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Mesozoic and Cenozoic history of Australia as it affects the Australian biota

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MESOZOIC AND CENOZOIC HISTORY OF AUSTRALIA AS IT AFFECTS THE AUSTRALIAN BIOTA

P. G. Quilty

INTRODUCTION

This chapter is designed to provide a geological background to the question of aridity in Australia and the effects of that aridity on the flora and fauna in the Triassic-Pleistocene interval (Figure 1), between 225 and 1.85×10^6 years ago.

With the advent of an understanding of plate tectonics, a new review of Australian history is worthwhile, particularly as the configuration of continental blocks can tell us a great deal about possible migration routes for land based animals and plants. Of course, it can also determine the possible operation of ocean currents which in turn affect continental humidity and temperature.

The shortest interval recognisable geologically on the basis of fossil zones is about one million years (m.y.). When compared with the much finer dimensions recognisable in Quaternary studies - that is, during the past 1.85 m years - it is clear that much fine scale geological history is going undetected and that my comments here are gross generalisations compared with our knowledge of the Quaternary. This is complicated further by the grouping of time units into longer intervals.

Data are best for areas which were tectonically most active. It is here that thick rock units accumulate and from which information is most likely to be preserved, although some tectonic environments lead to severe deformation of rocks which renders understanding very difficult. It is also true that, so far, data are best for marine sediments. Vast areas of Australia have been under non-marine conditions for hundreds of millions of years and have been tectonically stable. For these areas, data are sparse and obviously there are risks involved in generalising.

Many geological statements on palaeoecology are based on studies of small areas and should be used only with reservation to make general climatic statements. For example, particularly in the Jurassic and Triassic, our insights into humidity are based on palynology - the study of fossil pollens - of coal measures which often are of regionally small extent and of a locally high humidity.

Not a great deal of review work of this type has been attempted for Australia since plate tectonics has become accepted but Brown, Campbell and Crook (15) and Beard (7) provide valuable regional summaries. Many syntheses have been compiled for less extensive areas and will be discussed where appropriate. New Zealand data have been reviewed several times, for example by Hornibrook (66).

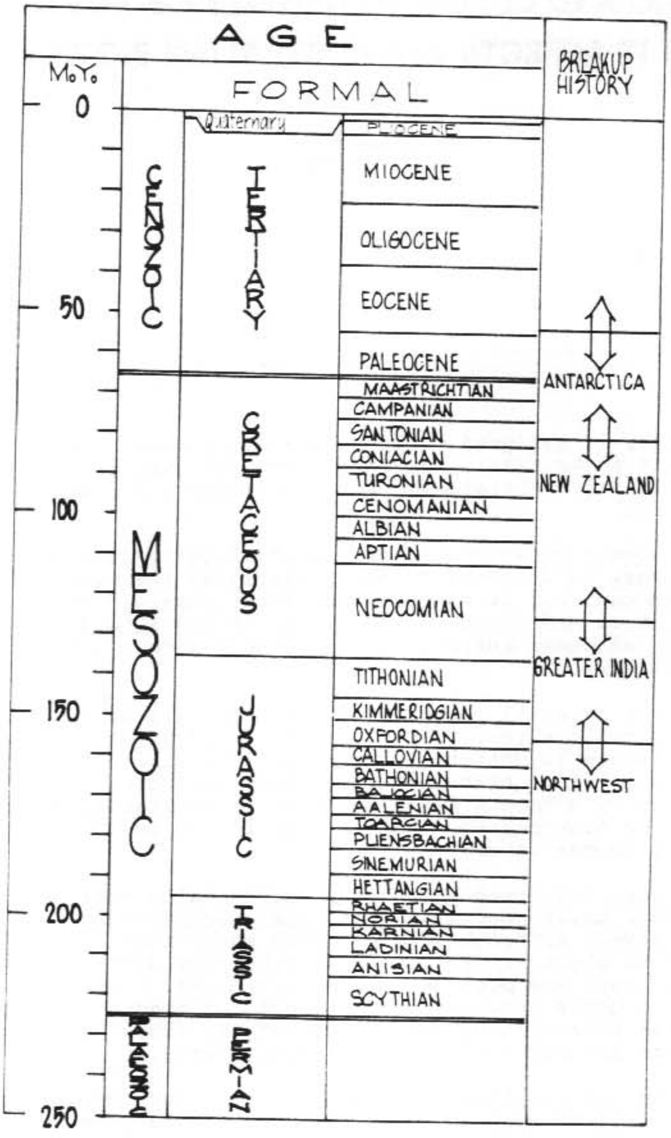

FIGURE 1. The Mesozoic-Cenozoic time scale.

THE ELEMENTS OF PLATE TECTONICS AS APPLIED TO AUSTRALIA

The earth consists of a series of concentric layers. The upper 50-100 km is termed the lithosphere which acts as a rigid layer overlying a more plastic layer, the asthenosphere, which is part of the mantle, the latter divided further into more layers (Figure 2). In this chapter I deal mainly with features occurring in the lithosphere.

The lithosphere has at its surface the crust of the earth of which two major types are recognised. Continental crust has a composition roughly of granite, a thickness of some 30-50 km and represents a lighter density (2.7) material differentiated very early in the earth's history. Oceanic crust is composed largely of basalt, has a thickness of some 5-8 km, is more dense (3.0) than continental crust and is considerably younger than continental crust (maximum age 160 million years in contrast with 3.5-3.8 billion years for continental crust).

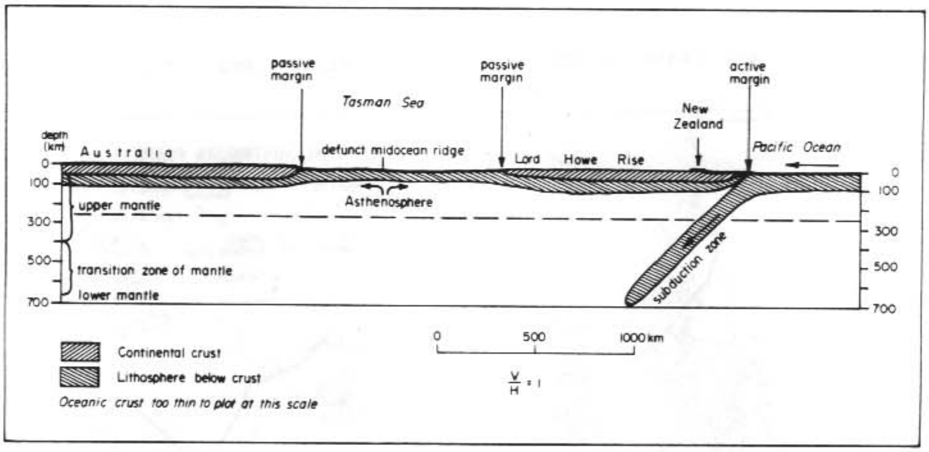

FIGURE 2. Basic elements of Plate Tectonics.

Running down the middle of most oceans is a mid-ocean ridge, a region of oceanic crust shallower than normal (say only 2-2.5 km water depth rather than the usual 4-6 km). It is now accepted that the mid-ocean ridges are areas in which oceanic crust is being formed by mid-ocean ridge spreading, often associated with volcanic and earthquake activity. As new crust is generated, older crust moves away on both sides of the ridge and sinks into deeper water (the abyssal plains). Sediment accumulates mainly by the deposition of skeletons of organisms and of volcanic debris and terrestrial and extra terrestrial clay.

As the liquid lava cools at the ridge, magnetic minerals crystallise and orient themselves parallel to the prevailing magnetic field, a magnetic field which we now know oscillates (on a geological time scale) from the present (normal) direction to reverse (the opposite of the present direction). The pattern is preserved in the rock and is readily detectable to provide a series of magnetic lineations on the sea floor. These are invaluable in interpreting the history of movement of the oceanic crust, particularly in calculating rates of movement.

Where the oceanic and continental crust meet, two types of contact can be recognised, a passive margin (e.g. all round Australia excluding the northern part bordering northern New Guinea) and an active margin (e.g. northwestern Pacific and western South America) where it seems oceanic crust is carried down below continental crust in what is termed a subduction zone, accompanied by major volcanism and earthquake activity (hence the term active margin).

Mid-ocean ridges are not continuous but are interrupted and offset by a series of transform faults, perpendicular to the ridge. The main features of this tectonic regime are shown in Figure 2.

The earth can be divided, on surface features, into a series of lithospheric plates (hence Plate Tectonics), of which seven major and several minor plates are now recognised. The boundaries of the plates are mid-ocean ridges, transform faults and collision zones (where subduction is said to occur).

The Australian Plate is one of the major plates and its features are shown in Figure 3.

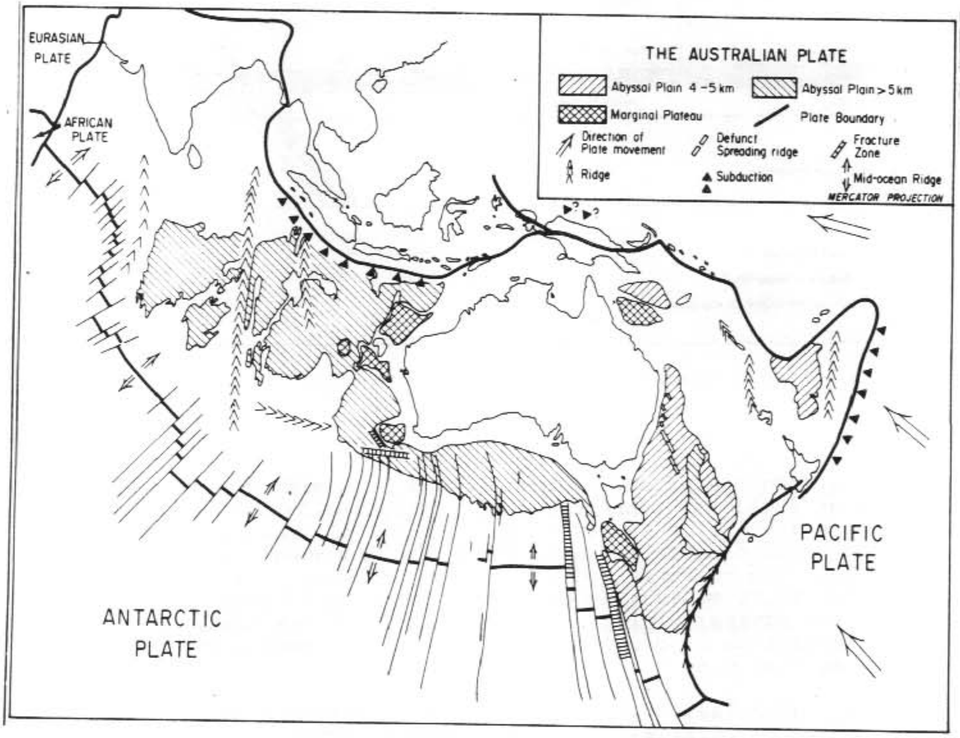

FIGURE 3. The present Australian Plate.

