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LATE CAINOZOIC ENVIRONMENTS IN AUSTRALIA

by

*R.W. GALLOWAY & E.M. KEMP

RECORD 1977/40

This paper forms Chapter 2 in
'Ecological Biogeography in Australia',
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Understanding the biogeography of Australia requires knowledge of both existing and former environments. The existing environment is discussed elsewhere in the volume but a few salient points should be reiterated. Three-quarters of Australia is either arid or semi-arid and even much of the better-watered fringes has long dry seasons. Vast stretches of ocean separate it from other land masses except in the north where New Guinea and Indonesia form "stepping stones" to and from Asia. It is also a low continent with over 99.5% of its area below 1000 m; even the highest summits barely exceed 2000 m. Since most of the surface has undergone prolonged weathering, poor soils are the rule.

The impact of man on the landscape has been less than in more densely settled continents. Aboriginal man has inhabited the continent for 40 000 years or more but agriculture and stock rearing have operated for less than two centuries and the present rural populations is sparse. Large parts of the dry interior are not occupied although they are affected to some extent by introduced feral animals.

We have attempted to consider both climatic and non-climatic aspects of the Late Cainozoic environments and to point out evidence that could relate to Australian biogeography. We have chosen the beginning of the Miocene, some 22 000 000 years ago, as the approximate starting point for this review because during that epoch a number of features of the present environment had their origin: continental ice started to form in Antarctica, grasses became common in the Australian fossil record and the marsupial fauna became well established. By then the deeply weathered landscape so typical of Australia was widely developed and a land mass was beginning to appear in the area of New Guinea.

The biogeography of Australia reflects the influence of many factors in addition to those of the present environment. Continental drift, tectonism and sea level change hindered or favoured migrations and interacted with climate to affect the biota. During the Late Cainozoic volcanism, marine and continental sedimentation and deep weathering have affected the lithology and hence the edaphic conditions and the flora. The varied climates of the Late Cainozoic have also profoundly influenced the distribution of plants and animals and presumably, over the long term, their evolution.

The sections on climate of the Miocene and Pliocene were written by Kemp*; Galloway wrote the remainder. For reasons of space only selected references can be given.

Continental Drift

Australia separated from New Zealand in the Late Cretaceous and from Antarctica at the end of the Paleocene (Veevers & McElhinny 1976). By the Early Miocene it lay far from these land masses and an extensive sea separated it from an island arc forming proto New Guinea. Continued northward movement in the Late Cainozoic effectively closed this gap and associated earth movements elevated the New Guinea Highlands. By the Pliocene interconnections with Asia were readily possible.

Tectonism

During the Late Cainozoic, and earlier, moderate uplift occurred in the broad highland belt which parallels the east coast but no high mountains were created and relief in the Late Cainozoic was never substantially greater than it is now. In South Australia there was sharp uplift in the Flinders and Mount Lofty Ranges and broad warping which combined with desiccation to isolate the Lake Eyre region from the sea. Broad-scale earth movements were also associated with marine incursions on the southern, northwestern and northeastern fringes of the continent.

Because of the absence of high mountains throughout this period sites for species living at and above the tree line must often have been very restricted. The tree line today reaches to within 300 m of the highest summits and consequently during Pleistocene intervals even moderately warmer than the present the alpine zone was repeatedly extinguished. At such times individual species must have survived very precariously in limited refugia such as rocky stream banks where even today alpine flora extends to comparatively low altitudes. Complete alpine communities probably did not survive such warmer intervals.

Volcanism

Cainozoic volcanism extended through eastern Australia from Cape York Peninsula to Tasmania (e.g. Wellman & McDougall 1974). It was still widespread in the Miocene but in the Pliocene and Pleistocene it

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was restricted to northeastern Queensland and western Victoria where the last ash fall occurred as recently as 1400 years ago. The rocks are predominantly basalt flows but scoria and lava cones, maars and ash falls are features of the latest events. The volcanism occurred in relatively restricted areas and in brief spasms separated by long intervals of quiescence and would not per se have seriously affected the biology of Australia. Perhaps raw, unweathered rock surfaces were sufficiently common to favour the development of pioneer species.

Indirectly, however, volcanism has significantly affected edaphic conditions and vegetation by providing substantial islands with favourable soil water conditions or relatively high nutrient status in a generally dry and infertile continent. In the warm, seasonally wet climate of the Atherton Tableland in northeastern Queensland red krasnozems on basalt provide readily available soil water and support more mesic vetatation than do soils on adjacent non-volcanic rocks. Similar soils are sandwiched between basalt flows at least as far south as the Hunter Valley in eastern New South Wales and their presence suggests that the long meridional chain of basalt outcrops in eastern Australia could have acted as a pathway for the spread of moisture-loving species.

On the other hand, basalt today is also associated with dark, cracking clay soils with generally good nutrient status and water retention but relatively low water availability. These soils are associated with grassland even if rainfall is adequate to support trees on other rocks.

Weathering

By the Middle Miocene Australia was a vast lowland covered by a deep weathered regolith. Deep weathering seems to have continued in places into the later Cainozoic (e.g. Gill 1971). It tended to create edaphic uniformity especially as it was often associated with poorly sorted detrital deposits over wide areas in northern and central Australia. However, quartz sandstone was hardly affected by deep weathering while soils on basalt seem to have retained some individuality and other volcanics proved surprisingly resistant. Relatively unweathered rock would have been confined to young basalt flows, areas of recent marine sedimentation, uplands on resistant rocks and limited areas of active dissection.

In the later Cainozoic the deep weathered regolith was extensively dissected especially in the eastern highlands, round the continental margin and in the Lake Eyre basin. This dissection greatly increased the edaphic diversity by exposing different horizons of the deep weathered profile or by removing it entirely to expose the varied underlying rocks. Where the weathered profile was only partially removed by later erosion present day soils and vegetation show a high degree of correlation with the various horizons exposed (Gunn 1974).

Marine Sediments

In the Miocene and Pliocene Epochs shales, marls, sandstones and limestones were deposited on the margin of the continent, notably in Victoria, in the Eucla Basin and in the northwest. These deposits increased the lithological diversity of the continent, particularly with respect to calcareous rocks. The Miocene limestones of the Eucla Basin, together with the Quaternary Roe Calcarenite on its seaward margin, with their shallow calcareous soils or stony residual loams interposed an edaphic barrier which accentuated the effects of aridity in isolating the southwest from the east of the continent.

Continental Sediments

As Fig. 1 demonstrates longitudinal dunes and sand sheets cover immense areas of Australia from latitude 15½°S near the Gulf of Carpentaria to 36½°S in Victoria with a possible extension to 41½°S in northeast Tasmania (Bowden & Colhoun pers. comm.). In the Simpson Desert which occupies the dry core of the continent semi-active dune movement continues today but in general the system is stabilized. The last period of widespread dune evolution seems to have coincided with the last glaciation (Bowler & Polach 1971; Jennings 1975; Bourne, Twidale & Smith 1974). Besides furnishing invaluable evidence for Pleistocene climates as discussed below, the sands form possibly the largest single edaphic entity of the continent and one which has existed for at least 300 000 years (Bowler 1976a). The existence of sand-dominated landscapes through such a great range of latitudes and in a variety of modern and presumably also former climates must have favoured the development and spread of psammophytes. The sand reinforced the effect of aridity in separating the northern and southern margins of the continent particularly in Western Australia where the dunes and semi-arid belt extend to the northwest coast. Many plants have disjunct distributions separated by the sand desert (Randall & Symon 1977).

