977) has interpreted Triassic palaeosols of the Sydney Basin as indicating a cool-temperate climate, and similar conditions have been suggested for the Bowen Basin, Queensland and south-eastern Australia (Townrow, 1964; Jensen, 1975).

The recent development of mathematical models of the climate system now allow simulations to be made of past and present climates. The General Circulation Models (GCM) lack fully linked oceans and suffer from other imperfections, but even with these limitations they can provide clues to forcing functions and the state of the climate in times past. Following attempts using conceptual models (e.g. Robinson, 1973; Parrish *et al*., 1982), Kutzbach & Gallimore (1989), Fawcett *et al.* (1994) and Pollard & Schulz (1994) investigated Triassic climates with a GCM under several scenarios. Fawcett et al. (1994) found extreme winter temperatures of less than -30° warming to +10°C in summer in the south-east, coincident with suggested high topography. The 0° isotherm extends nearly to the north coast in the Late Triassic in winter. The previously suggested monsoonal conditions in low latitudes were supported by the results, but high rainfall was also indicated for regions beyond about 35°S latitude. The segment which includes all of Australia at this time experienced precipitation in excess of 550 mm/yr; except for rather small areas in the centre and the far north, there was a positive precipitation minus evaporation balance, in keeping with most geological indicators. Regarding temperature, the model gave latitudinal ranges for summer of 15° to 25°C and winter of about 10° to -30°C, suggesting strong seasonality and continentality.

Jurassic

The Jurassic Period, like the Triassic before it, has few climatic indicators. During this time Australia briefly moved to slightly lower latitudes (range from c. 35–65°S, Fig. 38), before reversing its course in the Early Cretaceous. Again, despite its location in relatively high latitudes, there is no evidence for glaciation in Australia, although probable glacial deposits have been reported from adjoining Antarctica (Woolfe & Francis, 1991). Glaciation has not been reported elsewhere at this time, although seasonal ice rafting probably took place in high latitudes of Far-Eastern Siberia during the Middle Jurassic (Chumakov & Frakes, 1997).

Sea-level remained low, with the consequence that marine embayments were restricted to parts of the Perth, Carnarvon and Canning Basins in the west. A major palaeogeographic development was the initiation of the great interior lowland which still persists today, the Great Australian Basin, at this stage better known to palaeogeographers as the Eromanga Basin (Krieg *et al*., 1995). Accumulation here was primarily in the form of fluvial sediments of a large sandy river system draining to the east, but thin and discontinuous coals, indicating an excess of precipitation over evaporation, were common here and in coastal areas of Queensland. These indications of humidity, as before, can be attributed to the persistence since the Late Palaeozoic of proximal warm currents derived from the western Pacific. Hallam (1985) suggests that coal-delineated wet climates extended farther west and north to encompass most of Queensland and New South Wales in Late Jurassic time. The east-west orientation of the north-western continental margin would have favoured the initiation of seasonal monsoonal precipitation there. However, the only sedimentological information from that region comes in the form of fluvial deposits which lack coals or other indications of a wet climate.

Numerical modelling of past climates using General Circulation Models has now been applied to the Jurassic (Chandler *et al.*, 1992; Moore *et al.*, 1992; Valdes, 1994; Fawcett *et al*., 1994). Chandler *et al.* (1992), on the basis of qualitative evidence of mean global zonation, set boundary conditions for the model by assuming Early Jurassic sea surface temperatures (SSTs) of 14° and 9°C off northernmost (Darwin area) and southernmost Australia (Tasmania), respectively, and relatively subdued topography throughout the continent. Slight elevations are assumed for eastern Queensland. These and other inputs to the model for this time enabled the model to reach stability. One could conclude therefore that the use of these specified temperatures was justified, and that they provided an approximation of Early Jurassic conditions. Continental temperatures, which were not specified but instead produced by the model, showed moderate summer-winter variability (Darwin 10° to 19°; Tasmania -12° to 10°C) and zonal arrangement of isotherms. Despite the success of the simulation in some respects, the model cannot address the problem of how high temperatures can be maintained at high latitudes. Finally, the model indicated generally low positive values for precipitation minus evaporation over Australia, more or less in keeping with the known distribution of coals.

Mid-Jurassic climates were simulated by Fawcett *et al*. (1994), who found that Australian conditions had warmed considerably since the Late Triassic. They defined the climate as generally humid, warm temperate to subtropical, with a mean annual temperature range of about 30°C and rainfall totalling an average of about 1500 mm/yr. Rainfall was heaviest in the continental centre.

Moore *et al*. (1992) utilised a GCM to investigate the Late Jurassic. Their boundary conditions included increased levels of atmospheric carbon dioxide (at 1120 ppm, about 4 times the present level) and topography to 2 km elevation in coastal eastern Australia; both SSTs and continental temperatures were determined by the model. Winter to summer temperatures were calculated to be about -10° to 20°C for Darwin and -22° to 10°C for Tasmania, and winter sea ice would have formed off eastern Australia at this time. Annual precipitation was estimated to have been greater than 1000 mm/yr except for the south-east (where some of the Australian coals occur), but north-eastern Australia showed the greatest excess of precipitation over evaporation anywhere on the Jurassic globe. Storms would have affected the north-west of the country, as the axes of mid-latitude storm tracks trend from Darwin to North West Cape. Here, wind strengths above 60 km/hr would have been common.

The Valdes model of Late Jurassic climates (Valdes, 1994) assumed similar SSTs as estimated by Moore *et al*. and arrived at similar conclusions.

General Circulation Models are known to be imperfect in their attempts to simulate both present and past climates. But from the above results it can be said that increased carbon dioxide in the atmosphere contributes to relatively warm summers, which in turn suppresses the formation of permanent ice masses at the poles. Accordingly, although winter freezing was common in the centre, glacial deposits are not to be expected in the Australian Jurassic high latitude sites. Also, Jurassic coals appear to be fairly reliable but not precise indicators of high precipitation and excess precipitation over evaporation, and, in the case of Australia, this leads to the conclusion that the north and west of the continent experienced humid climates (rainfall of perhaps as much as 1300 mm/yr), while over the remainder of the continent precipitation was lower and there was an approximate balance between precipitation and evaporation. The Australian monsoon, which had its origins in the Late Permian, seems to have terminated within the first half of the Jurassic. As today, storminess seems to have been a feature of northern Australia, and the roughly east-west orientation of the north coast would have been conducive to monsoonal activity. While the geological information available to define Australian Jurassic climates is meagre, it is sufficient to sketch the general picture which can then be filled in by modelling.

Cretaceous

The climates of the subsequent Cretaceous Period (c. 145–65 Ma) are even more complicated, showing a greater degree of variation because Gondwana was beginning to divide. This created new seaways, which helped to moderate continental climates and provided new sources of moisture for evaporation and precipitation. The most significant separation, in terms of Australian climate, seems to have been the drifting away from Antarctica, which occurred in the Albian (112–97 Ma), as documented by the earliest marine sediments of the new seaway in the Otway Basin. Several lines of evidence indicate that Australia during the Cretaceous was characterised by surprisingly cool climates in the first half and warmer conditions thereafter. Also important for climates was the movement of the continent into higher latitudes. From the Valanginian (c. 140–135 Ma) to the Early Albian the bounding latitudes were between about 45° and 80°S, the highest they had been since the Late Palaeozoic. The Cretaceous also saw what were probably the highest sea-levels on record for the Phanerozoic (Turonian, c. 90–88 Ma; Haq *et al.*, 1987) and the creation of an extensive seaway occupying the central lowland areas. The lifetime of this continent-bisecting seaway almost precisely coincided with the duration of the first half of the Cretaceous (c. 145–97 Ma), and throughout its existence it would have hindered the spread of land plants.