RECOGNITION OF CLIMATIC FEATURES IN THE GEOLOGICAL RECORD

There are several features of palaeoclimate which can be recognised from the geological record with considerable detail. Other aspects, especially humidity, are often very difficult to assess, and are usually based on a summation of other characters.

a) Latitude - The study of palaeomagnetism (e.g.111) has allowed geologists and geophysicists to make positive statements concerning the pole positions at various times, and also the positions of continents on the globe. No method is available to determine past longitude.

b) Temperature - The study of the isotopic composition (O^{16}/O^{18}) of oxygen from marine fossils has shown that the ratio is largely temperature dependent and that palaeotemperature can be estimated from studies conducted on fossils (particularly belemnites and foraminifera) which have undergone no recrystallization or metamorphism since deposition. Early attempts to reconstruct palaeotemperature by this means were based on taking averages of a series of determinations but this technique has been seriously questioned (24, 117, 59), and the suggestion is that only minimum figures are significant. These factors are discussed further where relevant.

c) Faunal and floral information - Planktonic foraminifera are common in Late Cretaceous and Cenozoic marine sediments in the Australian region and many features of their morphology and distribution can be understood by analogy with modern faunas. Such features as size, faunal diversity, direction of coiling, planktonic percentage (that is, the percentage of a fauna composed of planktonic forms) can tell a great deal about palaeotemperature and water depth in the marine environment, and many of the conclusions reached in the Late Cretaceous and Cenozoic part of this chapter are based on these features. This aspect is discussed in some detail by Bandy (4).

Palynology (the study of organic walled microfossils) also has formed the basis for palaeoenvironmental reconstructions, one of great advantages of this science being its applicability to both the marine and non-marine environments. Many of the conclusions reached in the Triassic to Early Cretaceous parts of this paper are based on palynology. Filatoff (50) in particular, has provided an explanation of the rationale for the judgements made. Results from both foraminifera and pollen can be supplemented by studies on the significance of fossil leaves e.g. Townrow (125) or reptiles (54).

d) Evidence from rocks - Several rock types can be used to gain insight into fossil climates. Although not a major consideration in this paper, rock types which arose as moraines or tills, tell that an area was glaciated. Coals indicate considerable areas of reducing environment in a humid environment. Continental redbeds, a rock type with a red colour due to abundant iron minerals in a highly oxidised state, are usually taken to indicate the existence of aridity. The red sand dunes of large areas of Australia are in accord with this hypothesis. Redbeds can accumulate in the marine environment, such as is occurring at present in Exmouth Gulf, Western Australia where the red colour is due to iron oxides contained in wind blown material, itself attesting to aridity.

There are grave risks in invoking too much from the study of rocks and their contained fossils. For example, non-marine sediments formed over the last 100 million years (middle Cretaceous and younger) are thin and sporadic over large areas of continental Australia. Those sediments that are known, represent fluvial or lacustrine accumulations which indicate local drainage activity. Some of the rocks contain evidence of the existence of vegetation near a river channel. This should not be taken as firm evidence against aridity as even in arid environments, ephemeral streams often are tree bordered or pass into local lake systems. The Sudd in Africa is a classic example of a locally humid area in an otherwise arid zone (e.g., 138).

The presence of terrigenous sediment can be taken as evidence of active, or more appropriately, effective drainage (speaking geologically). The absence of such sediment may be due to several factors including absence of any drainage (aridity), low relief (so that a river's ability to carry sediment is very reduced) or to an extensive vegetation cover, which also inhibits a river's carrying capability.

If, however, a large area has been examined, and there is no evidence in either marine or non-marine environments for the presence of terrigenous sediment, it seems a reasonable conclusion that no drainage occurred. Even the Amazon River, which drains a large, low relief basin with very extensive vegetation, discharges some 10^9 tonnes of solid material into the Atlantic Ocean annually (80).

CLIMATIC ZONES

Geological evidence indicates clearly that the present marked differentiation of climatic zones between the equator and poles differs from many of the past patterns. For example, the Late Cretaceous and Paleocene (and other intervals) were times of low differentiation of climatic zones. The Maastrichtian rocks of Antarctica contain warm water foraminifera suggesting warm marine conditions even close to the position of the South Pole.

Thus it may be erroneous to assume that climatic zones have remained constant and that continents have simply moved through them under the influence of continental dispersion.

TRIASSIC (225-190 million years) (Figures 4,5)

The present Australian Plate has evolved, particularly over the last 160 million years, by fragmentation of the supercontinent (Gondwana), which had been a long lasting union of continental blocks shown in Figure 4.

The Triassic opened with Gondwana apparently still complete. The reconstructed Gondwana at the time consisted of essentially continuous continental crust, although tensional features preserved in the geological record suggest that it was not a very coherent mass. There is little evidence to suggest that the boundary between Australia and Antarctica showed any signs of tension at this time but all other margins have preserved evidence of tension or compression in some form. Details of the palaeogeography are shown in Figure 5.

Three broad patterns of sediment can be recognised, two of which are predominantly non-marine with short lived marine incursions. The other consists of very thick marine sediments associated with volcanics, generally andesitic. These patterns reflect different aspects of the continental margin. Where sediments are predominantly non-marine, it appears that sedimentation took place in graben structures formed as tensional features between continental fragments <u>within</u> the supercontinent, or, in marked

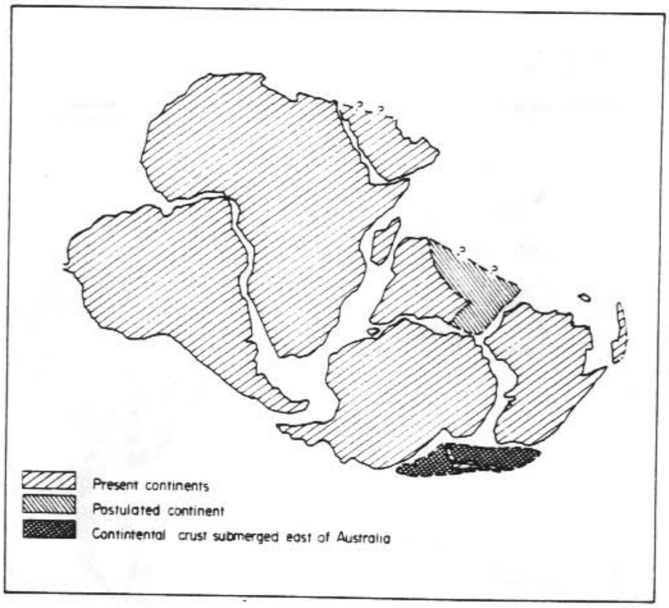

FIGURE 4. Gondwanaland.

contrast, in gentle downwarps such as the Sydney or Cooper Basins. The predominantly marine-volcanic units seem to represent sedimentation near the junction of oceanic and continental crusts, possibly associated with or near a subduction zone environment as indicated by the andesitic volcanism.

Western Australia was bounded to the south by Antarctica and to the west, in the southern part, by Greater India (71, 92, 73). Sedimentation began, except in the southern part of the Perth Basin, with a marine transgression which deposited fine grained terrigenous sediments (72, 53). This marine interval was short lived near its southern extent but lasted longer farther north: it is not known whether continental crust existed offshore from the Canning and Browse Basins. Graben structures were active, particularly in the Late Triassic, and accumulated over 3 km of terrigenous clastic sediments in the Perth Basin and over 4 km on the central south-western part of the Exmouth Plateau.

There has been much discussion of the role of Timor in the tectonic evolution of southeast Asia. Recent papers by Crostella and Powell (28) and Carter, Audley-Charles and Barber (23) reach some consensus of opinion. The basic findings of these papers are used throughout this review although it is clear that Timor will remain contentious for some time. The consensus reached by these authors suggests that the history of Timor broadly resembled that of New Guinea, which is to be expected if they occupied a similar position at the northern margin of the Australian Plate during the Triassic. Timor contains evidence (28) of deposition in an abyssal environment, perhaps under warmer water conditions than occurred elsewhere in the area at that time.

Middle and Late Triassic marine faunas and volcanics have recently been documented for Papua New Guinea by Skwarko, Nicoll and Campbell (115)

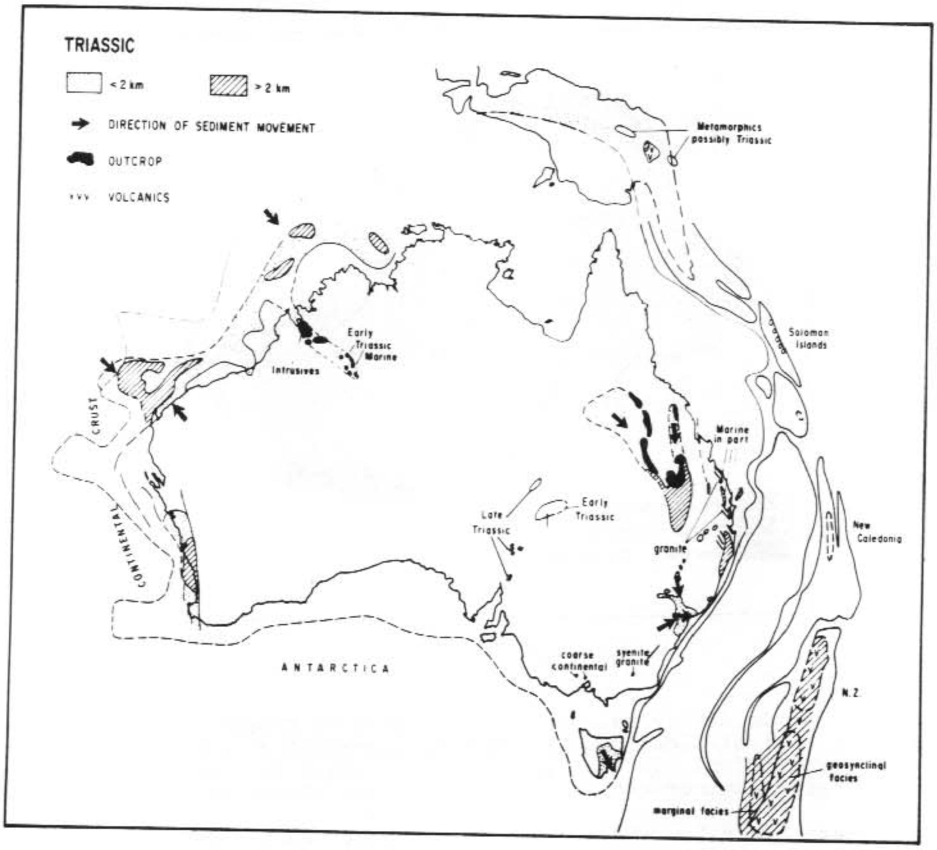

FIGURE 5. Triassic palaeogeography of Australia.

and Skwarko and Kummel (114), suggesting that this area was the northern marine boundary of the "Australian Plate" at the time, but much remains to be studied from this area. Triassic "red and green mottled clastics and carbonate" from West Irian (65) may be early Triassic and are consistent with the occurrence of a hot dry environment similar to that conjectured for parts of Australia at this time.

The reconstruction of the eastern margin of the Australian Plate during the Triassic is not yet complete and for this paper I have accepted the reconstruction proposed by Griffiths (57) which is generally consistent with the later continental breakup patterns discussed by Hayes and Ringis (63) and Roots (108). Two tectonically very active parts of this margin are recognisable.