On the other hand, by blocking the low gradient valleys of the interior, the sand helped to provide sites for innumerable lakes and lagoons ranging from freshwater to highly saline. During wet groups of years such as the early 1970s and also during moist phases of the Quaternary these water bodies created pathways for movement of water-demanding species into and across the arid zone.

Other types of terrestrial deposition have also profoundly affected plant distribution. An outstanding example occurs in south-eastern Queensland where Late Cainozoic depositional clays derived from older, deeply weathered, shaly rocks cover tens of thousands of square kilometers. Before clearing for agriculture the clays were closely associated with relatively uniform low forest communities dominated by brigalow (*Acacia harpophylla*) and gidgee (*A. cambagei*) (e.g. Pedley 1967).

Alluvial Deposits

Alluvial tracts along rivers provided routes for species associated with gallery forest, swamps, permanent water and better soils. The Darling River would have been particularly significant in this connection. However source-bordering dunes along the channels imply that moist conditions were not continuously present in the Late Quaternary. There are no comparable major north-south alluvial tracts in Western Australia where inland drainage lines appear to have been virtually dry since the mid Miocene further accentuating the isolation of the southwest corner. During low sea level phases links would also have existed between the river systems and alluvial terrains of Victoria and Tasmania and between northern Australia and New Guinea.

Coastal Dunes

Almost one-third of the coast of Australia is fringed by sand dunes. Along the southern, western and northwestern coasts the sand is dominantly calcareous and all but the youngest dunes are consolidated into limestone or at least have resistant aeolianite crusts. The resulting resistance to erosion has enabled extensive relics of coastal dunes to survive from Middle and even Early Pleistocene times. In the higher rainfall region of southwestern Australia the aeolianite is often capped by residual quartz sand bearing distinctive soils and vegetation.

By contrast, the sand on both eastern and northern coasts is dominantly quartz. Very little of the quartz sand predates the Last Interglacial and most is Holocene. It is a reasonable presumption, however, that similar dunes existed in the Middle and Early Pleistocene but were subsequently destroyed by erosion.

Stabilized dune cordons are found both below and above present sea level and indicate that coastal dune formation was active throughout the Quaternary. The coastal sandy belt was also wider during glacial regressions when the continental shelf was exposed. e.g. Pre-Holocene dunes on Fraser Island (Ward 1977) and King Island (Sutherland & Kershaw 1971) are but the surviving landward fringes of more extensive sand deposits now drowned and eroded by the sea. Ample corridors for coastwise movement of psammophilous biota must have existed throughout the Pleistocene.

Sea Levels

Sea level fluctuated repeatedly during the Pleistocene through a range exceeding 200 m in response to the growth and decay of continental ice sheets. Pleistocene sea levels from as low as -200 m up to +43 m and even higher have been reported (Jongsma 1970; Lawrence et al. 1976). The higher sea levels can have been but brief episodes otherwise associated deposits would be far more widespread on continental lowlands. Furthermore, there is evidence that sea levels were also low in relation to the continent for substantial periods in the Late Tertiary (Galloway 1970). It has been the rule rather than the exception for Australia, New Guinea and Tasmania to form one land mass during the last few million years.

The much discussed last opening of the Torres and Bass Straits during the Flandrian transgression was but the most recent of at least eight and probably many more such events. Torres Strait in particular with a sill depth of 9-18 m must have repeatedly opened and closed. The last opening happened between 6500 and 8000 years ago. Biological contrasts between the adjacent land masses reflect contrasts in their physical geographies rather than the intermittent presence of a seaway. To reach New Guinea from Asia even during glacio-eustatic regressions man must have crossed straits of the order of 50 to 100 km wide. Consequently he was not restricted to making the further progression to

Australia during a glacial low sea level period. It is interesting to note, however, that the practise of horticulture never crossed Torres Strait from New Guinea to Australia.

Bass Strait originated as far back as the Miocene. It is wider, deeper and stormier than Torres Strait and has presumably been a more effective barrier. It would have been open for thousands of years longer than Torres Strait during each glaciation and it may not have closed during many interstadials. The last severing of the land bridge took place c. 12 000 - 13 500 years ago. Dunes developed on the exposed floor of Bass Strait during the last glaciation and the resulting sandy surface would have restricted migration of many species while major contrasts between the environments of Tasmania and Victoria would also have helped to preserve differences between their biota. There is good archaeological evidence (Bowdler 1974) that man entered Tasmania during the last glacial low sea level and was isolated there by the ensuing transgression.

Lowered sea level during glacial times could also have affected the role of the Nullarbor as a barrier between the southwest and the east of Australia. A 200 km-wide belt of different (sandier?) soils would have been exposed on what is now the continental shelf.

The last glacio-eustatic transgression - and presumably its numerous predecessors - was very rapid and consequently imposed severe stresses on coastal species. At times during the Flandrian transgression the annual rate could well have exceeded 25 mm causing shoreline shifts of 10-30 m on typical continental shelves. In these circumstances mangroves would have had difficulty in surviving especially south of the latitude of Brisbane where the small tidal range of 1 m or less would not have effectively buffered the effect of rapid changes in sea level. Likewise, coral colonies could have been severely stressed by the rapidly changing water depth quite apart from possible effects of changing sea temperatures; drowned coral reefs are known from the Timor Sea. Many, if not all, of the existing reefs of the Great Barrier Reef have formed during the last few millenia by colonisation on dissected stumps of last interglacial or older reefs (Davies & Kinsey 1977).

The first coastal sediments laid down when the sea attained its present level in the Holocene some 6000 years ago were generally sand beaches and bars but with the switch from rapidly changing to near-constant sea level there was s significant expansion of coastal features characteristic of stable or accreting coasts such as swamps, mud flats, sand ridge plains and lagoons together with their associated biota. During the preceding Flandrian transgression when the shoreline was migrating rapidly and possibly during maximum glacio-eustatic regressions when the shore may have been situated on the steep continental slope beyond the shelf such coastal features may have been less widespread than they are now.

Biogeography and Palaeoclimates

Climate is the most significant environmental factor for biogeography. Not only does it largely determine the biota present and possibilities for change but it operates universally and can vary rapidly in time and space. Because of the rapid changes apparent from the Quaternary record accurate chronology is essential when seeking to correlate events in different areas. It is now apparent that Quaternary climate changes were as rapid and profound in Australia as they were in the better-known continents of the northern hemisphere. While there is general agreement that Tertiary climates were more stable this opinion may be a consequence of the scanty evidence and future research may change our ideas. Indeed there are strong indications from deep sea cores south of Australia, as discussed below, that Late Miocene and Pliocene sea surface temperatures were highly variable.

Palaeoclimatic reconstructions are extensively based on biological evidence (e.g. pollen) and there is some risk of circular reasoning when using the conclusions to analyse the effects of past climates on biology. Many uncertainties exist even with respect to the relatively well known Late Quaternary and for preceding intervals we can rarely go further than such general statements as "warm and wet" or "cool and dry".

While Australia has of course been subject to such global climatic controls as solar radiation and the position of the major pressure belts, regional factors have also influenced the climate. The topographic factor has been nearly constant throughout the period considered here though there may well have been a modest rain shadow effect related to the rise of the eastern highlands. Northward drift of the Australian plate in the Cainozoic carried it through different latitudinal and climatic zones while the climates were themselves changing. The presence or absence of ice in Antarctica presumably affected the climate although there are indications from glacial and periglacial evidence that the effect was not great in the Pleistocene (Galloway et al. 1972).