The evidence for cool conditions in the Early Cretaceous comes from several sources. Palaeontological and oxygen isotope data from the Aptian–Albanian of the Otway Basin are interpreted as signals of temperatures near zero (Rich *et al.*, 1988; Gregory *et al.*, 1989; Ferguson *et al.*, 1993). Strata of Valanginian to Albian age (c. 140–110 Ma; Alley, 1988) contain coarse clasts to boulder size, which apparently were dropped by melting ice floes into marine muds of the Eromanga and Carpentaria Basins (Frakes & Francis, 1988; Frakes *et al.*, 1995). This interpretation was first put forward by Brown (1894) and, after some alternative ideas were discarded, supported by David (1950). Because evidence of glaciation in the form of tillites is not present among Australian Cretaceous strata, ice floes formed in winter and melting in summer, as opposed to icebergs from glaciers, are preferred as the agent of rafting of the coarse material. Therefore, the suggested climate, at least for eastern Australia, is a strongly seasonal one which also included frequent storms, judging from sedimentary structures. GCM modelling results indicating an annual temperature range of about 45°C (between c. 27° and -18°C) for central Australia support such a view (Barron & Washington, 1982).

A second powerful line of evidence comes from oxygen isotope analyses of Late Aptian glendonites from the Eromanga Basin. Preliminary study of these stellate calcite pseudomorphs of ikaite, a cold-water carbonate mineral, demonstrates low salinity for the

Eromanga seaway, thus permitting calculation of palaeotemperature of bottom waters using a new value for the isotopic composition of high latitude oceans (De Lurio & Frakes, in prep.). Previously determined bottom water palaeotemperatures from the Eromanga/Carpentaria by the isotopic method on carbonate fossils (Dorman & Gill, 1959), when recalculated on this basis, yield values of generally less than 10°C. Thus this work indicates the presence of a seasonally cold seaway in the centre of the continent in the Early Cretaceous, which probably derived ice floes and large quantities of cold fresh water from highland sources lying to the south and east of the basin. The highland source is supported by other evidence. Frakes & Francis (1990) and Francis & Frakes (1993) showed that growth rings in Eromanga fossil araucarian and podocarp wood indicated both a lowland population displaying relatively broad rings and a highland group with narrow rings. It was pointed out that the first group had modern counterparts in warm- to cool-temperate forests of Australasia, while features of the second population were closer to those of trees from cold-temperate regimes of the western slope of the Patagonian Andes. The coastal ranges of south-eastern Australia were the likely source of the narrow-ringed wood types and the climate conditions there can be considered as analogous to those of Patagonia. Snowfields in this region also supplied the abundant fresh water which fed the Eromanga Basin and the ice floes, probably from rivers which underwent winter freezing. Still farther south, in the Otway Basin, meltwaters have also been suggested to explain large negative values of oxygen isotopes and low temperatures (-5° to 5°C) from carbonate concretions of Aptian-Albian age (Gregory *et al.*, 1989). A different explanation for these results is offered by Spicer & Corfield (1992). Palaeobotanical data (Parrish *et al.*, 1991) provide a MAT estimate of 5–8°C for the Albian of the south-east, somewhat at odds with the isotopic and other estimates. However, it must be remembered that because stratigraphic control is poor (Dettmann *et al.*, 1992), such 'inconsistencies' might be merely reflecting sharp climate fluctuations on time scales of 1 million years or less.

At this time the continent possibly had three climate zones (Frakes *et al.*, 1995). Beyond c. 72°S palaeolatitude, in the south-east of the mainland and probably including Tasmania, highland terranes suffered very cold winters but somewhat warmer summers causing much melting of snow. Between c. 72°S and c. 53°S rafting by river ice into marine basins affected the Eromanga and Carpentaria Basins, signifying strongly seasonal climates and bottom waters with temperatures less than c. 10°C. Beyond c. 53°S palaeolatitude, the climates were warmer and seasonality was less marked. From Fig. 40 it can be seen that the western half of the continent lay within this warmer zone.

The foregoing discussion relates primarily to the time most closely identified by the age of the Eromanga glendonites which have been studied, and not to the whole of the Valanginian to Albian interval in which dropstones occur. In fact, the sporadic distribution of the dropstones and the glendonites in Australian Cretaceous basins is more suggestive of fluctuating temperatures. It is likely that climates alternated between the Late Aptian conditions described above and more equable climates. However, this has not been confirmed, because of a lack of suitably dated sequences showing obvious cyclicity.

Australian palaeoclimatic conditions can be estimated in more detail, although not necessarily with more accuracy, by examining global temperature variations as a function of latitude and time. It is assumed, firstly, that temperature data from around the world can give a reasonable picture of global climate evolution, and secondly, that this averaging technique can then be applied in estimating the thermal history of Australia as it moved across lines of latitude. Continental and oceanic temperature data from a variety of sources yield the picture seen in Figs 41 and 42 respectively (Frakes *et al.*, 1994; Frakes, submitted). Isotherms swing towards the high latitudes at times of warming and towards the low latitudes when cooling is underway. For Australia, which occupied the space/time belt between the heavy lines, it can be deduced that the Early Cretaceous was a cool time with mean annual temperatures near freezing over a large part of the continent. However a warming, in part reflecting the acceleration in Australia's northward motion, was in progress. By the end of the Albian (c. 97 Ma) the 0° MAT isotherm lay along the southern margin of the Eromanga Basin and only the far north of Australia experienced MAT above 10°C, according to GCM modelling by Barron *et al.* (1995). This modelling experiment included a 30% increase in the