Queensland sediments seem to grade from purely non-marine, non-volcanic sediments of the Galilee Basin in the northwest, through the thicker, still non-marine eastern Bowen Basin (about 6 km thick), to the deep accumulations of marine, non-marine and andesitic volcanic units in the smaller basins of southeastern Queensland, such as the Abercorn and Esk Troughs and Gympie, Ipswich and Tarong Basins (34). Here, tectonic activity seems to have been greatest in the Early and Middle Triassic, and horst-graben structures in the area indicated that tensional tectonics were the norm. Granitic intrusives seem to have been part of this tensional regime (132).

Conditions in this area can be contrasted with those to the south-east on the margin which has since evolved into New Zealand. The south-eastern Queensland history is contained within the continental crust whereas there is no evidence in the New Zealand story of land to the east.

The New Zealand Triassic regime has been resolved by many authors (134, 52 , 15 , 58 ,131) into two facies - an inshore one of sandstone, mudstone, and conglomerate, occasionally containing plant fossils, and another of greywacke with some spilitic basalt. The former is believed to have accumulated on continental crust at the continental margin near the shoreline, and the latter to have formed a "geosynclinal" accumulation on oceanic crust. The thickness of both units is very great, up to about 9 km.

Most other Triassic units in Australia represent tectonically less active conditions. The Sydney and Tasmania Basins are both northwest-southeast trending crustal downwarps with dominantly deltaic-fluviatile sediments in them, and the details of their relationship with the active margin to the southeast are unknown.

Basins of smaller area in South Australia contain important coal (Wopfner in 94), and small deposits of continental sediments and intrusions of syenite and granite porphyry are known in Victoria and have been reviewed by Douglas et al. in Douglas and Ferguson (44).

In summary, Triassic accumulations are thickest and most diverse in basins marginal to the Australian Plate and accumulations within the area which eventually became Australia are much thinner and less diverse.

The Environment in the Triassic

Australia's position on the globe during the Triassic is not well known but Embleton (48) indicates that the present southwestern tip of the continent may have been at about 60°S and Tasmania close to the South Pole. Thus it was much farther south than it is now. It was also much less latitudinal in character as northwestern Australia was much farther north than southeastern Australia.

Sedimentary sequences including redbeds are abundant around the perimeter of the present continent showing that drainage systems were active throughout the Triassic in these areas. The little evidence available in the Sydney Basin suggests sediment sources at various times from the south-west, west, northwest and northeast. The northwest source agrees with that postulated for coeval sediments in the Galilee and Tasmania Basins.

In contrast, the sediment source in the northern Browse Basin seems to be from the west-northwest (96) which may be due to marginal uplift prior to continental breakup. Powell also suggests a Pilbara Block source for the detritus in the Carnarvon Basin and a possible western source for that forming the thick accumulation on the Exmouth Plateau.

Redbeds are common in the lower part of the Triassic succession in eastern Australia and throughout the fragmentary record of the Triassic in southern Australia and perhaps West Irian.

Little information is available on detailed palaeoclimate but several suggestions have been made for particular areas. The most recent statement is by Dolby and Balme (39), who distinguished two floras in the Middle and Late Triassic. The Onslow Flora contains both Gondwanan and European elements and was taken to indicate temperate rain forests, the latter apparently in minor conflict with Embleton's (48) palaeomagnetic interpretation. The Ipswich Flora, coeval with the Onslow Flora, is less diverse and contains no European elements and was taken by Dolby and Balme to be a higher latitude flora, consistent with the latitude of Australia at the time. Townrow (125) had already suggested a cool temperate climate for the Rhaeto-Liassic in Tasmania. The flora of the Late Triassic associated with coal measures in South Australia is said to have been warm and moist (Wopfner in 94) but the Early Triassic of the Cooper Basin is said tentatively to indicate "mildly evaporitic conditions". Douglas (43) suggested cool temperate climate for the Victorian Triassic. However, it must be emphasised that the South Australian and Tasmanian results are based on the study of coal measure floras, which may be of very local significance.

As a generalisation, it would seem that the Early Triassic was more arid than the Late Triassic, which commonly contains indicators of a humid environment.

Brown, Campbell and Crook (15) recorded a warm temperate climate for New Zealand during the Triassic, but this was based on lack of contrary evidence. The position close to Tasmania would suggest that cooler conditions prevailed.

It could be expected that the marine margins (particularly New Guinea and New Zealand) may have been somewhat mountainous if subduction was active, as it would have been judging from the presence of dacite fragments (45) in some of the New Guinea sediments, and andesitic volcanics in southeastern Queensland. The main volcanic element in the New Zealand sediments at this time seems to be spilitic basalt (52).

Cox (27) and Kalandadze (75) have both reviewed evidence for tetrapod affinities and migration in the Triassic but, as is clear from Kalandadze's work the data from Australia are not yet sufficient for definitive comparisons.

It is clear that theoretically any organism could migrate to any continent as all continents were linked, possibly with Tethys intervening between northern Australia and Asia. Carey (22) suggests that Tethys was closed and that migration was possible even here, although this is in conflict with the apparent palaeobathymetry and source direction indices of the New Guinea and Timor areas.

Although all continents were linked, it is probable that there were other terrestrial barriers to migration, such as climatic zones and mountain chains. The presence of European elements in the Onslow Flora and in Malagasy (39) suggests a link with Europe by way of northern Greater India.

JURASSIC (190-136 million years B.P) (Figure 6)

The Jurassic record indicates that this was the time during which Gondwana began to break up. Throughout the Early and Middle Jurassic, the continental pattern was more or less as during the Triassic, but in the Late Jurassic a mid-ocean spreading ridge entered the northwest coast of Australia, possibly causing the movement away of a piece of continental crust from between Timor and the northeastern flank of the Exmouth Plateau. Details of Australia in the Jurassic are shown in Figure 6.

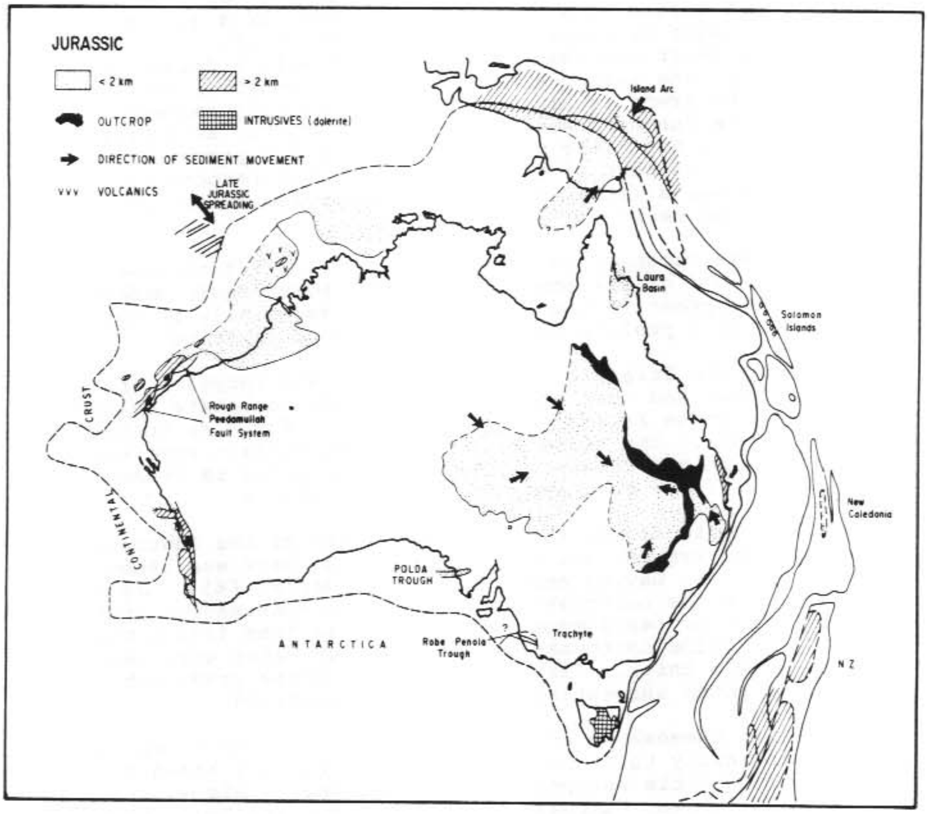

FIGURE 6. Jurassic palaeogeography of Australia.

The southern margin shows the first clear signs of tension between Australia and Antarctica. Middle Jurassic dolerites form a very prominent feature of the Gondwana continents, probably marking a supercontinent-wide tensional period before major breakup began. Australia is represented by the Tasmanian dolerites and also perhaps by such isolated bodies as the Prospect intrusion near Sydney, and the isolated trachyte of Western Victoria (Bowen in 44). Further evidence is provided by the east-west trending Polda and Robe-Penola Troughs, marking the onset of graben development as tension built up between Australia and Antarctica.

Along the western margin, sedimentation usually was continuous from the Triassic into the Jurassic. Coal measures developed in the Perth Basin close to sea level and flood plain sedimentation took place in the Carnarvon Basin. Graben development was much less active than in the Triassic, but tensional tectonics was still the norm (72).

The Middle Jurassic was a period of great change. The sea flooded the western margin as far south as the northern Perth Basin, in the same way as had the Early Triassic transgression. This transgression was short lived in the Perth Basin but marked the beginning of almost permanent marine conditions northwest of a major fault system - the Rough Range - Peedamullah Fault system, which became very active at about this time. The fault system formed the southeast margin of a graben system, part of a general northeast-southwest trend in major features on the northwest shelf. This trend includes the Browse Basin and the newly developed Malita Graben in the Bonaparte Gulf Basin, the latter a marked change from prior tectonic direction (78). The trend is also parallel to seafloor magnetic anomalies developed in the Late Jurassic west of the Browse Basin, as a midocean ridge system entered. It is not clear whether this caused a piece of continental crust to drift away. As part of the tensional regime responsible for all these trends, there was a short interval of widespread volcanism in the vicinity of the Browse Basin (96).

From the Late Jurassic on, most sedimentation off northwestern Australia occurred in a marine environment. The Perth Basin underwent renewed graben development in the Late Jurassic, especially in the Dandaragan Trough, as a prelude to a later period of drifting.

Again as in the Triassic, Timor seems to have formed a transitional zone between continent and deep ocean with deep sea carbonate sediments and closer inshore sand-shale facies, the latter also present as turbidites in the deep sea sediments. The closer inshore facies contain some volcanics, probably fewer than in the Triassic. Accurate thickness is unknown but Crostella and Powell (29) estimate it to be some 1500 m.

New Guinea again formed the northern margin of the Australian Plate. Data for the Jurassic are few and the comments made here are based on the works of Harrison (61), Davies and Smith (32), Hermes (65), Jenkins (70) and Milsom (91). On the northeastern edge of the continental crust of Australia, shallow water terrigenous sediments less than 1000 m thick accumulated. These grade northeasterly into deeper water argillaceous sediments up to 3000 m thick. Farther northeast, these grade into greywacke and basic volcanic rocks suggesting island arc conditions.