Glacio-eustatic sea level changes were both effects and causes of climatic changes. With low sea levels the vast continental shelf to the north (1 000 000 km^2) would be exposed and Torres Strait blocked. The reduced evaporation from the dry surface plus the changed oceanic circulation would have drastically reduced the precipitable water content of tropical air masses in the region (Webster & Streten 1972; Nix & Kalma 1972). The shelf is so flat that modest changes in sea level would switch most of it from dry land to sea and vice versa with major implications for the climate. A fall in sea level effectively shifts points on the present coast from a maritime to a continental situation and so could induce changes in the biota as Martin (1973a) has pointed out with respect to the Eucla area on the Great Australian Bight.

Climates in the Miocene

Miocene climates in Australia must have evolved in response to such external factors as the continued northward motion of the continent, the changing surface temperatures of the surrounding seas, and the development of the Antarctic icecap during the epoch. Data outlining changes in all of these external conditions are available from the record of marine sediments close to Australia and Antarctica, but detailed evidence for the climates of the Australian continent itself is sparse.

In the Early Miocene, the south coast of Australia lay in latitudes ranging from about 42°S to 50°S, and only the northernmost edge of the continent extended north of 20°S. Palaeomagnetic properties of Early Miocene basalts on the South Tasman Rise suggest that these were magnetised at about 52°S (McKenzie, quoted in Shackleton & Kennett 1975a).

Sea-surface temperatures determined for oceanic sites to the southeast of Australia show that the Early Miocene seas were warm in relation both to the preceding Oligocene and to present-day temperatures. Oxygen-isotope analyses from Tasman Sea sites indicate sea-surface temperatures of approximately 10°C for the Early Miocene (Fig. 2) at sites which then lay close to 55°S. Shallow shelf waters of the southern

Australian coast experienced temperatures which could be described as subtropical (15-20°C), on the evidence provided by isotopic data from Victoria (Dorman 1966), and by foraminiferal faunas from Tasmania (Quilty 1972). Renewed, or continued, warmth in the early part of the Middle Miocene is evident from both the open-ocean isotopic curve and from foraminiferal faunas in Tasmania, the St. Vincent, Murray and Eucla Basins in South Australia (Lindsay 1976), and from the Perth Basin (Quilty 1974a). For the Batesfordian (early Middle Miocene) of Tasmania, Quilty has estimated water temperatures in the range of 22 - 27°C.

At some time in the Middle Miocene temperatures fell and the isotopic composition of sea water underwent a pronounced change in response to the rapid accumulation of ice on Antarctica. This temperature history suggests that atmospheric and oceanic circulation patterns may have been sluggish in the early, essentially pre-icecap phase of the Miocene, but achieved something close to their present intensity in the latter half of the epoch. Both palaeogeographic and palaeotemperature considerations point to Australia having lain in a latitudinal zone dominated by westerly wind systems throughout the Miocene - for the Late Miocene at least these should have been of a strength comparable to those of today.

A minor rise in sea-surface temperatures in the Late Miocene (Fig. 2) is believed to have occurred without modification of the Antarctic icecap. A dramatic temperature drop in the latest Miocene, accompanied by major expansion of the Antarctic ice-sheet, is documented from a number of sources. There can be little doubt that this event influenced Australian climates, probably in the direction of an increase in the frequency of dry, anticyclonic circulation.

The Miocene, particularly the early part of it, is also characterized by extensive transgression of shallow seas over the southern margins of Australia. The interval was marked by maximum transgression in the Eucla, Murray and Otway Basins. There is little direct evidence of the climatic impact of these shallow seas, but at least local effects on precipitation levels seem likely. Lindsay (1976) has commented on the apparent correlation of warm, transgressive seas in the Middle Miocene with lacustrine strata probably deposited under high humidity regimes in the Lake Eyre and Lake Frome regions.

Evidence for wet, and perhaps relatively warm climates over much of Australia during the first half of the Miocene comes from palaeontological sources, and from the evidence for widespread deep-weathering. Dating of much of the evidence, however, remains uncertain. Palaeobotanical data were recently reviewed by Kemp (in press). Localities which have yielded such data are largely concentrated in the southeast of the continent, although new data recently have become available from central South Australia and from the southern part of the Northern Territory. No reliably dated Miocene palaeobotanical information has been published from Western Australia.

Although some of the major floristic elements of Australian open forests, such as Acacia, Casuarina, Gramineae, and perhaps Chenopodiaceae, were established in the fossil record by the Early Miocene, present knowledge indicates that rainforest communities were the dominant vegetation type, at least in much of southeastern Australia. Forests with a high proportion of Nothofagus of the brassi species group, and with abundant gymnosperms and broadleaf Lauraceae and Myrtaceae, extended from Tasmania, through the Gippsland Basin of Victoria, westward to coastal South Australia, and north through western New South Wales and the Southern Tablelands, reaching as far as coastal Queensland. The wide distribution of Nothofagus brassi pollen in the Miocene suggests very high precipitation levels; present requirements of the group are in the vicinity of 1500-1800 mm per year, and Miocene rainfall may have been of this order.

Away from this very broad coastal belt, there were at least localised developments of rainforest, according to palynological data, in regions close to Alice Springs, and in the Lake Eyre and Lake Frome drainage basins in central South Australia, suggesting deep inland penetration by rain-bearing winds. These inland deposits, which are dated as approximately Middle Miocene by palynological correlations with marine sediments, include lignites several metres thick at Ti Tree, north of Alice Springs, and carbonaceous clays in the Etadunna and Namba Formations in the Lake Eyre and Lake Frome regions. The pollen spectra from these lithological units differ from contemporaneous ones of the coastal belt in that they contain, for the first time in the Australian record, grass pollen in some abundance. High frequencies of Nothofagus brassi (around 35%) and podocarpaceous pollen are also present. These assemblages have been interpreted as reflecting the development of grasslands in the interfluvial areas which separated gallery forests growing along permanent watercourses. The suggested grassland development implies that precipitation may have been strongly seasonal, or at least periodic. Abundant remains of arboreal diprotodont marsupials in the Namba Formation, above the dated palynological horizon, supports rainforest development, and the presence of aquatic vertebrates - ray-finned fish, lungfish and chelid turtles - suggests permanent water (Tedford et al. 1977). The remains of river-dwelling platanistid porpoises provides evidence that connections to the sea were maintained at least periodically, probably southwards to the Murray Basin.

The picture of seasonally distributed rainfall which is invoked by the presence of grasslands is reinforced by the mineralogy of Namba Formation sediments. Dolomite and limy dolomite beds occur a few metres above the pollen-bearing horizon. These, according to Callen & Tedford (1976 p.140) are best explained 'in terms of protracted arid phases superimposed on a sub-tropical or warm-temperate climate'. Palaeogeographic and palaeoclimatic information suggest that the southern half of Australia would have lain under the influence of westerly wind systems at this time, although the intensity and regularity of these remains uncertain, particularly in the Early Miocene. Seasonal, or perhaps less regular shifts in the position of this westerly belt might explain the periodic aridity at the inland sites.