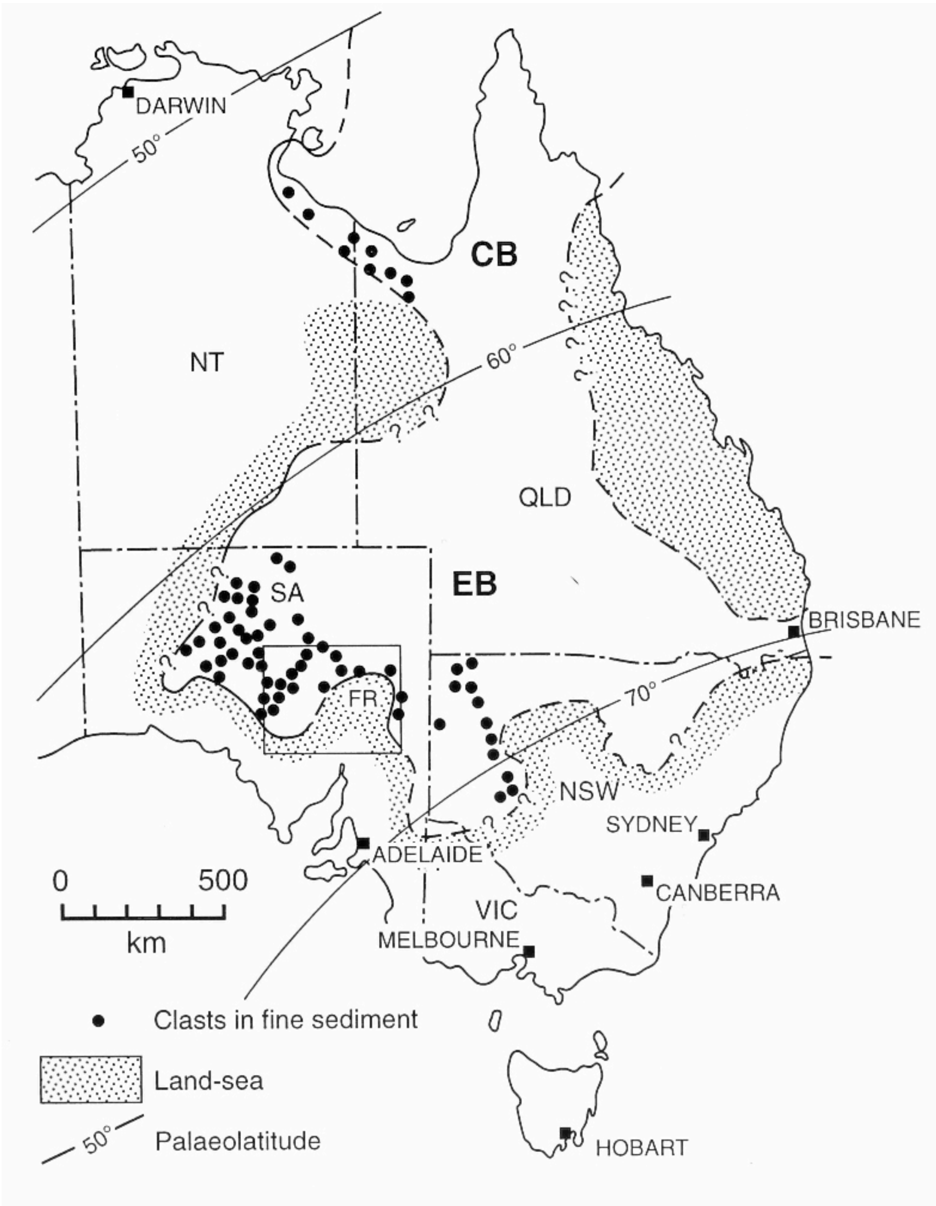

Figure 40. The distribution of ice rafting and the climatic zonation of eastern Australia during the Early Cretaceous. EB= Eromanga Basin, CB= Carpentaria basin. (Modified from Frakes *et al*., 1995).

transport of heat by the ocean relative to the present, and a carbon dioxide level four times that of the present. The Turonian (c. 90–88 Ma) seems to have been the time when warming peaked, with MAT for Australia of about 13°C in the south and 23°C in the north of the continent. One result of this warming was the coincident extreme peak in global sea-level. Douglas *et al*. (1976) suggest that Victorian plant fossils suggest cool climates which continued until the Santonian (c. 86–83 Ma), but the global data indicate cool conditions persisted until the Maastrichtian (c. 74–71 Ma). The closing of the Cretaceous (c. 65 Ma) witnessed a short sharp warming followed by a marked cooling at the opening of the Tertiary Period.

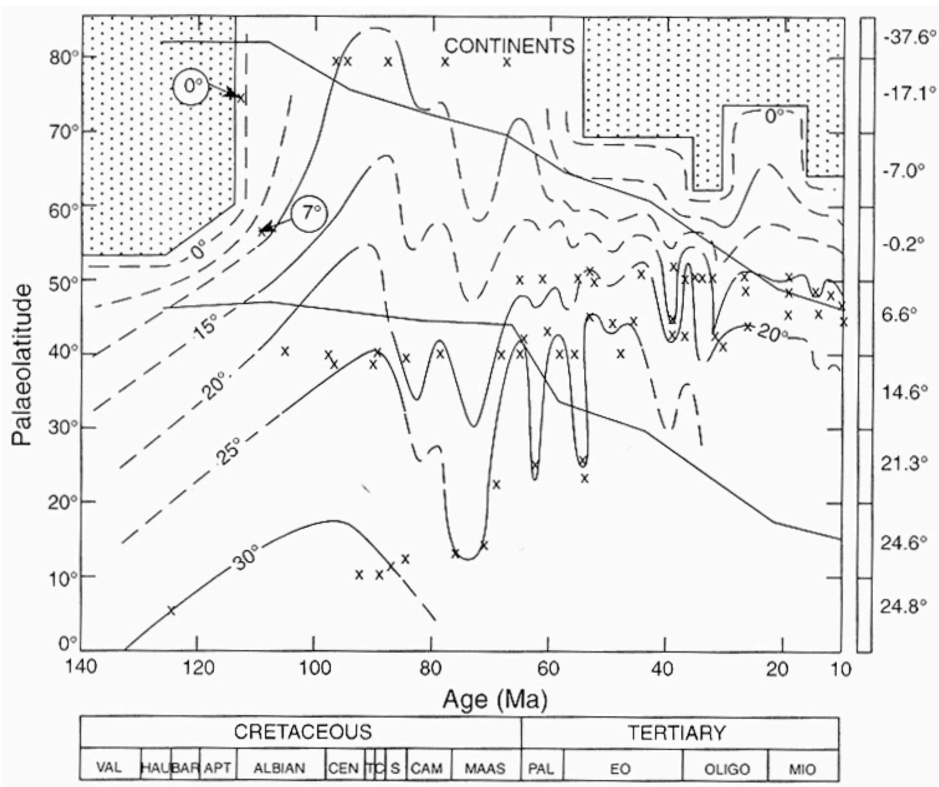

Figure 41. Space/time plot of published global palaeotemperatures for continents, Cretaceous to Middle Miocene. Note that both Hemispheres are included. The hatched boxes represent the distribution of known ice rafting and the numbers along the right margin are mean surface temperatures for each 10° latitude band at present (Willmott & Rowe, 1985). The diagonal lines represent the northern and southern extremities of Australia. (Modified from Frakes *et al*., 1994).

It is known that the global climate fluctuated in the second half of the Cretaceous (post-97 Ma), but such changes are not well documented in Australia because of a general scarcity of data. The interior seaway had dried up and there were only minor incursions of the sea onto the continental borders. A major warming effect was felt on the North West Shelf of Australia, where clastic sedimentation was replaced by the widespread accumulation of carbonate sediments. This occurred approximately in the Turonian, a time of warming in the world oceans (Fig. 42), and carbonates have continued to form there up to the present. It has been suggested that conditions were warm enough for carbonate minerals originating largely as shell materials of marine organisms to be preserved from dissolution. It is possible that formation of Late Cretaceous carbonates of the North West Shelf benefited from relatively warm surface waters diverted southward from the equatorial currents. It is also possible that these mid-latitude carbonates are of the temperate carbonate types which can form in comparatively cool conditions, but this has not been investigated.

Precipitation is an often ignored aspect in palaeoclimate studies, partly because it is often difficult to separate precipitation from temperature effects but also because what is likely to be preserved in fossil and sedimentary materials reflects the balance between precipitation and evaporation. The abundant Australian palaeosols, although potentially of value, provide few opportunities for determining precipitation rates because they are poorly dated, some as Early or Mid Mesozoic, others as pre-Late Mesozoic or even Permian (Bird & Chivas, 1989; Benbow *et al*., 1995a). Studies of leaf morphology and palaeo-ecological comparison with nearest living relatives has sometimes been of use. However, given the vast differences between Cretaceous plants and modern forms, such approaches have not always been wholly reliable in estimating past rainfall. Yet, on the basis of Eromanga Basin palynology and sediment types, Krieg *et al*. (1991) and Benbow *et al.* (1995b) suggest humid climates for the south of the Early Cretaceous Eromanga Basin, and Evans (1967) considered that thin Late Albian coals near Nhulunbuy in the Northern Territory indicated abundant rainfall there.