Southeastern Queensland and northeastern New South Wales continued to be active tectonically throughout the Jurassic but all known rocks are nonmarine with one possible exception - the Evergreen Shale - during the Liassic mentioned by Brown, Campbell and Crook (15) and Day, Cranfield and Schwarzbock (34). It was during the Jurassic that the area became tectonically stable and the Jurassic was the last time that very thick sediments formed. Except for the Maryborough Basin, and possibly the Moreton Basin, where sediments are less than 2000 m thick, Jurassic rocks are more widespread than their Triassic predecessors and form an extensive blanket derived from granitic sources. Sediments in the Maryborough Basin exceed 2000 m and include about 1000 m of andesitic and trachytic volcanics. A basalt occurs in the Jurassic of the Moreton Basin.

The Great Artesian Basin assumed its form during the Jurassic, enlarging from earliest Jurassic times. Sediments were derived predominantly from the west, northwest and east (15) in the early Jurassic. The relationship of the northern Great Artesian Basin to the non-marine sediments in southern New Guinea and the Laura Basin is not known but some connection is suggested.

Throughout most of the Jurassic, New Zealand continued to behave as in the Triassic, with the same elements of the geosyncline being recognisable. However in the Late Jurassic there occurred a depositional hiatus, followed immediately by the onset of the Rangitata Orogeny (e.g. 131) which continued into the Cretaceous. Elements of this history can be followed farther afield into Antarctica (104,105) and New Caledonia (79).

The sediment on the Australian Plate throughout the Jurassic is predominantly terrigenous, attesting to considerable active drainage. This is particularly true along the western margin, in the plate centre where the Great Artesian Basin formed, and in southeastern Queensland. In general, the pattern is similar to that of the Triassic but with greater interior drainage to the Great Artesian Basin.

Palaeogeography

The Jurassic is one of the most interesting episodes in geological history and many fundamental principles of geology are based on studies of Jurassic rocks. The Jurassic has been the subject of many major studies of which Arkell's (2) is the classic. To some extent it has been extended by Hallam (59).

Enough is now known of this time interval to show that sea level fluctuated, rising generally from the beginning of the period to the latter part of the Late Jurassic, when it seems to have fallen again quite dramatically, the control everywhere being tectonic (see 104 , 105 and 126).

Climate during most of the Jurassic was less differentiated than it now is. There is no evidence of any polar ice even from regions close to the poles (104, 105 and 59). Cosmopolitanism of the biota in the Early and Middle Jurassic indicates very uniform worldwide conditions, although some differentiation occurred, and in the Late Jurassic more bioprovinces can be recognised, indicating some differentiation of further climatic zones.

Better palaeoclimatic information is available from the Jurassic of the Australian region than from the Triassic and comes from three sources - palaeomagnetism, palynology and oxygen isotope studies of fossils.

Palaeomagnetic data are not available from Western Australia but eastern Australia was in approximately the same palaeolatitude as it was in the Triassic (48), that is, with Tasmania close to the South Pole.

Bowen (14) gave palaeotemperature measurements of 18.5-29.2 (average 24.4) ^{o}C for belemnites from the Middle Jurassic Newmarracarra Limestone in Western Australia. These results have been questioned because the area was subject to mid Tertiary lateritisation and the technique itself has been impugned by Hallam (59). However, Bowen's results are in general agreement with the result obtained by detailed palynology by Filatoff (50) who in a very well supported analysis suggested that the early Jurassic of the Perth Basin was warm to hot and arid and that in the Middle and Late Jurassic it was wet and tropical to subtropical. The early Jurassic interpretation is supported by the presence of a redbed sequence.

The Algebuckina Sandstone in the Great Artesian Basin shows a change of climate during its deposition from seasonally arid in its lower part (indicated by large scale aeolian cross stratification) to moist subtropical in its upper part. Unfortunately age control is not very reliable and the upper part could be either Late Jurassic or Early Cretaceous in age (Wopfner in 94). Aeolian Jurassic sands have also been identified recently in the Canning Basin (19).

Clayton and Stevens (24) and Stevens and Clayton (117) have analysed belemnites from New Zealand but the analyses for the Jurassic are mainly for the Kimmeridgian-Tithonian, and some could be considerably older if doubts about the place of the Heterian (104, 105 and 49) are justified. The values obtained by Stevens and Clayton show a very great spread and they took only the minimum value as significant. Thus they would take 15-16 ^{o}C as the Late Jurassic marine palaeotemperature. A mean figure based on their analyses is about 20°C with a maximum of 30°C, although means must be questioned (59 , 117).

Townrow (125) has suggested that Tasmania's climate was temperate in the very early Jurassic.

Throughout the Jurassic in the Australian region, there is no evidence of tropical marine conditions. If there were, very characteristic large foraminifera could be expected. Further, coral faunas and limestone, which are a common component of coeval tropical shallow water sediments, are absent.

Overall, throughout the Jurassic, there may have been a gradient from cool temperate-warm temperate in the present southeast to warm to hot on the present west coast. There is some conflict between the non-marine positive evidence and marine negative evidence of tropical conditions on the west coast.

CRETACEOUS (136-65 million years)

The Cretaceous was perhaps the most significant period in the Gondwana dispersal story. India and Australia separated and throughout the Cretaceous lay on separate plates, divided by active midocean ridges. In the Late Cretaceous, New Zealand and Australia separated. Thus, at the close of the Cretaceous the only remaining episode to be accomplished was the Australia - Antarctica breakup.

The Turonian saw major changes in the pattern of sedimentation around Australia, and thus the Cretaceous will be discussed as two time-intervals: Earlier (Neocomian - mid-Turonian) and Later (Late Turonian - Maastrichtian).

Sea-level was high during the Aptian-Albian and perhaps Cenomanian, and Australia underwent its greatest inundation. Thus, marine sediments of Aptian-Albian age are very widespread. The mid-Neocomian sea-level apparently was low.

Earlier Cretaceous (Figure 7)

Between Australia and Antarctica tensional tectonics continued and the graben sedimentation which commenced in the Jurassic accelerated, so that up to 6000 m of sediment were laid down. Control of this episode was purely geophysical (26, 13) in the western part. This was the most dramatic episode of sedimentation in the area, all later sections being considerably thinner. Details of the rocks are unknown, but probably marine conditions prevailed in the Aptian-Albian.

As part of the tension between Australia and Antarctica, a large gentle downwarp developed and became the Eucla Basin (84). Fine-grained terrigenous sediments were the main input, reaching a little over 500 m at the present continental shelf edge.

In the eastern part of the boundary, graben development initiated the Gippsland Basin where up to 6000 m of sediment accumulated. Included in this are significant basaltic volcanics. The Robe-Penola Trough also was active at the time, and was the depocentre for up to 3000 m of predominantly nonmarine mudstone with volcanics.

Major activity occurred along the western margin between the

Naturaliste Plateau and southwestern margin of the Exmouth Plateau and was the most important aspect of the tectonic history in the Cretaceous. This area was linked by continental crust to what is now known as Greater India (129, and others).

The violent Late Jurassic graben faulting had diminished by the beginning of the Neocomian, but a less intense reactivation occurred over several million years. Up to 6000 m of sediment, deposited close to sea-level, accumulated west of Perth in the Vlaming Sub-Basin. An equivalent but thinner sequence is to be expected in the Houtman Sub-Basin (120).

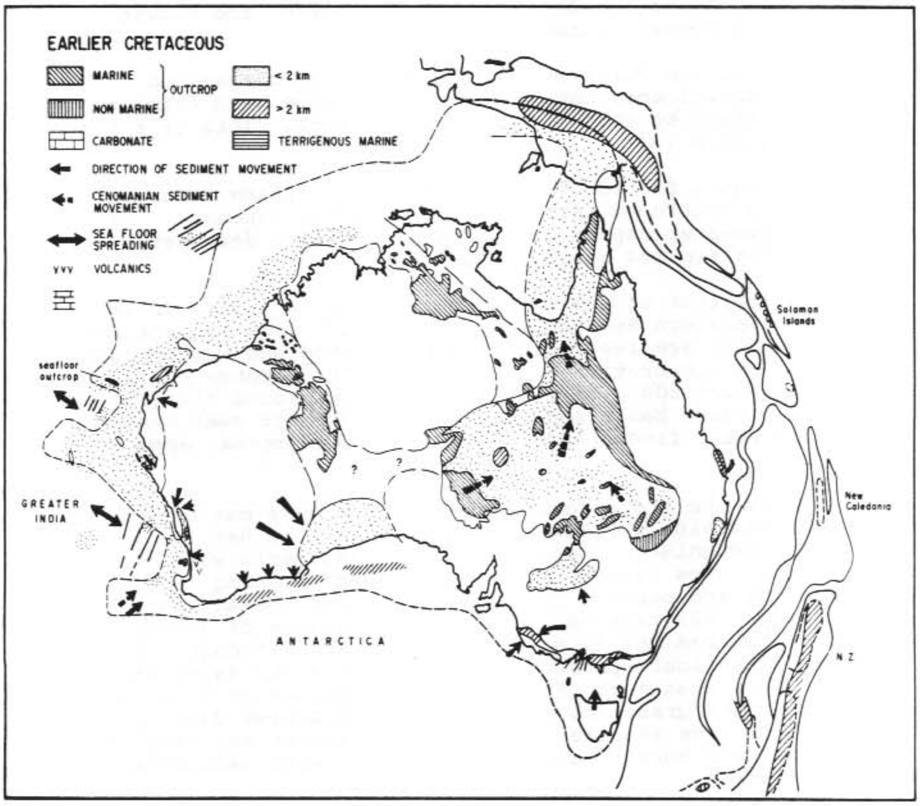

FIGURE 7. Earlier Cretaceous palaeogeography of Australia.

In the mid-Neocomian, a midocean ridge system developed between Australia and Greater India (90), allowing the sea to enter and initiating violent elevation of the Australian margin in the area. This in turn led to erosion down to the earlier sediments and the development of a widespread "intra Neocomian unconformity" (71, 74).

Following this violent interval, the margin began to subside and marine conditions were initiated. The entire western margin of Australia now experienced marine conditions, and has done so ever since.

At the same time India moved away from Australia and the separation has continued to the present time. From the time of the breakup (127 m.y.) until the Early Tertiary (53 m.y.), Australia and India were separated by midocean ridge spreading systems and were thus on separate lithospheric plates (71). The separation of India and Antarctica generated, until 80 m.y. ago, a classic rhombochasm (22) in which deep-sea carbonates accumulated (100).

The area immediately northwest of the Rough Range-Peedamullah Fault system also was active in this interval and accumulated a considerable thickness of marine, predominantly terrigenous fine-grained sediment (96, 71, 83). Several well-defined depocentres are obvious, in particular the Exmouth, Barrow and Dampier Sub-Basins. Farther north, the Browse and Bonaparte Gulf Basins formed broader depocentres.

In contrast to the Jurassic and Triassic, the Cretaceous in Timor seems to have been nonvolcanic but still seems to have been transitional from the Australian continent to abyssal marine conditions. This is reflected in the sedimentary sequence (28).

New Guinea again formed the northern margin of the Australian Plate, sedimentation having continued uninterrupted from the Jurassic. Glauconitic sandstone of shallow-water aspect grades northward into deep-water shale (61). Volcanoes contributed basic rocks.