Generally wet conditions, perhaps with seasonal variations in precipitation, are further reflected in the widespread evidence for mid-Cainozoic deep weathering. A greater precision in the dating of iron-enriched weathered profiles has recently been achieved by comparing palaeomagnetic pole positions derived from them with the apparent Cainozoic polar wander curve for Australia. Application of this technique reveals two clusters of ages for weathered profiles; the older of these suggests intense weathering in the Paleocene and Eocene; the younger suggests another important weathering phase in the Late Oligocene to Early Miocene interval. In the Eromanga Basin in southwestern Queensland, the Canaway Profile, which is the younger of two weathered profiles identified there, has been dated as 30 m.y. ± 15 m.y. (Idnurm & Senior in press). Widespread lateritisation in the Perth Basin has been established as 20-25 m.y. old (Schmidt & Embleton 1976); similar ages have been obtained for weathering in the Ord Basin of the Northern Territory (Luck, in Schmidt & Embleton 1976), and in the Springfield Basin near the Flinders Ranges in South Australia (Schmidt, Currey & Ollier 1976). In the Barossa area of South Australia, laterite formation is now thought on largely stratigraphic grounds (Alley 1977) to have persisted from pre-Eocene to Miocene times.

Off the west coast, widespread sandstone deposits of Middle Miocene age on the Northwest Shelf have been attributed to the intense flow of Carnarvon Basin rivers during that interval (Quilty 1974b). The reconstruction of ancient drainage patterns offers further information concerning climates in the Tertiary, but most of the available data point to stream erosion being most active on the ancient shield areas in the Early Tertiary and dwindling progressively thereafter. The reduction in erosional activity after about the end of the Eocene may have been due to both topographic and climatic factors. Peneplanation may have been achieved during the Early Tertiary so that later wet intervals, such as that of the Early and Middle Miocene, did not result in major channel development. In the Nullarbor Plain area, incised channels flowing towards the southeast were probably cut during the Early Tertiary; their possible southward extension is covered by the deposits of the Miocene sea. Channel development on the uplifted Miocene surface is minor, although Lowry & Jennings (1974) consider that the post-Middle Miocene erosion reflects somewhat higher precipitation levels than at present.

The rapid development of the Antarctic icecap in the Middle Miocene is shown by the change in the isotopic composition of sea water. Shallowing and retreat of the seas from most of the southern coastal basins also occurred from some time in the Middle Miocene, and can probably be associated with glacio-eustatic regression. The cooling of surface waters of the seas surrounding Australia would have led to a precipitation decrease, but evidence to support this is sparse. Most data come from the southeast, which is likely to have remained wetter for longer than inland areas. There is some palaeobotanical evidence for increasing aridity in western New South Wales, where Martin (in press) has noted that the deposition of carbonaceous clays in the Murray Basin ceased in the Middle Miocene. Pollen of Nothofagus decreases in the region at about the same time. This apparent precipitation decrease appears to have occurred earlier in the Murray Basin than in the Gippsland Basin area, where coal deposition continued through the Miocene, and Nothofagus (especially the brassi type) did not show a marked decline in abundance until the Late Miocene. Dryness in western New South Wales may have been increased by uplift of the eastern highlands from as early as the Middle Miocene.

Climatic events associated with sudden chilling of the Southern Ocean in the latest Miocene may also be expressed in the fossil record, although precise interpretation is hampered by poor dating. In borehole sequences at Hay and Narrandera in western New South Wales the disappearance of Nothofagus brassi pollen forms a pronounced datum (Martin 1973b), and it has been argued that this disappearance occurred in response to an abrupt precipitation decrease. Such an event may have been the result of sudden lowering of sea-surface temperatures. The disappearance of this rainforest type from the region apparently occurred in the latest Miocene but age control of the event remains poor. That the event was comparatively shortlived is evidenced by reappearance of some of the associated rainforest species in the Pliocene.

Climates in the Pliocene

For the Pliocene, climatic data from the Australian continent are even more sparse than for the Miocene, and the picture of the Australian environment remains extremely sketchy. This contrasts with the quantity of data which is available from deep-sea localities to the southeast and south of Australia which provide evidence of rapidly fluctuating sea-surface temperatures throughout the epoch. The marine data provide some grounds for speculation concerning widespread climatic changes but the lack of continental data makes interpretation of the effects of these changes on the Australian landmass almost impossible.

Fluctuations in Southern Ocean and Tasman Sea temperatures during the Pliocene have been documented from a number of sources, and have been summarised by Frakes (in press). Isotopic data relating to sea-surface temperatures have been presented by Shackleton & Kennett (1975b), and climatic data relating to foraminiferal population statistics by Kennett & Vella (1975). From these sources, it is apparent that the severe cooling event of the latest Miocene was followed by a marked warming of the Early Pliocene seas - the warming phase has been dated as spanning the interval 3.9 to 4.3 m.y. B.P. It may have been severe enough to cause melting of part of the West Antarctic ice sheet. Renewed cooling followed and subsequent fluctuations in sea-surface temperatures through the Late Pliocene and Pleistocene were rapid. Changes in isotopic composition and in the marine faunal record in the Late Pliocene about 2.6 m.y. ago mark the relatively rapid accumulation of ice-sheets in the northern hemisphere. Shackleton & Kennett (1975b) note that the latest Pliocene appears to have been associated with northern hemisphere ice-sheets which were about one-third to one-half their maximum Pleistocene volume.

The repercussions of these widespread changes in sea-surface temperatures are difficult to detect on the Australian continent. The period of markedly warm seas in the Early Pliocene is likely to have been associated with high precipitation, and it may be that the documented reappearance of rainforest in western New South Wales reflects this. Martin (1973b) speculated that the early rainforests may have retreated to highland refuge areas during the relative aridity of the Late Miocene, to expand again (without Nothofagus brassi) at an undetermined date later in the Pliocene. These later Pliocene floras suggest that a clear east-west climatic gradient existed in western New South Wales comparable to that of the present day (Martin, manuscript).

Faunas of wet forest aspect at Grange Burn in western Victoria (Turnbull & Lundelius 1974), which are probably early Pliocene on radiometric evidence, may be related to the same wet interval. Climatic interpretation of the associated floras, however, is ambiguous. Nothofagus pollen is present, but in low amounts; pollen of Chenopodiaceae and of Acacia and Gramineae from the Grange Burn Coquina (Harris 1971) suggest that a more open vegetation grew in the vicinity. Certainly the pollen spectrum differs from that produced by the closed rainforests of the Early Miocene. Faunas from Alcoota, in the southern part of the Northern Territory (Woodburne 1967) suggest that precipitation in that region was considerably greater at the time of their deposition than at present. An abundance of crocodiles in the fauna suggests a permanent water body, and the presence of a small macropodid, Dorcopsoides, whose closest relatives now live in New Guinea forests, suggests that the lake margin supported a fairly luxuriant vegetation. Dating of the deposit is uncertain, however, and has been given broadly as Late Miocene-Early Pliocene.

Weathered and lateritised surfaces to which Pliocene ages can be reasonably firmly assigned are confined to the southeast. The Dundas Surface of western Victoria which is capped by laterite is dated as 'post-Early Pliocene to about mid-Pliocene' by Jenkin (1976 p.333). Gill (1971) noted that deep weathering, or incipient lateritisation, had affected Late Pliocene basalt in the same region. He visualised the existence of conditions suitable for deep weathering in the Early Pliocene, and probably also in the middle part of that epoch, then diminishing in the later part of the Pliocene. This accords with the picture of a progressive cooling and drying following relatively warm and moist conditions in the early part of the Pliocene. Ferruginisation in the Karumba Basin of the Gulf of Carpentaria has been equated in time with the Victorian weathering (Doutch 1976) but dating remains problematical. There is also meagre evidence for a weathering period of Pliocene age in the Eromanga Basin of southwestern Queensland, suggesting high seasonal precipitation in this inland area, but the age of this occurrence is less reliable than for the coastal regions.