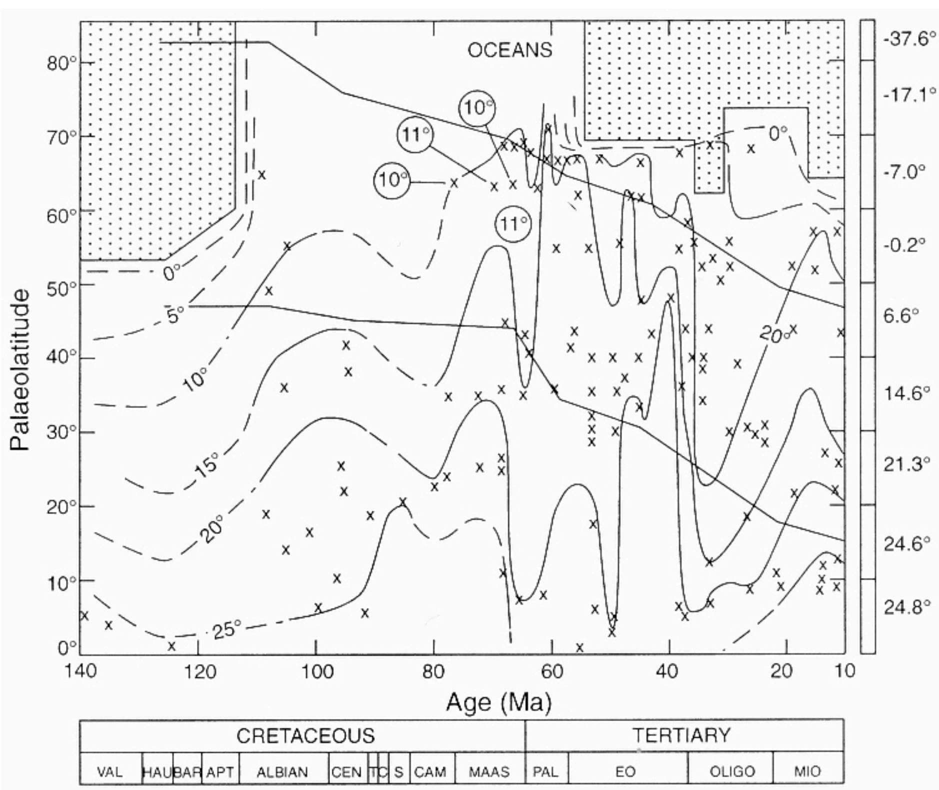

Figure 42. Space/time plot of published palaeotemperatures for world oceans, Cretaceous to Middle Miocene. Hatched boxes and diagonal lines are as in Fig. 41 and numbers on right are mean sea surface temperatures for 10° latitude bands (Shea *et al.,* 1990). (Modified from Frakes *et al*., 1994).

Others have favoured widespread low-latitude aridity (to c. 45°S latitude in Africa and South America) on the basis of fossil floras and evaporites from the Aptian (c. 124–112 Ma), a time when the equatorial humid zone apparently did not exist (Chumakov, 1995). The latter study also suggested that a humid tropic zone came into being in the Albian and extended until at least the Cenomanian.

An alternative method of estimating, and perhaps predicting, palaeoprecipitation relies on the global relationship between precipitation and temperature (Fig. 43). From this information, it can be stated that MAT less than 20°C corresponds on average with precipitation of less than 500 mm/yr, and MAT of 25° generally leads to rainfall of more than 1580 mm/yr. These isotherms, from Fig. 41, can thus be taken as defining precipitation rates and are plotted on Fig. 44. Interpretations from this method do not take into account the possibility that unusual circumstances (coastal oceanic currents and upwelling, regional orographic effects, continentality) may have caused substantial deviations from the global norm, and indeed, such deviations are well known among modern climates. Assuming strict conformity with the globally averaged conditions, the results suggest that Cretaceous Australia was mostly semi-arid, except for northern regions near the temperature maxima (Albian to Turonian; c. 112–88 Ma, and Late Maastrichtian, c. 70–65 Ma). This dryness is surprising because throughout the Cretaceous Australia lay with the northern margin in east-west orientation (at c. 45–50°S latitude), in a situation where a seasonal monsoon might have developed. It seems that only in the Albian–Turonian interval and the Late Maastrichtian were conditions in the north entirely suitable for monsoons. It appears that the whole of Australia occupied a cool dry zone until the Albian.

Palaeogeography also played a role in setting the Australian climate during the Cretaceous. Most important were the predicted tracks for the polar easterly winds, which would have blown strongly across the continent from what are presently the east and north-east (Fig. 38). These winds, first moving over the cold seas beyond New Zealand and then over the breadth of the continent, would have been mainly dry, and any available moisture would have been precipitated on the elevated terrain in south-eastern Australia, thus leading to the formation

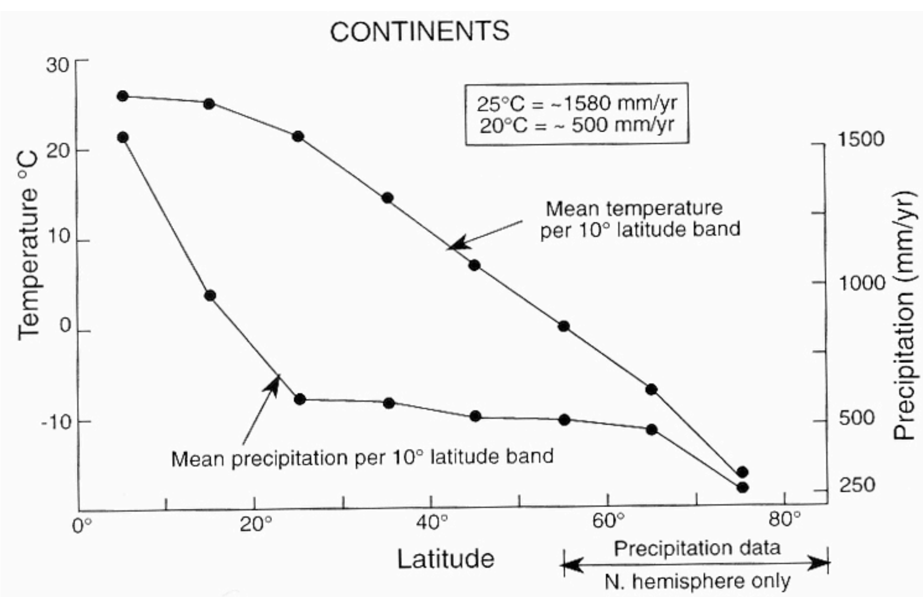

Figure 43. The global relationship between temperature and precipitation on continents over the range of latitude. Mean precipitation values from Hauschield *et al.*, 1994.

of snowfields and possibly permanent ice. Beyond the mountains, the further depleted winds contributed to dry inland and western climates. In the north, westerly winds moving off the developing Indian seaway would have supplied some rainfall to the north-west. After the Aptian, the north apparently collected at least intermittent and local high rates of precipitation, suggesting that eastward-moving surface currents of the adjacent Tethys seaway represented a pool of easily evaporated warm surface waters, as is indicated by various Albian and younger climate indicators around the western and northern margins of the seaway (Chumakov, 1995).