With the exception of the Maryborough Basin, activity in southeastern Queensland and northeastern New South Wales was much less violent than in the Jurassic, and sediments are restricted to the Moreton and Maryborough Basins; all others had become inoperative by this time. The Moreton Basin incorporated up to about 500 m of fine-grained terrigenous clastics. In contrast, the Maryborough Basin received about 4000 m of coal measures and marine to fluvio-deltaic fine-grained terrigenous sediments, apparently under a tensional regime.

Conditions in the Cretaceous of New Zealand were markedly different from those in the Jurassic, the last period in which the New Zealand Geosyncline can be recognised. Early Cretaceous sediments were deposited in two discrete "basins", the larger, more easterly one forming the transition between the continent and ocean. The Northland Basin contains spilitic basalt which Fleming (52) took to indicate the presence of oceanic conditions west of New Zealand (i.e. the Tasman Sea), although this conflicts with the sea-floor spreading ages determined by Hayes and Ringis (63). It is probable that much of the movement obvious at this time is due to jostling of horst and graben blocks prior to the active development of the Tasman Sea. Thus, the absence of a marine Neocomian may have resulted from New Zealand being a horst feature at the time, with sedimentation commencing in the Aptian.

Major flexures, intrusions of plutons, and high-temperature metamorphism are all features of the Earlier Cretaceous part of the Rangitata Orogeny, an orogeny which may have ceased in the Cenomanian (131).

In central Australia, the Great Artesian Basin achieved its maximum extent and after an initial phase of nonmarine sedimentation, marine conditions became very widespread, giving rise to the deposition of fine-grained terrigenous sediments, only locally exceeding 2000 m in thickness. In the Cenomanian, the sea retreated and a blanket of nonmarine fluviatile sediments (including the Winton Formation) was deposited.

Climate and biogeography

During the mid-Neocomian of the Earlier Cretaceous, India and Australia parted company and the migration route between the continents closed, and has remained so until relatively recent times. Australia and New Zealand were still connected, but for the last time. Consequently for terrestrial species this was the last opportunity for overland migrations.

Fleming (52) stated that Sphenodon had reached New Zealand before the end of the Jurassic, but argued that snakes and mammals had not arrived in Australia by that time, otherwise they also could be expected to occur in New Zealand. The means of arrival of Nothofagus, protaceous plants and ratite birds in New Zealand is not yet completely understood as according to Fleming, protaceous plants and Nothofagus need continuous land for migration; whether ratites lost their powers of flight before or after arrival is not known.

Australia, during the Aptian in particular, may have been divided into a series of large islands, as convincingly depicted by Brown, Campbell and Crook (15). It was less continental in character then than at any time prior to or succeeding the Aptian-Cenomanian. The westernmost of the islands was esentially the Yilgarn Block of Western Australia which had a greatly uplifted western margin early in this interval and on which two markedly different drainage systems developed. To the west were short-path, high-energy streams carrying coarse detritus into the new ocean developed as India departed. To the southeast, into the Eucla Basin, flowed long-path, low-energy streams which carried fine detritus, eventually forming the Madura Formation. There must also have been short-path streams carrying material into the graben between Antarctica and the Yilgarn Block. These streams are represented now by the submarine canyons of the southern Yilgarn Block and probably by infilled canyons under the Eucla Basin, initially filled in by the Aptian - Albian transgression (130). The locations of the river systems are marked now by the salt lake system of Western Australia, which will be discussed below. An interesting clue to provenance was documented by Ingram (68) who recognized a great variety of ages of palynomorphs in the Otorowiri Siltstone Member, suggesting a possible northerly source for some of the sediment.

Douglas (in 44) has summarised the available data from Victoria, all indicating that the sediments in the then newly developing Otway and Gippsland basin were mostly derived from Palaeozoic rocks. Denham and Brown (36) have added some useful comments, particularly on the direction of sediment transport.

Prior to the marine inundation of the Great Artesian Basin, the area seems to have been occupied, as in the Late Jurassic, by a series of lakes, marshes or river valleys.

Irving (69) suggested that eastern Australia had moved north some 5°-6° from its Jurassic position, and that Western Australia had moved about 3°-4° south. Major changes could be expected along the southern part of the western margin as oceanic conditions became established. The high land expected to the east of Perth, because of continental margin uplift, would have helped the development of a high rainfall belt to feed the rivers mentioned above.

The terrigenous sediments of the Winning Group (124) formed in a deltaic environment and can be taken as evidence of major river activity in the valley of the modern Fortescue and Ashburton Rivers.

There are few accurate palaeoclimatic indicators in the Early Cretaceous. Precipitation seems to have been considerably higher, as a continent-wide generalization, than it had been in the Triassic and Jurassic. No glacial sediments are known, although some were reported by Streich (119) from the Officer Basin. The hypothesis of Cretaceous glaciation is no longer held (15). There is also a lack of tropical indicators such as characteristic foraminifera, corals and shallow marine carbonate sediments.

Data for oxygen isotope studies on belemnites in this time-interval are fewer than for the Jurassic or the later Cretaceous, and all were reviewed by Stephens and Clayton (117). Information is available for the Aptian-Cenomanian, but not for the Neocomian. Stephens and Clayton took the lower temperature of about 16°C to be valid for the Albian-Cenomanian boundary. They did not include the data by Dorman and Gill (42) and Dorman (41) in their temperature curve. The Dorman and Gill figures suggest considerably cooler conditions for the Aptian, a temperature of some 12°C being more appropriate. New Zealand was said to have had a cool temperate climate.

The cooler than present temperatures suggested by these techniques agree with the low diversity seen in Early Cretaceous planktonic foraminiferal faunas (see particularly 110).

Gill (54) attempted to integrate the available data to explain disparities in reptile distribution and suggested a temperature gradient from cool in the present southeast to warmer in northwest Australia. The continental redbeds, so characteristic of the Triassic-Jurassic nonmarine rocks, appear to be absent from the Early Cretaceous, also suggesting the absence of the earlier hot, partially arid climate.

Several features of the Early Cretaceous are noteworthy and deserve further analysis. The most significant is the effect on many aspects of climate of a worldwide inundation by the sea, such as happened in the Aptian-Cenomanian when the exposed area of the Australian continent was reduced to about half its present area. This seems to have happened simultaneously in other continents. Scheibnerova (110) has examined and refuted the concept of reduced salinity.

<u>Later Cretaceous</u> (Figure 8)

The Later Cretaceous saw several important changes in the Australian region. Australia and New Zealand drifted apart, leaving only Australia - Antarctica of the original Gondwana. The Tasman Sea assumed a configuration close to its present one during this time. In the western half of Australia, drainage systems were very much diminished and carbonate sediments of biogenic origin became the norm. Large areas of plate margin provinces such as New Guinea and New Zealand underwent great changes in tectonic style, allowing widespread uplift and erosion or only shallow marine conditions.

The southern margin should be discussed in two parts. First, from southwestern Australia east to the western coast of Tasmania and southwestern Victoria, the observed features can be related to the impending separation of Australia and Antarctica in the Early Tertiary. The Gippsland Basin, while having a similar initial age and east-west orientation, is related to the Australia-New Zealand breakup which occurred in the Late Cretaceous (63 ,108) and will be discussed later.

The first part of the southern margin continued to be a series of graben structures (oriented roughly parallel to the present coast and thus changing attitude quite markedly at the Great Australian Bight) into which flooded terrigenous detritus from both Antarctica and Australia (36). Sedimentation in the western part was much less dramatic than in the Earlier Cretaceous but, in the eastern end graben development was very active and 6000-7000 m of Later Cretaceous sediments accumulated in the Otway Basin. In many seismic sections south of the Yilgarn Block, there is no evidence of rocks of this age, and even in the Eucla Basin sections are only a few metres thick. Marine conditions were not well developed, but palynological and

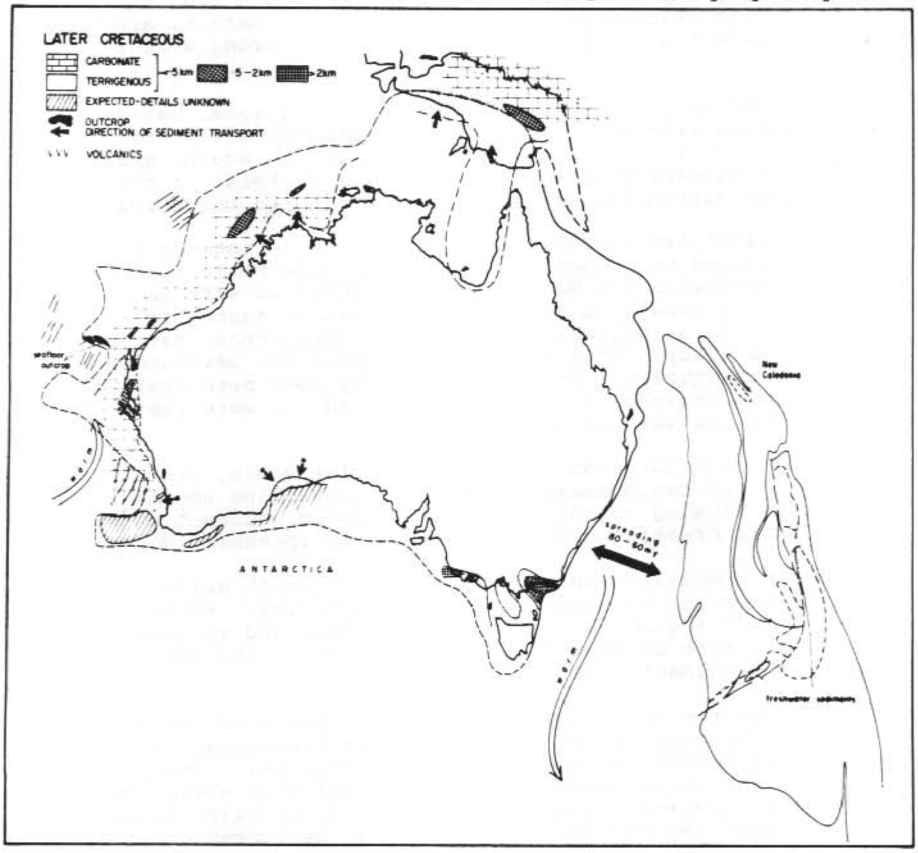

FIGURE 8. Later Cretaceous palaeogeography of Australia.

foraminiferal (121) studies indicate some marine influence. Quilty (100) and Douglas in Douglas and Ferguson (44) suggested that the sea entered from the west, but Davidson (30) is more in favour of eastern openings by a slight dextral divergent rotation of Antarctica. This may be more in accord with what we now know of Late Cretaceous sediment distribution. Basaltic rocks north of Melbourne (136) probably are related to early movement of the system before the early Cenozoic breakup of Australia and Antarctica.

Conditions along the entire western margin changed greatly from those occurring in the Earlier Cretaceous. Sediments deposited in the interval are biogenic carbonate, often with some fine-grained detrital material and even, in the Perth Basin, with some quartz sand (106). Biogenic carbonate is dominant and reflects the existence of marine conditions down the entire coast. The degree to which sediments accumulated in basins was very much reduced, a feature of the western margin even until the Recent. The thickest axes of accumulation apparent on isopach maps reflect the prograding habit of the carbonate, not a basin configuration. Sedimentation was influenced greatly by sea-level fluctuations (107), and so the main sedimentary rock units recognizable are Late Santonian-Early Campanian and Maastrichtian in age.