Climatic information specifically referable to the Late Pliocene appears to be more sparse than for any other Cainozoic interval in Australia. The very lack of data may itself reflect increasing desiccation; opportunities for the preservation of fossil remains are rare in arid environments, so that the fossil record contains an inevitable bias in favour of the wetter phases of the past. Deep weathering is also limited in drier times. The severe global cooling which occurred at the time of inception of the northern hemisphere ice-sheets would have been reflected in a widespread precipitation decrease. Bowler (1976a) has stressed that the trend towards aridity began as early as the Middle Miocene. Wetter oscillations, such as that of the Early Pliocene, were mere interruptions to this general trend.

From the Middle Miocene to the present Australian faunas and floras adapted or migrated in response to this general increase in dryness and it seems likely that the Pliocene was an important phase of change. A major vegetation change probably occurred during the epoch, involving transition from the widespread rainforest cover of the Early Tertiary to the predominantly xerophytic communities of the present day. The older rainforests, dominated by Nothofagus and by gymnosperms, were replaced during the Pliocene by a vegetation dominated by such genera as Eucalyptus and Casuarina, and in which grasses and Compositae were of increased importance. The transition started when Australia was furthest removed from other continents and hence it seems likely that immigration of species from elsewhere would have been minimal during this period of relatively rapid environmental change.

The chronology of the transition is poorly documented, and times and rates of change no doubt varied from region to region. The persistence of 'subtropical' taxa through much of the Pliocene in southern coastal regions such as the Gippsland Basin has been observed (Partridge 1976), suggesting that in these areas at least, climates wetter and perhaps warmer than at present persisted until the first Pleistocene cool interval. Sediments of Late Pliocene age from offshore Queensland contain high frequencies of Compositae and of chenopodiaceous pollen (Hekel 1972), suggesting that the source area of these sediments may have supported an open savannah vegetation (Martin, manuscript).

Evidence from the composition of fossil faunas reinforces the suggestion of a change to a drier, more open type of vegetation cover from the Miocene to the Pliocene. Archer (this volume) has summarised faunal data relating to the transition from widespread rainforest habitats to more open, savannah environments; the browsing kangaroo Prionotemnus palankarinnicus from the Mampuwordu Sands of the Lake Eyre Basin provides some evidence for savannah woodlands in central Australia during the Pliocene. The relative abundance of grazing and browsing macropodids in probable Late Pliocene deposits of the Darling Downs in south-eastern Queensland is additional indirect evidence for open sclerophyll and grassland vegetation in that interval (Bartholomai 1973).

Climates of the Early and Middle Pleistocene

During this interval Australia was certainly affected by world-wide changes in sea level and climate. However there is a dearth of palaeoclimatic evidence even from the better-known stratigraphic record of the southeast and dating is most inadequate. Sea bed cores should provide valuable additional evidence in the not too distant future.

The climate seems to have been dominantly dry and there is little reason to believe that Australia as a whole experienced high rainfall for significant periods. Lacustrine, fluvial and aeolian sediments in the Lower Murray Valley record an irregular trend from humid to generally dry conditions (Gill 1973). Aeolianite barrier systems in Victoria, South Australia and Western Australia together with the palaeosols preserved therein imply interglacial climates not vastly different from those of the present though slightly wetter at times and show that strong winds have been a persistent feature of the coastal zone. Inland, sand deposits in western Victoria and New South Wales and presumably in other parts of the continent were last mobile in the Late Pleistocene but had originated much earlier. Bowler (1976a) stresses the correlations between world glacial maxima and episodes of continental dune formation and concludes that the continental dune system originated at least 300 000 years ago. The paucity of karstic or fluvial features on the Nullarbor demonstrates that the Late Tertiary dryness of this region continued into the Pleistocene (Lowry & Jennings 1974). Jessup & Wright (1971) find evidence in semi-arid South Australia for alternating periods of wind action and soil formation well back into the Pleistocene.

Evidence is likewise sparse with respect to temperature during this interval. There was glaciation during at least three widely-separated intervals in Tasmania (Colhoun 1976) implying cold phases. Corals from near Newcastle, New South Wales (Marshall & Thom 1976) and the Roe Calcarenite on the northern shore of the Great Australian Bight indicate rather warm seas during interglacials. By analogy with modern sea temperature/rainfall relationships these interglacials would have been relatively moist.

Late Pleistocene and Holocene Climates

The reconstructed Late Pleistocene and Holocene climates can be regarded as models for the numerous comparable climatic events during the last two million years. Although far more information is available than for earlier periods there are many contradictions and uncertainties and reasonably adequate dated evidence is available only for the southeast and for northeastern Queensland. Furthermore it should not be forgotten that the period reviewed in this section occupied but one fiftieth of the Quaternary Period and one five hundredth of the total interval we are considering. Its significance for evolution should not be over-emphasised though it certainly has profoundly affected the present biogeography.

Most of the following account is drawn from the comprehensive review by Bowler *et al.* (1976) and references cited therein; a few additional references are mentioned here. A recent review of modern and Pleistocene climate changes in the Australian context has also proved useful (Anon. 1976).

PRE 40 000 B.P.

Studies in northeastern Queensland, Lake George near Canberra and the Willandra Lakes in southwestern New South Wales all point to drier and probably cooler conditions than at present. Recent unpublished work by Kershaw has extended his published palynological studies from Lynch's Crater in northeast Queensland (Kershaw 1976) back to *c*. 123 000 years ago. From *c*. 123 000 to *c*. 80 000 B.P. there was tropical rainforest with precipitation at least as high as it is today. From 80 000 to *c*. 38 000 there was moist Araucarian forest with annual precipitation about half its present value of 2500 mm.

There is no satisfactory evidence for glaciers or periglacial features on the mountains of the southeast during this interval but they were present in Tasmania.

c. 40 000 - 30 000 B.P.

Conditions became drier and cooler in northeast Queensland whereas in southeastern Australia both rising lake levels and pollen data reflect increasing humidity. This contrast suggests a northward are considering. Its significance for evolution should not be overemphasised though it certainly has profoundly affected the present biogeography.

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c. 40 000 - 30 000 B.P.

Conditions became drier and cooler in northeast Queensland whereas in southeastern Australia both rising lake levels and pollen data reflect increasing humidity. This contrast suggests a northward ively warm water in the Willandra Lakes of western New South Wales (Allen, quoted by Bowler 1976b). Furthermore there are persistent indications of comparatively high sea levels around this time which would required substantial global warmth to melt the ice sheets (Thom 1973). A fairly mild interstadial of "Mediterranean" climate in southeastern Australia with wet winters and dry summers might account for the high lake levels, the soil development and the small glaciers in the Snowy Mountains but would require a non-periglacial explanation for the slope mantles on the highlands and cannot readily be reconciled with extensive continental dune formation. Perhaps the evidence really relates to a variety of successive climates during this relatively brief period.

c. 26 000 - 16 000 B.P.

This interval was very dry in northeast Queensland with maximum exposure of the continental shelf. Eucalyptus and Casuarina dominated the vegetation at Lynch's Crater.

In the southeast and the southwest closed lakes fell though with some oscillations and clay lunettes (crescent-shaped dunes composed of clay aggregates blown from adjacent seasonally dry lake beds) accumulated on their lee shores. The increasing aridity culminated between 16 000 and 17 500 years ago when lakes dried completely, the continental dunes were active for the last time and lunette development was completed. This is also a likely time for renewed evolution of continental dunes in the west and northwest fringe of the continent (Wyrwoll & Milton 1976). According to limited ^{14}C evidence, glaciers in the Snowy Mountains were not as extensive during this interval as they had been at some earlier Late Pleistocene advance whereas in both Tasmania and New Guinea they advanced to their Late Pleistocene maximum in common with most glaciers around the world. Slope instability continued to low altitudes in southeastern Australia and if due to periglacial processes it points to continued low temperatures - a conclusion supported by pollen analysis of sediments at Lake George.