Global sea-level remained low in the Early Cretaceous, but from the Valanginian (c. 141–135 Ma) a punctuated series of rises began that continued until the Turonian (c. 90–88 Ma). Short-term Early Cretaceous sea-level changes (on time scales of up to about 500 000 years) have been shown to correspond with oxygen isotope values, indicating that polar ice may have existed through this time (Stoll & Schrag, 1996). The extremely low sea-level of the Valanginian has never been repeated. In Australia, this history is reflected in the gradual encroachment of marine seaways in the west (Perth and Carnarvon Basins, and most extensively, the Canning Basin) and in the east-central region (Carpentaria, Laura, Surat and Eromanga Basins). The western seaways withdrew by the beginning of the Albian (c. 112 Ma), not to be seen again on the continent, while the Carpentaria/Eromanga seaway occupied as much as the central one-quarter of the continent throughout the Albian, but withdrew early

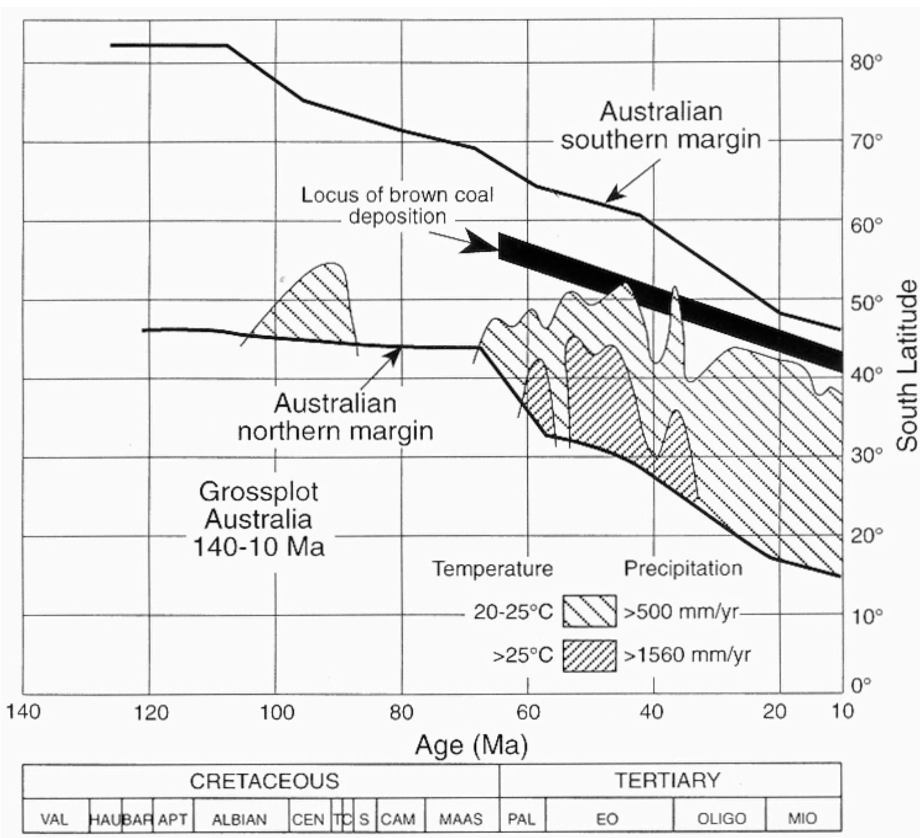

Figure 44. Space/time distribution of precipitation over Australia (<500, 500–1560, and >1560 mm/yr), Cretaceous to Middle Miocene, using the temperature/precipitation relationship of Fig. 43 and the distribution of palaeotemperatures from Fig. 41.

in the Cenomanian (c. 96 Ma; Frakes *et al.*, 1987). A major fresh water basin draining mainly to the north replaced the extensive Eromanga/Carpentaria seaway in the Cenomanian. The final major encroachment in the Cretaceous took place along the southern margin, beginning in the Late Albian in response to the opening of the Southern Ocean as Antarctica and Australia drifted apart. The opening of the Tasman Sea (Santonian to earliest Tertiary: c. 83–60 Ma) did not lead to development of new seaways on the Australian continent but initially permitted funnelling of cool high-latitude water northward along the present coast (Quilty, 1994). Late Cretaceous sedimentation was common, however, in the narrow Perth and Carnarvon Basins on the western continental margin, where periodic warm intervals are identified by the occurrence of specific foraminifera (Quilty, 1994). It is interesting that the sea-level record of Australia diverges most markedly from the global eustatic history (Haq *et al.*, 1987) precisely at the time of separation of most continental fragments from its margins, i.e. in the Late Albian. From then on, while global sea-level continued to rise for another 20 million years, the sea largely withdrew from Australia.

Tertiary evolution of climates towards the present

The climate history of Australia becomes much better documented from the opening of the Tertiary Period. The younger sedimentary materials are more abundant and generally more accessible than are older sediments. Furthermore, Tertiary fossil floras and faunas have closer relationships with their modern counterparts than do their ancestors and thus conclusions about their palaeo-ecological significance are more firmly based. Finally, marine climate indicators on the continent were more dispersed than previously, although the total area occupied by marine basins was only slightly larger than in the Late Cretaceous.

Evolution of the Australian climates in the Tertiary involved two significant factors. Firstly, the continent began a rapid transit to the lower latitudes, thus providing a background warming together with increased humidity, and secondly, the earth as a whole experienced progressive cooling, drying episodes. The balance of these opposed trends is reflected in slight warming over the Palaeocene to Mid-Miocene interval (c. 65–10 Ma) and more marked cooling since then. Throughout the Tertiary, fairly wide swings in temperature were apparent. Globally, the first indications of freezing conditions occur in the Middle Palaeocene, at which time ice rafting may have taken place in North Island, New Zealand (Leckie *et al.*, 1995). This event is interpreted as being probably short-lived, and the significant global cooling, as indicated by isotope records and Antarctic dropstones, began in the Middle Eocene (c. 55 Ma) (Frakes *et al.*, 1992).

Quantitative palaeotemperature determinations are not abundant for Australia in the Tertiary Period although there are abundant data which yield information of a qualitative sort, particularly for the Late Miocene and younger times. As indicated earlier, the climates of the Quaternary (the last c. 1.6 Ma) are not dealt with here, but information on modern climates can be found elsewhere in this volume (see Fox, this volume).

Palaeotemperatures during the Tertiary

Throughout the global record (Frakes *et al.*, 1994), and in Australia, the early part of the Tertiary Period presents a unique climatic picture, in this case characterised by evidence of very humid climates as well as high temperatures at middle to high latitudes. During this time, Australia moved northward at a rate exceeding 3 cm/y and into warmer climate zones. The south-eastern part of the continent remained at some significant elevation (Ollier, 1977).

Sources of information on the climates of this interval include several types of palaeobotanical/palynological investigations. Studies of foliar physiognomy of fossil plant materials have yielded quantitative palaeotemperature estimates for assemblages from South Australia, Victoria and New South Wales (Christophel, 1981; Greenwood, 1994). The most useful data of this type come from the Middle Eocene of southern Australia. Here, Anglesea (Victoria) yields a MAT range of 15–18°C, Maslin Bay (South Australia) a MAT range of

23–26°C, Garden Grove (South Australia) a range of 17–20°C, and Nerriga (New South Wales) a range of 16–21°C (Greenwood, 1994). On the basis of palynology and other fossil plant studies (Palaeocene to Early Eocene), the interior Lake Eyre region featured rainfall in excess of 1800 mm/yr and temperatures above 18°C (Sluiter, 1991). Fossil crocodilians, requiring year round temperatures of more than about 5°C, also are known from central Australia.