In Timor also, the terrigenous input is very much reduced during this time-interval, and calcilutites, as on the western margin, are the usual sediments. The parallels with the western margin are strong at this time (28).

New Guinea continued to exist in a state transitional between continental and perhaps island-arc conditions, with Australia-derived terrigenous sediment (65) less than 1000 m thick in the south, a zone of deep-water shale and volcanics up to 3000 m thick peripheral to that and to the north, deep-water carbonate, agglomerate and spilitic volcanics.

During the Later Cretaceous, sea-floor spreading between Australia and New Zealand developed the Tasman Sea (63) and completely broke the land connection between Australia and New Zealand. Associated with this spreading episode was a series of events on the eastern margin of Australia. Perhaps the most significant was a regional uplift of the continental margin at the time of continental breakup. This probably initiated the development of the highlands of eastern Australia. In consequence any long path drainage systems which may have drained to the southeast died and were replaced by those flowing more to the west or southwest.

The sea had withdrawn from the Great Artesian Basin, probably in the Albian (95, 109) and the basin became an area of non-marine sedimentation, probably with rivers flowing roughly north and feeding sediment to the New Guinea regions. Later Cretaceous sediments are only sporadic (Wopfner in 94).

Southeastern Queensland and northeastern New South Wales were uplifted and erosion became the dominant surface activity. However, in the Maryborough Basin older sequences were strongly folded and faulted during the Later Cretaceous, with structural trends parallel to the approximately northwest-southeast continent edge.

The opening of the Tasman Sea had great influence on New Zealand also. The Rangitata Orogeny ceased, perhaps in the Cenomanian (131), and also perhaps a little before the opening of the Tasman Sea. The coincidence with the closing of the marine phase in the Great Artesian Basin, and of events in southeastern Queensland-northeastern New South Wales is obvious and all changes reflect the tectonic events during the formation of the Tasman Sea.

Fleming (52) commented that the distribution of Late Cretaceous sediments indicated tectonic stability, in marked contrast to the immediately preceded Rangitata Orogeny.

In the Gippsland Basin, Late Cretaceous sediments are restricted to a narrow (less than 100 km wide) east-west trending graben offshore from the present coast of Victoria. Herein accumulated over 3000 m of the non-marine to marginal marine Latrobe Valley Group sediments. Sedimentation continued without major interruption through much of the Early Tertiary. The rocks are mainly fine to coarse terrigenous material with some olivine basalts (Abele et al. in 44), the latter representing the onset of basaltic volcanism which was to become much more widespread in the Cenozoic.

Palaeogeography

During this interval Australia was still quite close to the South Pole (69), the Pole situated only a few degrees south of Tasmania.

Conditions were markedly different in the Later Cretaceous than in the Earlier. The sea had retreated from central Australia and after a brief episode of fluviatile sedimentation (Winton Formation), even the rivers disappeared.

On the western margin, effective drainage virtually ceased with a minor exception near Perth (106). The foraminiferal fauna indicates open, warm water marine conditions. Overall a warm environment devoid of effective drainage is envisaged. Conditions were apparently not tropical, as no coral reef or characteristic foraminifera or rudistid bivalves are known even though ideal depth conditions apparently prevailed. The only hint of "tropical" large foraminifera is Glaessner's (55) record of Pseudorbitoides israelskyi from Papua. Cold water indicators also are absent. As Australia and Antarctica are still united, it seems probable that a northerly flowing current passed along the western margin, in the form envisaged by Gordon (56).

Sandstone and other terrigenous sediments occur in the Browse and Bonaparte Gulf Basins suggesting some active drainage on the Kimberley Block. Active drainage is also obvious along the northern margin of the Australian continent, i.e. draining to the New Guinea region, and also in graben along the south coast. All drainage probably consisted of short path streams, carrying locally sourced sediment.

Several attempts have been made to estimate temperature, and the results for southeastern Australia are summarized by Douglas et al. (in 44). Their results based on palynology and some foraminiferal analyses suggest cool conditions until the Santonian, then temperature and humidity increasing to the end of the Cretaceous.

Oxygen isotope studies of many individual belemnites from this interval are summarized by Stevens and Clayton (117). The care that must be taken in interpreting the available data is emphasized by Stephens and Clayton. Their results suggested that in the Turonian-Coniacian (the earliest part of the time interval under consideration) New Zealand seas were "markedly warmer" than at present, that temperatures decreased somewhat in the Santonian (but remained "slightly warmer" than at present), and rose again during the Campanian and Maastrichtian. In general these results are in keeping with the faunal evidence from Western Australia but by the Campanian-Maastrichtian, New Zealand and Australia were well separated. The results for the Santonian are markedly different from the foraminiferal evidence for cold conditions in the Otway Basin.

An interesting report is that by Webb and Neall (133) of Maastrichtian warm water foraminifera from Taylor Valley, Antarctica, suggesting that the warm current down the eastern Australian margin flowed far enough south to carry warm waters to about 85°S. There is also the possibility of sedimentary basins existing below Antarctic ice, through which waters may have flowed from a western direction.

In summary, there is evidence that the Later Cretaceous was markedly less humid than the Earlier Cretaceous. Effective drainage is restricted to a few coastal areas. Coal swamps were present sporadically in the offshore Gippsland Basin and Otway Basin but the coal swamp environment was probably much less prevalent than at any prior period in the Mesozoic.

Study of the palynology of Cretaceous rocks, particularly from

Queensland (37 , 95) has revealed angiosperm pollen present in Late Albian-Early Cenomanian rocks, but apparently it is absent from earlier sediments. It thus seems that angiosperms arrived in Australia later than they did in Europe. Their arrival in Australia foreshadowed major vegetation changes.

CENOZOIC (65 million years - present)

Information for the Cenozoic is much more readily available than for earlier time intervals. There are several reasons for this.

Firstly, outcrop is much better and more accessible than for older rocks. This is accentuated by the fact that Cenozoic rocks are more abundant near our centres of population and also because they are penetrated very commonly during oil exploration. Secondly, the rocks are more commonly marine than are older sequences. Thirdly, the fossils recovered from the rocks are more closely allied to living forms and therefore environmental interpretations are more reliable. The Cenozoic is of immediate relevance because we live in it and because events in the Cenozoic can be seen to have been directly involved in shaping our present environment.

Sedimentary rocks are the most common rocks in the Cenozoic of Australia, but igneous are still common, being very important in eastern Australia, and also of interest in the Canning Basin of Western Australia.

New Zealand and Australia separated in the Late Cretaceous (63) but the opening of the Tasman Sea continued until the end of the Paleocene, about 60 m.y. ago. There is no evidence of sea floor spreading in the southern and southeastern part of Australia until 53 m.y. ago, when a spreading ridge entered between Australia and Antarctica. This spreading system put Australia and Antarctica on separate lithospheric plates and the system is still operating. At the same time (53 m.y. ago)) the spreading system between Australia and India ended and the two continents were then joined on one lithospheric plate.

In the following discussion of the Cenozoic, I will to a large extent restrict my remarks to Australia and New Guinea, consisting of one piece of continental crust. From this time New Zealand is separate and no longer part of the Australian story.

The history of rock accumulation in the Cenozoic of Australia is dominated by three factors. Firstly, on the western and southwestern margins, sediments are dominantly carbonates reflecting the absence of effective drainage activity. Secondly, and superimposed on the first is the probability that, as in the Late Cretaceous carbonates, sedimentation occurred in a regime of fluctuating sea-level probably usually under tectonic control (103, 107). Thirdly, in eastern Australia, the configuration of basins and the history of volcanism are controlled by tectonic factors related to the Australia - Antarctica breakup.

The Cenozoic history will be discussed under the four sedimentation cycles recognized by Quilty (103).

Much of the evidence on Tertiary environments, particularly sea water depth and temperature, is based on studies of foraminifera by numerous authors, but the papers are too numerous to list in a work of this scope and in recent years there have been further results based on palynology. Palynological studies are greatly advancing our understanding of history in the central part of Australia, but we are still far less knowledgeable about that area than about the marine environment. Large areas of the non-marine Cenozoic, particularly in Western Australia, the Northern Territory and

Queensland, are very poorly dated and they make little contribution to the following discussion even though potentially they have a great deal to tell. Some have been discussed by Lloyd (81 ,82).

Zonation

The Cenozoic was divided into a series of zones based on planktonic foraminifera by Blow (12) and Berggren (10) and while some new schemes with finer time intervals (e.g., 116) have been devised, Blow's scheme is employed here (Figure 9).

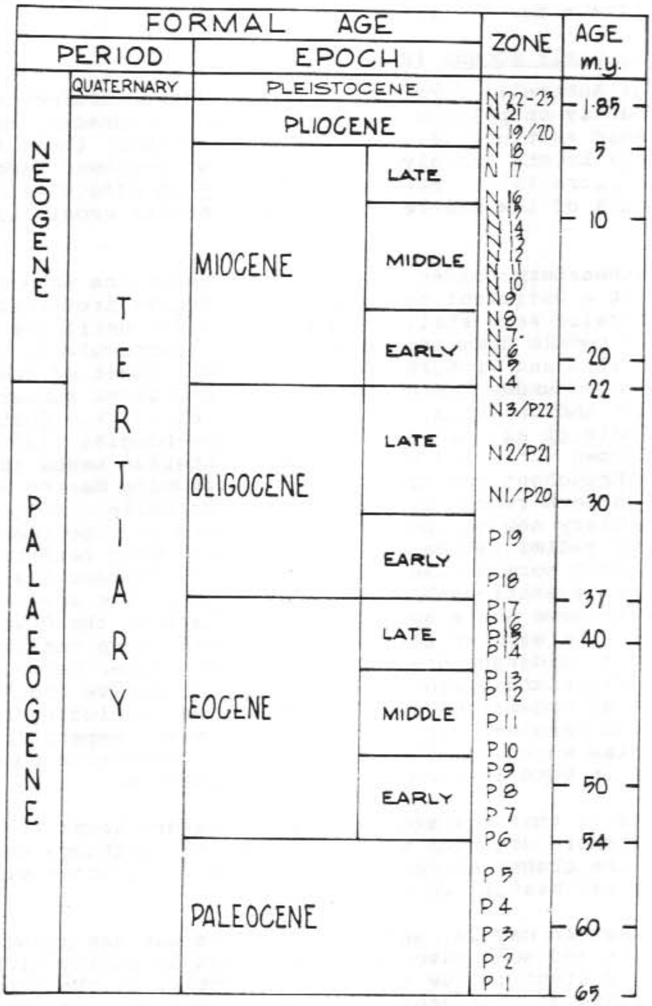

FIGURE 9. Zonation of the Cenozoic (after Blow, 1969).

The transition from the Cretaceous to Cenozoic was very marked especially in planktonic organisms. Within about one million years there was almost a complete change in the composition of the marine plankton worldwide. The cause is unknown and many theories have been proposed to account for the drastic change. It seems to correspond to a marked depression of sea-level, so that sections representing the transition are rare. In Australia there are no known transition sequences on shore and sediments older than the P3 or P4 zones (Figure 9) are very rare.