A cold dry climate with strong winds and high summer radiation could account for the evidence. Clay lunettes, which require seasonal wetting and drying of lacustrine clay surfaces to produce clay pellets moveable by the wind, would have formed in spring or summer as the water table fell. The orientation of lunettes and of continental dunes in the southeast follows the dominant direction of modern spring winds which are the strongest of the year. In northwest Australia the longitudinal dunes are likewise parallel to the modern strongest winds - in this case winter ones - suggesting that pressure systems lay near their present position. High summer radiation would dissipate the minor glaciation in the Snowy Mountains despite low temperatures whereas in the cloudier climates of Tasmania and New Guinea ice could continue to accumulate. Central Patagonia with a windy climate and active lunette development offers a modern homoclime for late-glacial southeastern Australia.

An alternative hypothesis (Bowler 1975) proposes west to northwest winds bringing dry warm continental air to the southeast in summer and causing lunette development beside lowland lakes and glacier retreat in the mountains at a time when ice sheets in the northern hemisphere were still expanding. The combined effects of aridity and continuing cold winters would ensure absence of dense vegetation and hence active mass movement on slopes with provision of coarse material to streams. The hypothesis implies that the subtropical high pressure belt lay well north of its present position which could agree with the dry conditions in northeast Queensland.

<u>c</u>. 16 000 - 10 000 B.P.

Dry conditions continued in northern Queensland while rising treelines and retreating glaciers in New Guinea and Tasmania prove a significant warming trend. In the southeast conditions likewise generally remained dry except for a brief rise in some closed lakes around 14 000-15 000 B.P. but there was an increase in herbaceous cover and stabilisation of dunes pointing to some increase in precipitation as temperatures rose. Unpublished pollen analysis of lake sediments at about 1800 m above sea level in the Snowy Mountains by J.I. Raine shows that the essentially bare ground of the preceding interval was colonised first by short alpine herbfield and then by tall herbfield and bog communities indicating a reduction in snow cover but not in humidity. Peat began to accumulate after 15 000 B.P. in sheltered hollows previously occupied by permanent snow patches.

There is no evidence (yet?) for a sharp climatic oscillation about 10-11 000 years ago corresponding to the Allerød-Younger Dryas events so clearly marked in the pollen record of northwestern Europe. The Allerød oscillations has not been detected in Morrocco and Spain which lie in latitudes corresponding to southeastern Australia.

c. 10 000 B.P. - PRESENT

This interval opened with a rise in temperature and precipitation. Closed lakes in the south attained a high level at various dates between 9000 and 5000 B.P. and tropical rainforest returned to northeast Queensland after an absence of some 70 000 years. Temperatures are believed to have been a little higher than they are today and precipitation was substantially greater. The warm moist peak was followed by slightly drier conditions during which there was some dune development in semi-arid New South Wales, renewed mass movement at higher altitudes and a decline in closed lake levels. The last two millenia have seen only modest fluctuations of climate and conditions were essentially the same as they are today.

Discussion of Late Quaternary Climates

Clearly the major fluctuations of Quaternary climate were extremely rapid in geological terms but the imprecisions of dating and uncertainties regarding the exact climatic connotations of the evidence preclude precise estimates of the rates of change. So far there is no reason to believe that Pleistocene changes were more rapid than historic changes such as the rise of approximately 0.8°C in mean temperature of the New Zealand region since 1935 but they must have persisted for much longer.

Specific figures for temperature and precipitation are not easily assigned even to the comparatively well-known last glacial maximum around 18 000 years ago in southeastern Australia. A commonly held view is that temperatures were 5-10°C lower than at present and precipitation perhaps 50% less but claims that summer temperatures were already well above the glacial minima (Bowler 1975) and that precipitation was higher than at present in northwestern New South Wales (Dury 1973) call for serious consideration.

The capacity of Australian plants and animals to cope with substantial year-to-year vicissitudes in climate must have buffered the impact of climatic changes and reduced the apparent difference between the Middle Miocene. Wetter oscillations, such as that of the Early Pliocene, were mere interruptions to this general trend.

From the Middle Miocene to the present Australian faunas and floras adapted or migrated in response to this general increase in dryness and it seems likely that the Pliocene was an important phase of change. A major vegetation change probably occurred during the epoch, involving transition from the widespread rainforest cover of the Early Tertiary to the predominantly xerophytic communities of the present day. The older rainforests, dominated by Nothofagus and by gymnosperms, were replaced during the Pliocene by a vegetation dominated by such genera as Eucalyptus and Casuarina, and in which grasses and Compositae were of increased importance. The transition started when Australia was furthest removed from other continents and hence it seems likely that immigration of species from elsewhere would have been minimal during this period of relatively rapid environmental change.

The chronology of the transition is poorly documented, and times and rates of change no doubt varied from region to region. The persistence of 'subtropical' taxa through much of the Pliocene in southern coastal regions such as the Gippsland Basin has been observed (Partridge 1976), suggesting that in these areas at least, climates wetter and perhaps warmer than at present persisted until the first Pleistocene cool interval. Sediments of Late Pliocene age from offshore Queensland contain high frequencies of Compositae and of chenopodiaceous pollen (Hekel 1972), suggesting that the source area of these sediments may have supported an open savannah vegetation (Martin, manuscript).

Evidence from the composition of fossil faunas reinforces the suggestion of a change to a drier, more open type of vegetation cover successive periods as deduced from pollen. Furthermore, much of the best evidence obtained to date comes from localities with steep environmental gradients where quite short migrations of plant communities would radically alter the vegetation (Costin 1971). For instance barely 40 km today separates the tropical rainforest at Lynch's Crater, northeast Queensland, experiencing 2500 mm annual precipitation, from dry sclerophyll eucalypt woodland with c. 1200 mm precipitation; both types of vegetation have existed at different times round the crater (Kershaw 1976). We need pollen evidence from the heart of wide, uniform environmental regions to truly evaluate the extent of climatic changes.

Survival of distinctive biota in the relatively well-watered southwest corner of Australia with no access to extensive cooler or wetter refuges sets some limits to possible climatic changes. Obviously since the biota appeared the climate can never have been totally desertic nor wet enough to foster completely free interchange with the eastern part of the country. Individual species could probably survive climatic changes in locally favourable sites whereas communities could well have been eliminated.

The Late Pleistocene record for southern Australia resembles that for the northern Adriatic (Bortolomi, Fontes, Markgraf & Saliege 1977) and we can expect further parallels between events in Australia and the northern hemisphere to emerge as work proceeds. However, the first serious attempt to correlate Late Quaternary climates in Australia and equivalent latitudes of North Africa (Rognon & Williams 1977) has revealed parallels at some times, divergences at others and some phase lags of several millenia. From 40 000 to 20 000 B.P. southern Australia and the northern and southern margins of the Sahara generally experienced high moisture conditions but northern Australia was dry as was the Afar region of eastern Ethiopia around 30 000 years ago. Between 17 000 and 12 000 B.P. both margins of Australia and the tropical margin of the Sahara were dry while the northern Sahara was relatively wet. After c. 10 000 B.P. in the Sahara and central Africa and after c. 8000 B.P. in Australia there were extended periods of high temperature, high rainfall and high lake levels. Some of the difficulties may arise from comparing places in the two hemispheres with similar latitudes rather than with similar modern climates. For instance, the Canberra region is Spain.