A recent study of Early Eocene foliar physiognomy and nearest living relatives (Greenwood & Wing, 1995) estimated southern Australian continental MAT as being between about 17°C and 21°C, and everywhere warmer than today. The paper presented the contrasts between data derived from such methods and the results of computer modelling of global climate, particularly as regards the continental interiors of Australia and North America. The latter efforts (e.g. Sloan, 1994) suggest sub-freezing winter temperatures (for the North American interior), greatly at odds with the palaeobotanical information derived from physiognomy and the environmental tolerances of nearest relatives such as palms. Climates of the Middle and Late Eocene (Langford *et al.*, 1995) may have been 2 to 4°C warmer than today, and rainfall in the extensive areas of *Nothofagus* rainforest may have exceeded 1500 mm/yr.

Carbonate sedimentation, indicative of bottom waters sufficiently warm that the minerals are not dissolved, but not necessarily documenting tropical temperatures, became a feature of southern Australia in the Middle to Late Eocene. Previously, carbonates had continued to accumulate on the North West Shelf (Apthorpe, 1988) and down the west coast to Cape Leeuwin at the south-western extremity, but now they were spread irregularly onto the southern marginal basins (Bremer, Eucla, St. Vincent, Murray and Otway Basins; Langford *et al.*, 1995). The initial stages of Great Barrier Reef development saw a wide area of carbonates accumulate on the Queensland Plateau at this time.

A major event in global climate history took place at the end of the Eocene (c. 35 Ma) (Frakes & Kemp, 1973). This was the marked cooling of the earth, which led to development of an ocean-atmosphere system similar to that of the present. This perhaps resulted from increased vigour in the lateral and vertical circulation in the world ocean, and marked expansion of the polar ice cap in Antarctica. The impact on Australia, still situated in relatively high latitudes, was immediate and of great significance for the environment, which had experienced warm, wet climates for most of the previous 25 million years For example, Kamp *et al*. (1990) recorded a drop in temperature from c. 20° to c. 13°C across the Eocene/Oligocene boundary, based on isotopic analyses on marine sites in southern Victoria. In addition, carbonates ceased to be developed on the Queensland Plateau in the Early Oligocene. Although the results are largely qualitative, palaeobotanical studies show marked changes in floras compatible with cooling (Macphail *et al.*, 1993, 1994). Perhaps predictably, due to the topographic relief, the south-east seems to have experienced continued high humidity.

The Oligocene to Middle Miocene world saw a slow and probably irregular warming, which is especially obvious in sea surface temperatures and calculated Antarctic ice volumes. From Deep Sea Drilling data, Zachos *et al*. (1993) suggest ice on Antarctica first reached its present volume in the Early Oligocene and may have attained 200% of the present volume at the Early/Late Oligocene boundary. Australian conditions mirror these trends (Feary *et al.*, 1991). Here, the effects included a return to carbonate sedimentation, of a temperate type, in the St. Vincent, Murray, Otway and Gippsland Basins, as well as renewal of carbonate deposition, and the first biogenic reefs, on the Queensland and Marion Plateaus. The Karumba Basin, located beneath the present Gulf of Carpentaria, likewise accumulated carbonates, and biogenic reef structures on the North West Shelf, which originated probably in the Middle Miocene, were common. Paradoxically, reefs did not develop in offshore Queensland waters during the Late Miocene and Pliocene, only recurring and continuing after the Pliocene. An explanation for these trends in sub-tropical waters can possibly be found in changes to circulation patterns in the low latitudes of the world ocean as a result of the changing thermal state.

The space/time diagrams for oceans and continents, contoured as to temperature (Figs 41 & 42), provide a means of estimating Australian palaeotemperatures for any time and palaeolatitude through the Tertiary until the end of the Middle Miocene. Remembering that the concept assumes that Australian temperatures conformed to the mean global values within latitude bands, it can be predicted that, with some notable reversals, particularly in low latitudes, Australian temperatures warmed more rapidly than the northward migration of the continent would suggest. If warming was due to migration alone, the isotherms should roughly parallel the orientation of the boundary. However, convergence of isotherms towards the southern (high latitude) boundary of the Australian time/space zone indicates a warming trend greater than that due to migration. Conversely, if there was a net cooling, isotherms would converge toward the northern boundary. The strongest warmings probably took place (in rank order) in the Middle Eocene, the Early Eocene and the Middle Oligocene. As for the coolings, the rank order would be the Early Palaeocene, Late Palaeocene-Early Eocene and the Late Eocene. To generalise, the Palaeocene-Eocene was a time of rapid change, while the Oligocene-Middle Miocene was characterised by more equability. Only the southern fringe of Australia appears to have endured MAT less than the present global MAT (c. 13°C) and this only during the interval from the Palaeocene to the Middle Oligocene. These quantitative estimates of temperature may be useful in deciding on the relative usefulness of fossil taxa in Australian palaeoclimatology.

Tertiary palaeotemperatures derived from space/time contours of the continents can also be compared with modern MAT on Australian palaeogeographic maps (Fig. 45). The important differences between Early and Late Tertiary climates immediately become apparent. Early Tertiary (Palaeocene and Eocene) climates are seen to be nearly everywhere cooler than at present. The exceptions are small coastal areas adjacent to the Tasman Sea and to sources of warm water from the equatorial zone, and there is a further area of warmth along the Victorian coast. But the Miocene maps show that over the entire continent, temperatures were likely to have been warmer than at present, a result perhaps not expected given the northward drift. The explanation lies in the fact that present temperatures reflect the general glacial condition of the Earth even though we are currently in an interglacial stage. The growth of polar ice which led to intense global cooling only began in earnest in the Late Miocene.

The estimates of Australian palaeotemperatures in Figs 41 and 42 collectively differ little from the geological data, thus suggesting that such plots can be used to supplement or expand on the 'hard' information. This compatibility also demonstrates that across Australia temperatures were not greatly different from those which characterised comparable global latitude belts.

Precipitation history

Indicators of precipitation or precipitation-evaporation balance in the past include the distribution of palaeosols by type, organic accumulations such as coals or peats and evaporitic deposits, in addition to information deriving from studies of plant materials themselves. Australia began the Tertiary in wet to extremely wet conditions, but a drying phase extending through most of the period was initiated in the Mid-Tertiary, probably during the Oligocene. According to Langford *et al.* (1995), evaporite formation in the Australian centre was a dominant process only in the Holocene, which suggests that extreme evaporative conditions did not characterise the region during the Tertiary.