The Cenozoic of Australia is not well known in Queensland, but elsewhere there seems to be adequate data available for some reliable assessment. The marine data from Queensland are post Eocene (93, 64) and the non-marine data are few (60).

Cycle 1. Paleocene-Early Eocene (Figures 10, 11)

In areas of Australia marginal to ocean basins, sedimentation consisted predominantly of pelagic carbonate with a prograding habit well documented by seismic sections (e.g.107). In this case, there formed a Late Paleocene-Early Eocene (mainly P4-P6) wedge of sediment under high sea-level conditions (Figure 10). There was virtually no effective drainage so intervening intervals of low sea-level produced neither erosional relief nor sediment.

On the southeastern corner of Australia conditions were different tectonically so that a different sedimentational regime prevailed. Antarctica and Australia were still joined (Figure 11) until the late part of the interval and gentle downwarping was active, particularly in south-eastern South Australia and Victoria and on the west coast of Tasmania. Sedimentation commenced under restricted marine conditions summarised by Boeuf and Doust (13) and Deighton, Falvey and Taylor (35). Further details are available in Abele et al. (in 44), Wopfner and Douglas (140), Ludbrook (85), Denham and Brown (36) and others. Sedimentation seems to have been almost continuous throughout the early Tertiary becoming marine when sea-level rose in the pattern recognized in Western Australia (Quilty, op. cit.). Some very early Tertiary non-marine sand accumulated in topographic lows but the main interval of sedimentation was in P3-P6 time when restricted marine conditions held. Seven more marine intervals are recognized (Taylor in 140) and can be related to eustatic sea-level fluctuation. The sediments are mainly sandstone with some shale and marine carbonate in the Otway Basin. In the Murray Basin, the earlier part of the Renmark Group consists of dominantly non-marine sandstone grading upwards into finer carbonaceous sediments. In the Gippsland Basin, many faults were active and the sediments accumulated consist of non-marine and deltaic facies, including coal, in the northwestern part and marginal marine to the southeast (especially offshore). The basaltic volcanism which commenced in the Late Cretaceous continued, and is recognised (136) in both eastern and western Victoria.

No sediments of this age are known from western South Australia or from southern or offshore southern Western Australia, although equivalents can be expected in the graben along the south coast. No other evidence is available of geological history in this interval.

Along the western margin, sediments of this age are known from many oil exploration wells and some have been documented by Quilty (101, 102). Usually terrigenous content is low and the sediments show the progradational habit so characteristic of continental margin carbonates. Thicknesses are generally less than 200 m, but more than 500 m are recorded from the Ashmore Block and 300-400 m occur on the southwestern Rankin Platform.

An exception to the clean carbonate regime occurs in the Perth area, where an embayment under the present city extended east to the Darling Fault and was filled with marine shale and siltstone. Details are contained in Quilty (106).

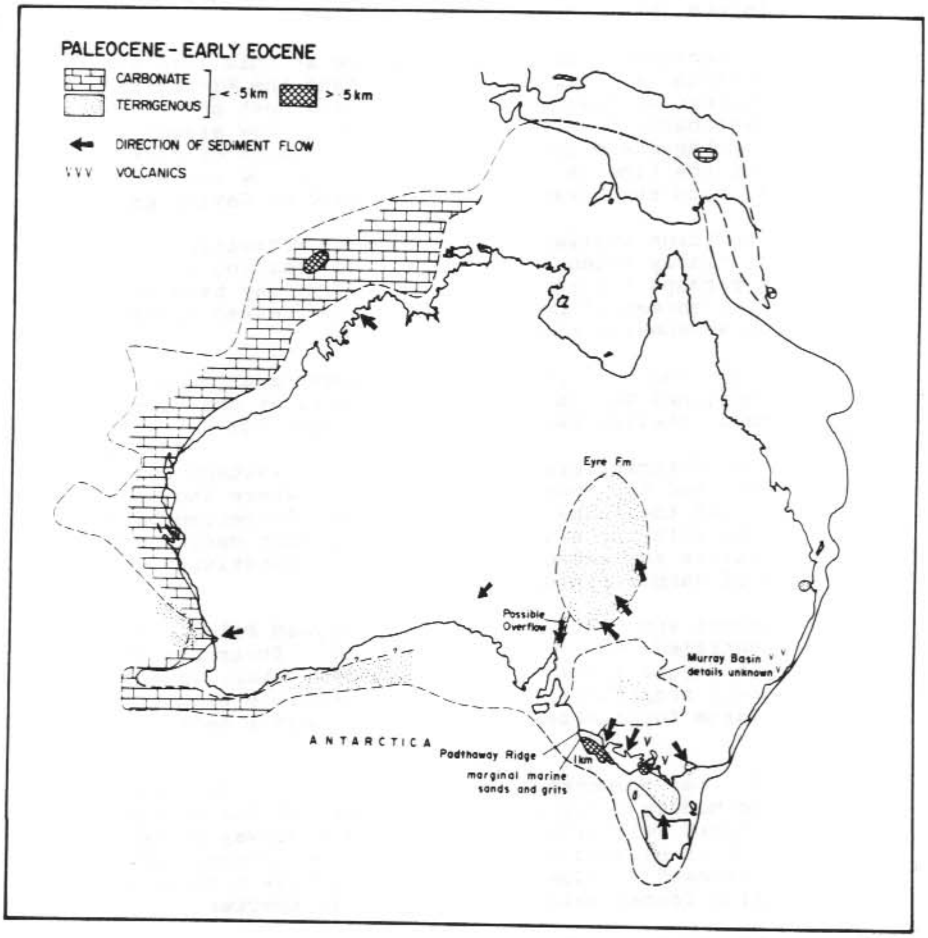

FIGURE 10. Paleocene-Early Eocene palaeogeography of Australia.

Farther north, Timor seems to have accumulated the same carbonate facies as did the Northwest Shelf of Western Australia, but drainage was active on the Kimberley Block, and continental to marginal marine sediments are known around the margin of the Kimberley Block (96).

The little known of the Paleocene in New Guinea is based on Belford (8, 9) who showed that quite thick sections of P4 age are present. The total thickness of zones of particular ages is not yet known. The sediments identified with this interval consist of limestone and calcareous mudstone.

In central Australia, the Eyre Formation (141) accumulated as a thin blanket over Cretaceous rocks, separated by an unconformity probably representing approximately 40 m.y. Epeirogenic movements in the Paleocene may have initiated the development of a broad depocentre, perhaps with an overflow to the southwest. In this the Eyre Formation accumulated, with an average thickness of about 40 m but locally as great as 100 m. Details of stratigraphy within the Eyre Formation are not well known and sedimentation may have been continuous until the Late Eocene.

Evidence of significant effective drainage at this time is restricted to southeastern Australia, the Perth area and around the Kimberley Block, with that in southeastern Australia being by far the most effective. In consequence it is reasonable to suggest conditions of low effective drainage except in southeastern Australia. This scenario of little effective drainage at the time is consistent with the low input of terrigenous material into the ocean basins suggested by Davies et al. (33).

All the information available from the Eyre Formation (141) suggests the presence of a spatially extensive river system draining into a broad depression, forming perhaps a large lake system which may have drained to the south by way of an ancestral Lake Frome. The suggested climate was "warm temperate with seasonally high precipitation".

Deighton et al. (35) in part following Boeuf and Doust (13) suggested the area marginal to southeastern Australia at the time was of low relief with "broad, shallow marginal marine areas" (35).

The planktonic foraminiferal faunas from southeastern Australia are sporadic in occurrence and not abundant in the rocks where they occur, a character in common with the fauna in the Kings Park Formation beneath Perth. This contrasts with the situation in the western margin carbonate facies where foraminifera are extremely abundant and constitute an important component of sample residues.

Berggren, Aubert and Tjalsma (11) have analysed Paleocene foraminifera and identified three main faunal types. Their Tethys Carbonate Fauna (with larger foraminifera of shallow water, inner to middle shelf aspect) is absent from Australia, with the possible exception of New Guinea (8), where large foraminifera occur in the Lagaip Beds, of unknown age.

McGowran (88) has commented on the similarity of the Victorian forms to those of the Midway Group of the Gulf Coast of the United States. These similarities accord well with the concept of a Midway Faunal assemblage (11), which is equated with a middle to outer shelf environment in a shale-marl environment. McGowran (88) further saw a difference in northwestern Australian faunas which lack aragonitic species.

The Paleocene was a period of rather cosmopolitan faunas suggesting low differentiation of polar-equatorial environments, as in the Maastrichtian. The Australian evidence supports this concept. Australian palaeogeography in the Paleocene was probably very similar to that in the Maastrichtian, with neither cold nor tropical conditions but with a generally arid climate, except in southeastern Australia.

A scheme of oceanic circulation patterns was proposed by Edwards (47) and agrees with that of Deighton et al. (35). In the Paleocene, Australia and Antarctica had an essentially continuous continental crust but were separated by a major rift valley system. No oceanic circulation occurred between them and perhaps the ocean entered southeastern Australia as a result of a slight sinistral rotation of Australia (30). Evidence from south of Western Australia is needed to clarify this point.

With the continents of Australia and Antarctica still in contact, it would be expected that a northerly directed current (apparently warm but not tropical) bathed the western margin and that a southerly directed offshoot of the Pacific equatorial current operated down the eastern coast passing between the Lord Howe Rise-New Zealand continental block, and Australia.

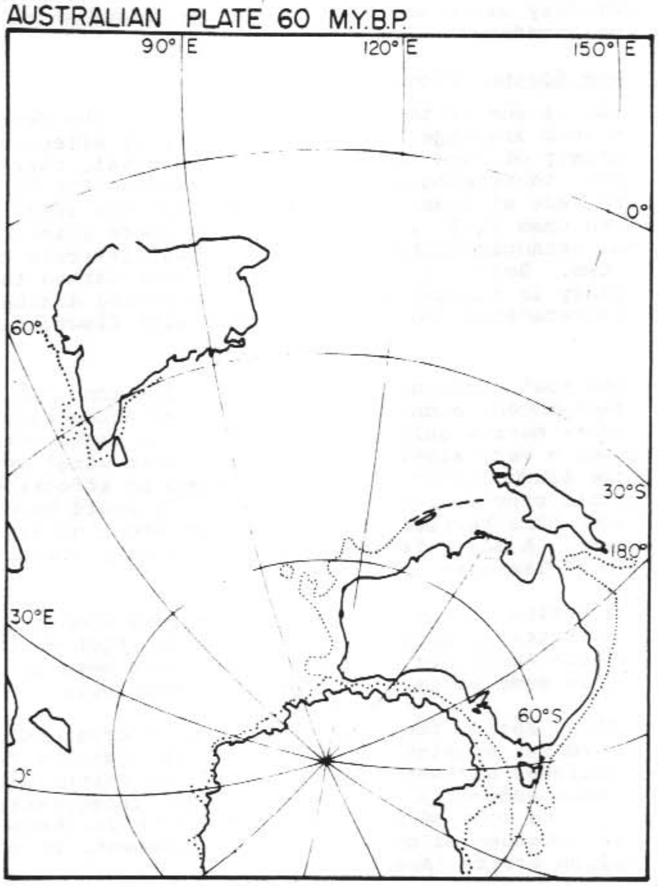

FIGURE 11. The location of Australia in the Paleocene (60 m.y.).