While major Quaternary changes affected both hemispheres at about the same time the effects were not necessarily identical. Even the short historic record illustrates a major divergence (Salinger & Gunn 1975). The first forty years of this century saw warming in most parts of the world but cooling in New Zealand and in comparable latitudes of the southern hemisphere; subsequently these trends reversed.

Palaeoclimates in Australia must be related to the position and intensity of the subtropical anticyclonic belt but much remains to be learnt concerning the pressure movements and their causes (Rognon & Williams 1977). The grand concept of pressure, rainfall and vegetation belts sweeping north and south across the continent as world glaciers waxed and waned (e.g. Fairbridge 1962) must be abandoned while the contrasted idea of a fixed high pressure belt expanding during glacials and contracting during interglacials (Galloway 1965) now seems too simplistic. If and when an understanding of the pressure changes is achieved it could well be the basis for a new paradigm to replace the outmoded concept that "Glacial = pluvial and interglacial = arid period".

Fire

The humid climate of the Early Miocene would have inhibited fire but the succeeding long-term trend to dryness increasingly favoured it. Stresses induced by fire must have been an important factor over millions of years long before the advent of man with his fire stick in the Late Pleistocene.

It has been claimed (e.g. Merrilees 1968) that man-induced fires have been important in determining the vegetation and in particular the occurrence of grassland over significant portions of the continent. However in the light of the biophysical evidence caution is needed in evaluating man's role. He certainly increased the frequency of fires but thereby reduced their intensity through reduction of fuel just as modern control burning seeks to do. From Cape York to Tasmania clay soils on basalt and shales closely correlate with grassland even where rainfall is adequate for trees. To claim these grasslands as anthropogenic would require primitive man to carefully extinguish his fires once they had burned beyond the outcrop of these rocks! At most man's firing modestly reinforced the natural edaphic factors tending to grassland.

Similarly the tree line in the Snowy Mountains cannot be ascribed to man's activities despite his occupation of the alpine areas in summer. The Australian upper tree line follows the world-wide rule in being very close to the 10°C isotherm for the warmest month (Costin 1967) and hence is most unlikely to be a consequence of man-induced fires.

Summary and Conclusion

Throughout the past twenty-two million years in Australia tectonism has been modest and there have been no really high mountains. Most of the continent has experienced prolonged weathering giving poor and relatively uniform soils. Extensive Cainozoic basalt flows in the east, marine incursions mainly in the south and the exposure of varied and relatively fresh older rocks by erosion in the Lake Eyre Basin and the more humid parts of the continent have resulted in a greater range of edaphic conditions in these areas. Lithologic and edaphic diversity have tended to increase since the Middle Tertiary.

Sea level has fluctuated repeatedly through more than 200 metres during the Pleistocene and there is some evidence that it was also well below its present position for substantial periods in the Late Tertiary. Land links with New Guinea and Tasmania have been the rule rather than the exception over the last few million years. Torres Strait has rarely acted as a barrier to plant and animal migration; Bass Strait being wider and deeper may have been more of an obstacle. Coastal changes associated with glacio-eustatic sea level fluctuations were very rapid on the continental shelf and the approximate sea level stability during the last 6000 years and the present relatively wide zone of coastal environments may be rather exceptional. Coastal dunes in the east and north are dominantly quartzose, elsewhere they are mainly calcareous; both types provided extensive, specialised environments during the sea level changes and perhaps formed routes for migration. Extensive fields of longitudinal dunes and sand sheets in the interior, currently stable, have been evolving for at least a quarter of a million years.

During the Early Miocene the climate was wet and Nothofagus - dominated forest covered much of the continent while the surrounding seas were warm. Around the Middle Miocene the sea surface cooled and precipitation on land declined especially in the centre where grass appears in the fossil record. A sudden extra cooling of the sea surface in the latest Miocene may be associated with a period of increased dryness in the south also.

Little is known of the continental Pliocene but marine data suggest rapidly fluctuating sea surface temperatures with an overall cooling trend after a brief warm and relatively wet interval. There has been an overall trend to dryness from the Middle Miocene onwards associated with the change from dominantly rainforest to xerophytic forms; wetter phases occurred only as relatively brief interruptions.

Lower and Middle Pleistocene climates are largely unknown but presumably Australia experienced fluctuations resembling those known to have occurred elsewhere. Considerable information on conditions over the last 40 000 years has been derived from recent studies of fossil pollen, closed lake basins, dunes, and glacial or periglacial features. Prior to 40 000 years B.P. the climate was slightly cooler than it is now and active dunes point to relatively dry conditions. Between 40 000 and 30 000 B.P. conditions became drier in northeast Queensland but relatively more humid in the southeast, perhaps because temperatures, and hence evaporation, were lower. From 30 000-26 000 dry conditions persisted in Queensland and high lake levels and solifluction features down to low altitudes in the south-east implied cold conditons with low evaporation. The period 26 000-16 000 was very dry with maximum exposure of the continental shelf, declining levels of closed lakes and possibly rising temperatures. Aridity culminated about 17 000 years ago when the continental dunes moved for the last time and lunettes formed on the lee of playa lakes. Between 16 000 and 10 000 years ago temperatures and tree-lines rose but conditions were still dry apart from a brief rise in some lake levels in the southeast. During the last 10 000 years warm conditions and relatively high rainfall occurred about 6-9 000 years ago. Since then there have been only modest climatic changes associated with some fluctuations in closed lake levels and minor changes in pollen spectra. Man-induced fires have been a feature of the environment for tens of thousands of years but probably the effects were not greatly different from those of natural fires.

Changes comparable to those of the last 40 000 years presumably occurred repeatedly through the Pleistocene, and climates were far from stable, even during the Miocene and Pliocene. Dryness has generally been a marked feature of Australia since the mid-Miocene. Throughout the Late Cainozoic dry conditions seem to have coincided with relatively low temperatures and wet conditions with warmer temperatures. The doctrine of "glacial pluvials" must be abandoned together with the concept of a mid-recent hypsithermal major period of aridity.

The vicissitudes of the Quaternary were extremely rapid in geological terms and must have imposed severe stresses on the biology, particularly in alpine, coastal and coralline environments. Modern communities in these situations are probably recent agglomerations of individual species which had survived in small, scattered refuges. The present distribution of plants and animals in Australia is a very recent - and temporary - phenomenon.