Palaeosols are important, although qualitative, indicators of precipitation rates. Deeply weathered profiles containing abundant iron oxides and kaolinite clay minerals are considered diagnostic of seasonally high rates, while silcrete and calcrete profiles are more representative of drier, and in some cases alternating wet and dry, conditions. Many attempts have been made to date the episodes of weathering documented by abundant palaeosols in Australia. Taylor (1994) suggests that, taken together, these data show that deep weathering has been a long term feature during the whole of the Tertiary. Difficulties in determining the age of formation of fossil soils have led to a variety of dating methods being employed, the most recent utilising palaeomagnetism and the isotope geochemistry of clay minerals. Idnurm & Senior (1978) determined that fossil soils from several locations (south-western Queensland, southern South Australia, and near Perth, Western Australia) all possessed

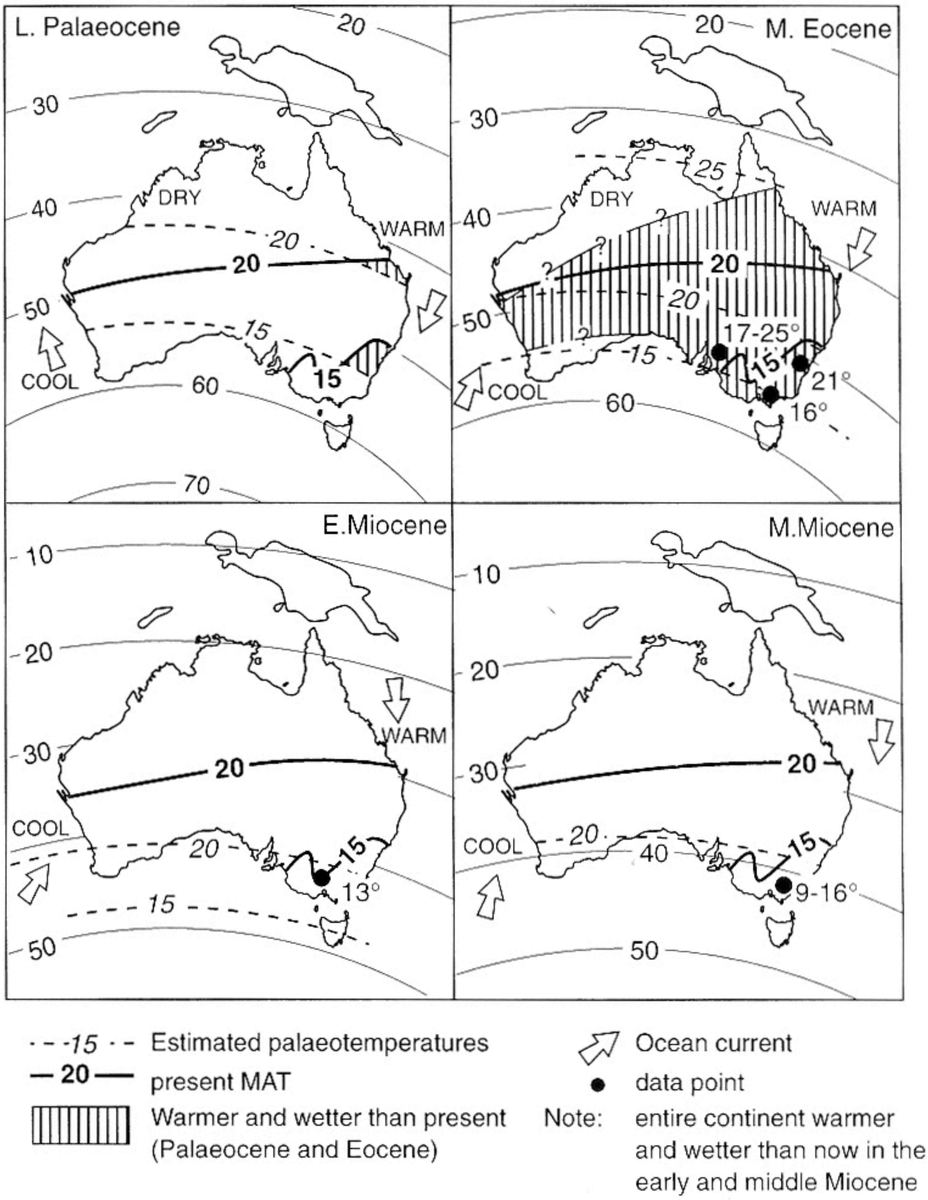

Figure 45. Palaeoclimatic elements of Australia during the Tertiary Period.

remnant magnetism consistent with formation during the Maastrichtian to Early Eocene (c. 74–50 Ma). Their study also suggested formation of another Queensland palaeosol in the Late Oligocene. McGowran (1979) accepted the Early Eocene as a time of deep weathering and high precipitation. He also suggested that the Late Eocene, the Middle Miocene and the Late Miocene experienced similar conditions, based on extra-tropical excursions of large foraminifera. Deep weathering to form major bauxite deposits requires an annual rainfall higher than about 1700 mm, less than 4 months of dry season and a MAT greater than 20°C (Tardy *et al.*, 1991). Australian bauxites are very poorly dated: 'Tertiary' is normally cited. Bauxites at Weipa, Gove, the Kimberleys and the deposits in the Darling Ranges were all located in the appropriate rainfall/temperature zone (Figs 44 & 45) during the Eocene, and thus would have conformed to the optimum conditions. Rainfall in the Perth region may have been insufficient for bauxites to form during the Miocene.

Other types of palaeosols can be used to interpret palaeoclimatic conditions. The most useful, calcrete or calcretised palaeosol, is considered to be the product of weathering in semi-arid environments where evaporation exceeds precipitation (Reeves, 1978). The great episode of pedogenic calcrete formation in Australia seems to have begun in the Mid-Tertiary and continues today. Silcrete is another guide to climatic humidity conditions, its development often being ascribed to arid settings, but because silcrete is frequently found as a component of lateritic soil profiles, it has also been suggested as an indicator of strongly seasonal climates (Stephens, 1978). A major episode of pedogenic silcrete formation around Lake Eyre, possibly related to silcretes extending north-eastwards over much of the Eromanga Basin, is dated as between Middle Eocene and Early Miocene (Alley *et al.*, 1996). A second Lake Eyre silcrete event is of Late Miocene to possibly Pleistocene age (Benbow *et al.*, 1995b). In central Queensland silcrete ranges may date back to the Late Miocene. To sum up, calcretes and silcretes support other evidence of increasing Late Tertiary dryness in the interior.

Brown coal, or lignite, is a common feature of the Australian Tertiary, ranging over sizeable areas of the south-east (Gippsland, Bass, Otway, Murray and St. Vincent Basins), in the Duntroon sub-basin and the Ceduna Terrace of offshore South Australia, and in association with deeply weathered profiles palaeomagnetically dated as Late Eocene in the Arunta Block of central Australia (Senior *et al.*, 1994). Long-ranging brown coal sequences (Palaeocene to Middle Miocene) developed in the Gippsland and Murray Basins. The deduced overall trends in precipitation through the Tertiary on the basis of such deposits are as follows.

- Palaeocene–Early Eocene: high rainfall especially in the south-east (Gippsland and Otway, but also in the St. Vincent and Eucla Basins, near Lake Eyre and along the north-west coast).
- Middle Eocene–Late Eocene: continued high humidity on the south coast (Gippsland, Bass and western part of the Nullarbor Plain) and in the centre (Arunta Block), as well as the north-west coastal area.
- Early Oligocene: a major drying out of the continent took place, with coaly deposits forming only in the Gippsland region and south-western New South Wales.
- Late Oligocene–Middle Miocene: despite the warming trend at this time, on the evidence of coaly deposits, only relatively small areas in the Gippsland and Murray Basins recorded high precipitation rates (Hocking *et al.*, 1976; Rogers *et al.*, 1995).
- Late Miocene–end Pliocene: continued relative dryness across the continent; no coals recorded.

In summary, the Tertiary record of coals suggests a decline in precipitation (or precipitation-evaporation balance) throughout the period.