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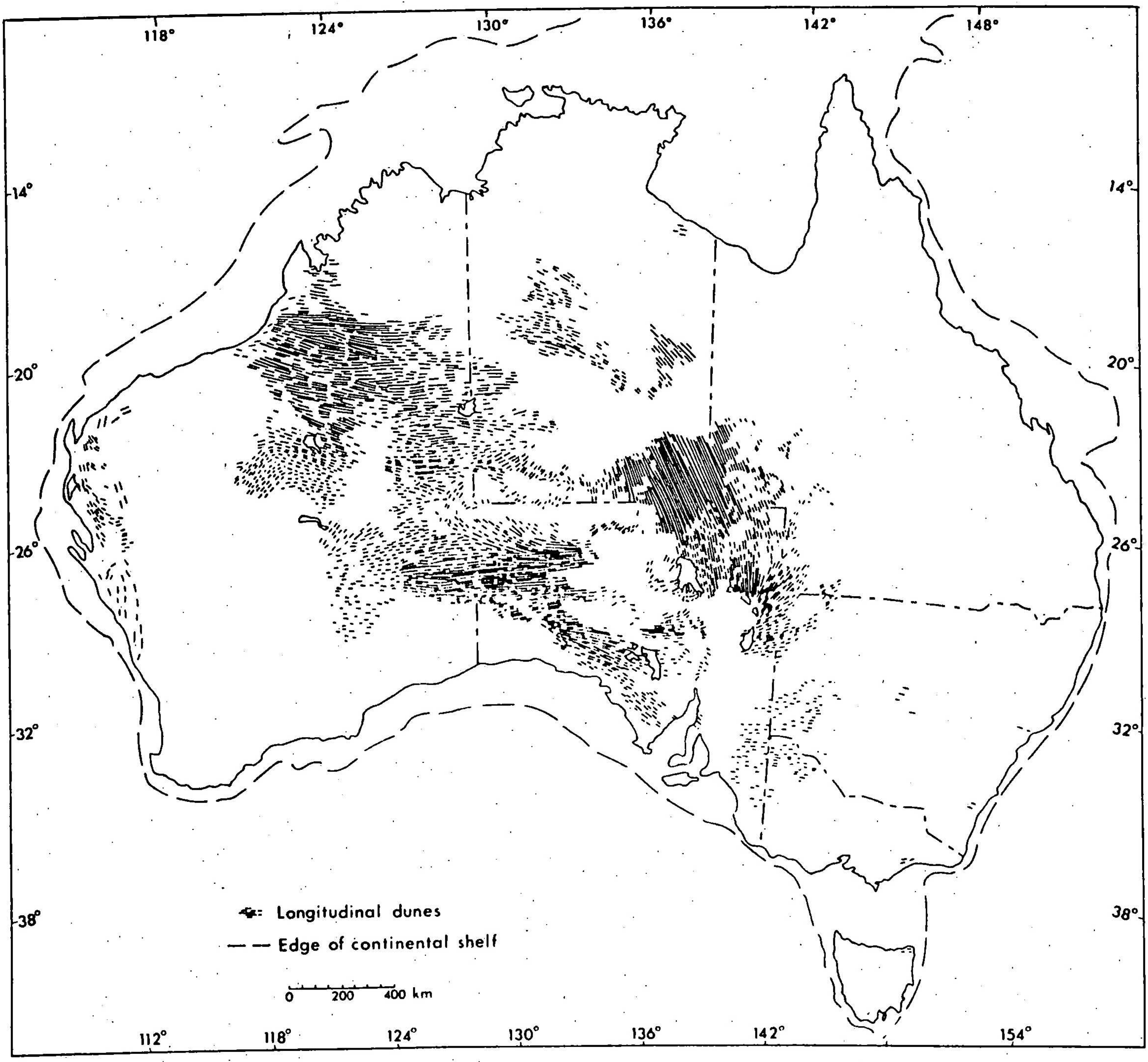
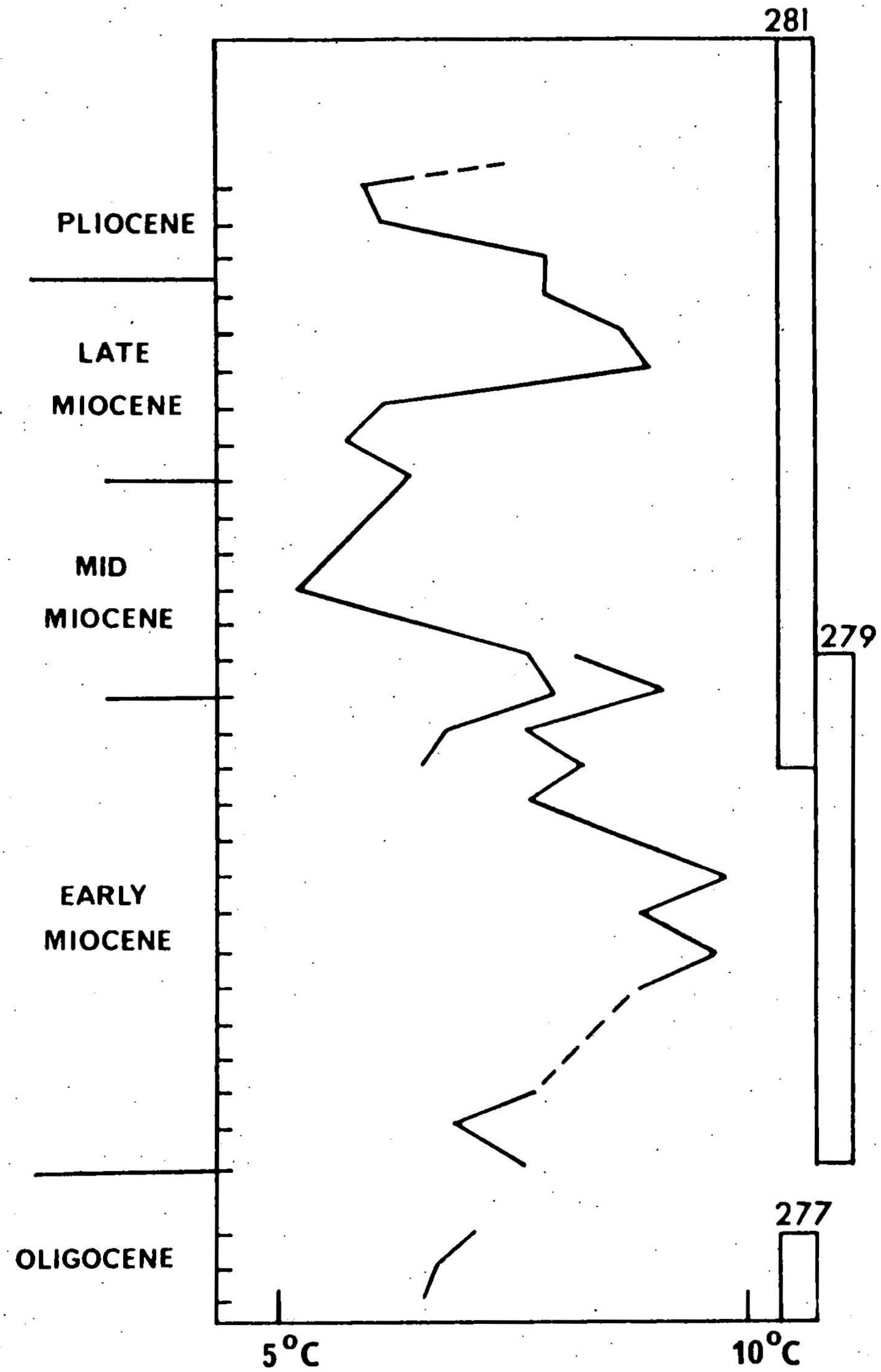
Figure Captions

Fig. 1. Pleistocene longitudinal dunes in Australia. Mainly based on Jennings (1968) with additions based on Wyrwoll & Milton (1976) for Western Australia and unpublished data by Bowden and Colhoun for Tasmania; also some field and air photo observations.

Fig. 2. Surface water temperatures for Miocene seas to the southeast of Australia. Based on oxygen isotope data from planktonic foraminifera at Deep Sea Drill Sites 281, 279, 277; from Shackleton & Kennett (1975a).


118°
124°
130°
136°
142°
148°
14°
20°
26°
32°
38°
Longitudinal dunes
Edge of continental shelf
0 200 400 km
112°
118°
124°
130°
136°
142°
154°


281
279
277
PLIOCENE
LATE
MIOCENE
MID
MIOCENE
EARLY
MIOCENE
OLIGOCENE
5°C
10°C