Strong indications of Australian climatic conditions in the Tertiary come from climate-related studies on fossil plant and animal material. For the Late Oligocene to Middle Miocene interval, high rainfall is indicated by abundant lake deposits in the centre (Langford *et al.*, 1995), and rainforest conditions are suggested by the faunas at Riversleigh in north-central Queensland (Archer *et al.*, 1991). The Late Miocene saw a remarkable change due to widespread drying (Martin, 1977, 1991; Kemp, 1978; Sluiter & Kershaw, 1982; Truswell, 1993). The transition to the modern vegetation was largely completed by about 6.6 Ma through the widespread replacement of the abundant extant rainforest floras by xerophytic types. An example of the change to aridity can be seen in the reduction of *Nothofagus* as a component of fossil assemblages. Pliocene climates featured apparently short intervals of increased rainfall in southern Australia, and Bowler (1982) has suggested that, continent-wide, conditions first approximated those of the present by about 2.5 Ma (Late Pliocene).

It would be advantageous to summarise the information available from a wide variety of global sources into a quantitative precipitation chronology. This can be attempted by first using the contoured global temperatures (Fig. 41) to estimate the thermal condition on Tertiary Australia. Then, knowing the relationship between MAT and mean annual precipitation (Fig. 43), it is possible to suggest the distribution of rainfall over the continent through this period. Three bands are delimited:

1) less than 500 mm/yr, corresponding to temperatures less than 20°C;

2) 500–1560 mm/yr for temperatures in the range 20–25°C; and

3) greater than 1560 mm/yr for values above 25°C.

Figure 44 indicates that, assuming no unusual circumstances such as oceanic currents or upwelling and 'normal' continentality effects, northern Australia was very wet in the Palaeocene, the Eocene and the Early Oligocene. In the Eocene, very humid conditions extended almost halfway to the southern margin. Moderate rainfall prevailed over most of the continent and extended farther southward throughout the interval. The remainder of Australia, at the higher latitudes, appears to have been relatively dry. Figure 45 presents the information in a different way. It is apparent that the cooler-than-present continent in the Early Tertiary was also mostly drier (except in the south-east), while the warmer-than-present Miocene saw wet climates over a large proportion of Australia.

The usefulness of this method can be judged by a comparison of the foregoing trends with Australian data derived from geological indicators of precipitation. The Tertiary brown coals of the south, in South Australia and Victoria, lie adjacent to the belt of moderate rainfall, which establishes some reliability for this method of estimating precipitation from temperature. Lake Eyre fossil floras (Middle Eocene) lack significant proportions of *Nothofagus* and other indicators of high precipitation rates (Alley *et al.*, 1996). Further, the deeply weathered palaeosols described above lie within or near the zones delimited as very humid to moderately humid (Queensland, South Australia and Western Australia). Although only broad estimates can be obtained in this way, they are at least of a semi-quantitative nature, and may even prove to be of value in inferring tolerances of ancient plant taxa as regards rates of precipitation. Results derived by this method do not compare well with those of another study based on a conceptual model of climate, based in turn on the climate parameters governing the distribution of modern peats and evaporites (Parrish, *et al.*, 1982). The inferred rainfall patterns of the latter study show only occasional agreement with the location of Australian brown coals.

Summary

This account has outlined the temporal spacing of important continental and global events contributing to the history of Australian environments, and through these has examined the systematic interactions of landscape and climate over a long span of geological time. As in all such studies involving historical information, it is necessary to discriminate between the several types of evidence. The evidence of landscapes, as seen in global positioning of the continent, its relationships with other landmasses, and its orography, helps to sketch the framework in which recognised climates of the past have operated. The variation of climatic elements (derived from both global and, where possible, strictly Australian data) is influenced by features of the landmass, that is, by its palaeogeography in terms of altitude, continentality, and land-sea geometry. In a reverse sense, the intensity and type of climate exerts a control on landscape, primarily through erosional processes. While the causal mechanisms for well-defined climates of certain intervals at a regional scale can be confidently attributed to the influence of landscape on palaeoclimate (for example, the tectonic raising of mountainous terrain in south-eastern Australia in the Cretaceous; the likely high continentality effects of the Gondwanan Late Palaeozoic), the relative strengths of these continental versus global evolutionary factors in contributing to perceived palaeoclimates unfortunately remain uncertain. Here, we have applied global mean temperatures and precipitation rates of the past 140 Ma to the latitudes occupied by the continent and have introduced slight modifications to the perceived climates due to landscape. For earlier times, we lack adequate summaries of these climate parameters on both local and global scales, and thus neither the description of climates by latitude belts nor the reckoning of the landscape factors can be rigorous.

The primary control on the grand sweep of environmental evolution in Phanerozoic Australia has been the position of the continent on the surface of the Earth. The two lengthy periods when the landmass occupied the polar and sub-polar zones coincided with a time of severe global cooling, in the Late Palaeozoic, and another time of regionally intensive cooling, in the Early Cretaceous. These intervals can be considered as benchmarks in a broad cyclicity of climate and the cooling effects are seen in strata around the globe. Glaciation affected Australia from about 330 to 269 Ma, and ice rafting continued until about 250 Ma. Over much of this time, Australia was positioned in a manner very similar to that of Antarctica at present (c. 60–90° latitude), yet the only substantial ice sheet was limited to the elevated eastern part of the continent, and this could perhaps be attributed to the likelihood that significant moisture sources were limited to adjacent parts of the Pacific. It would appear that polar/subpolar climates were less cold than in the present interglacial stage and may have had MAT as much as 5° warmer than now, possibly in the range -2 to -30°C. The spread of Late Palaeozoic glacial deposits in many basins over a large proportion of Australia leaves open the possibility that ice sheets were more extensive than is now commonly thought.

The Early Cretaceous cooling, featuring ice rafting only, was more regional in scope and less intense; it lasted from about 140 to 110 Ma. Palaeolatitudes of the continent for this interval appear to have been about 40° to 70°, and MAT ranged from possibly as low as zero to as much as 15°C. These temperatures were significantly higher than during the height of Pleistocene glacial times, and would be from 5° to 12°C warmer than at comparable latitudes today (10° to -12°C). The driving force for seasonal ice development was the tectonic elevation of south-eastern Australia at a time when it again occupied the higher latitudes. In the Early Cretaceous, moisture sources to build ice were not as limiting as in the Late Palaeozoic because of the seasonal nature of the climate, and the southern Pacific was nearby.

Australia was probably in its warmest stages in the early part of the Phanerozoic (Cambrian Period). The time was also notable for widespread aridity, which in fact extended through the Early Palaeozoic until the Devonian. Low latitude positioning in the pathways of Cambrian trade winds moving along the join with Antarctica generated no appreciable precipitation, as most moisture would have been dropped in the New Zealand sector. Desiccated areas formed in the east and north. The trade winds eventually reversed to move towards the Queensland sector from Tasmania in the Silurian as the continent rotated. All geological evidence supports the idea of low latitude warmth and low precipitation and/or high evaporation rates from the Cambrian through to the later part of the Devonian, when the long drift into high latitudes began.

For the period between the two cool intervals (most of the Mesozoic Era), the climates of the continent remain largely hypothetical, with a shortage of information from climate indicators, particularly for the Triassic and Jurassic. Using a geochemical model to quantify consumption of atmospheric carbon dioxide during weathering of surface silicate rocks, Berner (1994) found that in the Early Mesozoic carbon dioxide was nearly at its lowest for the Phanerozoic. This suggests a type of reverse greenhouse cooling for the interval. Suggestions of at least regionally high rates of precipitation come from the sparse distribution of coal deposits and from the development of major riverine systems in the interior in the Early Mesozoic.

Finally, the slow warming of Australia since the Early Cretaceous is documented both from geological data and from estimates of global latitudinal controls on temperature and humidity. This resulted from the drift towards lower latitudes, and despite the progressive cooling of climates on a global scale.

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