The latter current, being close to its warm source, would account for the warm surface water temperature (18-20°C) recorded by Shackleton and Kennett (112). Equivalent information is not available for Australia but perhaps the situation in New Zealand also held true for southeastern Australia at that time. Hornibrook (66) has summarised the New Zealand biological evidence which suggests conditions were warmer than at present.

One of the important contributions made by Shackleton and Kennett (112) is that subsurface waters were warmer than in post-Eocene time. This was the time immediately preceding breakup of the continents. In the East African Rift mode of breakup (128) which is readily applicable to the Early Cretaceous breakup of southwestern Australia, general doming precedes breakup and continental margin subsidence follows. Along the southern margin of Australia there is no evidence for this mode of breakup. The continents simply drifted apart, apparently leaving the margin more or less unaltered.

The separation of Australia and Antarctica by continental drift began at a date variously given as 53 or 55 million years which approximates the Paleocene-Eocene boundary.

Cycle 2. Middle-Late Eocene (Figure 12)

This interval is one of the most interesting in the Cenozoic as it marks the last time when drainage systems show signs of effective activity. There is a great variety of rock types from this interval, representing marine and non-marine, terrigenous and carbonate facies (Figure 12). Within this interval, there were at least two phases of high sea level, with a brief sea level low between them (103, 107) and in areas where planktonic foraminifera and calcareous nannoplankton are absent, it is difficult to distinguish the results of the two. Beard (7) suggested that this marked the onset of the modern cycle of aridity in Australia. From the foregoing discussion I believe it began in the mid-Cretaceous and has continued, with fluctuations, ever since.

The first and most obvious area of change was along the south coast. At about the Paleocene-Eocene boundary, Australia and Antarctica began to move apart and a narrow marine gulf opened between the continents. However there probably was not a very significant flow of ocean water between, as south of Tasmania the South Tasman Rise still formed an effective submarine barrier to free oceanic circulation. West Wind Drift would have carried surface sea water over this barrier but Bass Strait shows no signs of being a conduit of this type. A major fracture zone of closely spaced transform faults operated west of Tasmania.

Early Eocene marine conditions became much less widespread after P6 and there followed an interval until about P11 during which marine sediments are seldom recorded from Australia. This may well have been an interval of considerable erosion in some parts of southeastern Australia.

In the Gippsland Basin, the history in this interval is complex and consists of fault movement, erosion of channels in the Latrobe Valley Group (while deposition continued elsewhere), filling of the channels by estuarine fine grained terrigenous sediments as a major marine transgression occurred, and basalt intrusion using some of the faults as intrusive channels. The faulting probably was accompanied by anticline development, in turn causing erosion of the anticline crests (Abele in 44).

In the Otway and Murray Basins the late Early Eocene and early Middle Eocene often are represented by an unconformity but elsewhere by continuous non-marine terrigenous sediments. Following this phase, marine conditions developed, more strongly in South Australia (85) and more weakly to the east. Where open marine conditions prevailed the Late Eocene is carbonate rich in contrast to the more terrigenous Middle Eocene.

Farther west, the Middle Eocene pulse of this cycle has been identified in the Eucla Basin in terrigenous sandstone (89) and the Late Eocene pulse in both the Eucla Basin and Bremer Basin, the latter in the form of the Plantagenet Group (98,25) which is predominantly terrigenous with carbonate lenses.

Along the western margin, the Middle and Late Eocene pulses can be separated (103), in particular in the Perth area where the Middle Eocene is terrigenous and the Late Eocene is biogenic carbonate. In the Carnarvon Basin, the sediments near the present coast are carbonates which can be divided readily into shallow water, shelf and slope or deeper facies (101,102). To the east there are two areas of Middle or Late Eocene terrigenous sediments, one marine (Merlinleigh Sandstone) and one non-marine (Pindilya Formation). By analogy with the Perth Basin situation, it is reasonable to suggest that the terrigenous phase was Middle rather than Late Eocene. Farther north, Timor still accumulated carbonates, as did the Kimberley Block, in contrast to earlier times.

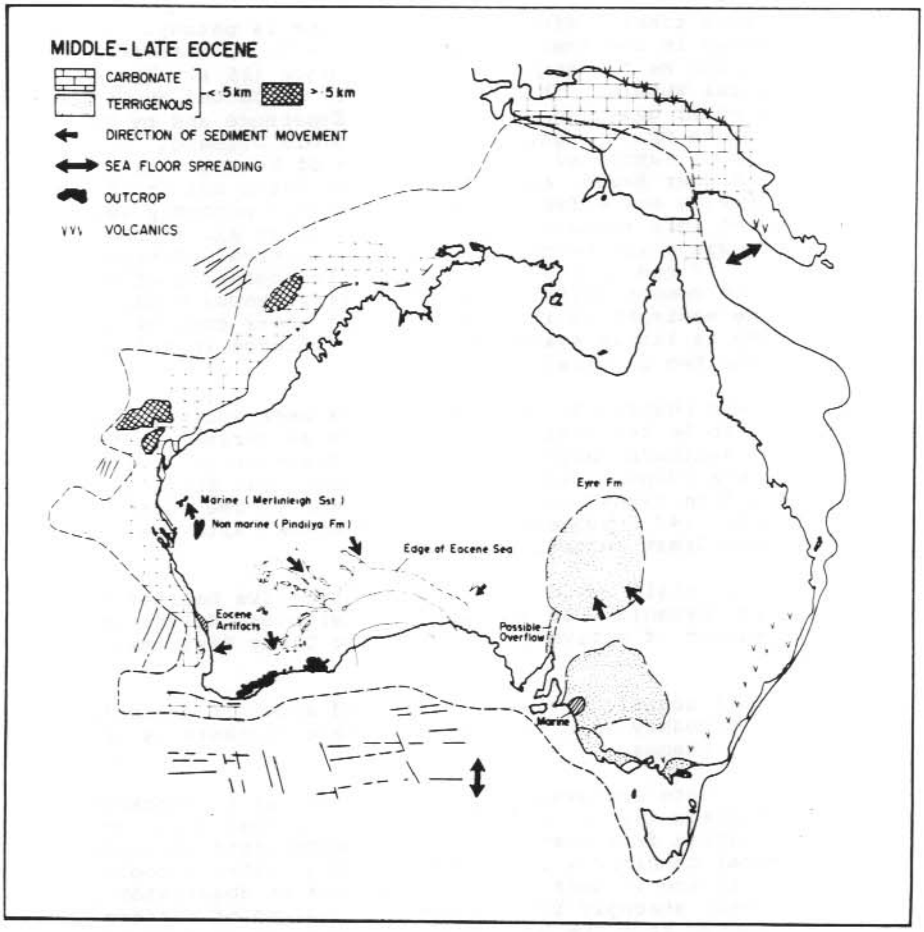

FIGURE 12. Middle-Late Eocene palaeogeography of Australia.

In New Guinea, the Eocene was a period mainly of shallow water carbonate accumulation, with very little Australia-derived terrigenous content. Some locally derived terrigenous material was supplied by emergent areas. Along the present north coast, deep water carbonates were laid down and include submarine volcanics.

There is some evidence of the Eocene on the continental areas of Australia. Lake Eocene was recorded by Balme and Churchill (3) from Coolgardie and by Hos (67) from the south coast. Wopfner, Callen and Harris (141) suggested that the Eyre Formation was still forming in the Late Eocene but that there may be a disconformity within it. The major development was in the Middle and Late Paleocene.

Central Australia underwent some epeirogenic movement in the Eocene (141) and following this, there was a period of silcrete development, perhaps continuing into the Oligocene.

As with earlier times, information on climate is patchy. Large foraminifera are common in the shallow marine sediments of Western Australia and New Guinea and occur as far southeast as Esperance (25). These indicate subtropical to tropical waters. This hypothesis is supported by Cockbain's (25) record of warm water dasycladacean algae at Esperance and by Hos' (67) analysis of palynomorphs which suggested a warm, humid climate. The humid aspect of the climate is supported by the presence of terrigenous sediments in the Eucla Basin, Bremer Basin, onshore Carnarvon Basin and in the area of Perth. Thus an extensive and effective drainage system probably was active, the last time in which this seems to be true. Davies et al. (33) have suggested that there was a worldwide Middle Eocene interval of higher sedimentation and runoff and in the Late Eocene, the beginning of an arid, low runoff phase. The common differentiation of terrigenous Middle from carbonate Late Eocene sediment is in agreement with their conclusion, particularly as there is little evidence of any difference in relief conditions between the two intervals.

In southeastern Australia, drainage systems were actively supplying terrigenous sediment to be redistributed by the sea as marine conditions prevailed across the southern margin. The characteristics of several species of foraminifera (unpubl. information) suggest that there was a temperature gradient from higher in the west to lower in the east. This conflicts with Edwards' (47) suggested gyre development with its westerly flowing current in the Great Australian Bight.

The Tasman Rise still would have been an effective barrier to much current flow south of Tasmania. In consequence, Deighton, Falvey and Taylor's (35) suggestion of active currents in the Otway Basin may have merit.

Because no full oceanic circulation existed south of Australia, the east and west coasts probably were washed by the same currents as in the Paleocene and Late Cretaceous.

Oxygen isotope data are available from Dorman (40), Shackleton and Kennett (112) and Devereux (38). Hornibrook (66), Dorman (41) and evidence from foraminifera from Australia all are consistent in suggesting subtropical to tropical conditions in the Late Eocene, after a cooler Early and Middle Eocene. All are in conflict with the data in Shackleton and Kennett (112) which very strongly imply a general cooling of surface waters over the Campbell Plateau from the Late Paleocene through Late Eocene. The pattern is of Australia and New Zealand in the Eocene being considerably warmer than the waters of the Campbell Plateau. This is consistent with the palynological evidence of Kemp and Barrett (77). The general change in surface waters of the Campbell Plateau occurred also in the deeper waters. There was still no significant difference in temperature between surface and bottom waters. Thus there was no substantial cool current input caused by major glaciation on Antarctica and Nothofagus-dominated vegetation probably was still widespread on Antarctica (77).

Bunting, van der Graaff and Jackson (16) and Lowry (85) and especially van der Graaff et al. (127) and Finkl and Fairbridge (51) have contributed very significantly to our knowledge of Eocene palaeodrainage systems with an analysis of such systems in southern Western Australia and Barnes and Pitt (5, 6) have done similar work in South Australia. They show convincingly that a major drainage system operated towards the south coast, with major activity at some time between the earliest Cretaceous and Late Eocene. Their evidence further shows that the large valleys formed by this major drainage system were filled by the Late Eocene marine incursion and that any subsequent drainage in them has been very minor. The evidence of terrigenous sediments in the Eucla Basin (84) suggests very strongly that the main period of activity was Early Cretaceous, and, one may add by analogy with the Perth Basin and southeastern Australia, in the Late Paleocene.

In central Australia, there may have been some active drainage into the area where the Eyre Formation continued to accumulate under conditions similar to but less active than in the Late Paleocene - Early Eocene. Wopfner, Callen and Harris (141) suggested increasing seasonal aridity to explain the development of the widespread silcrete in the Eocene, possibly continuing into the Oligocene.

Throughout the Eocene, Australia and Antarctica were separating and across most of the southern Australian margin, contact was completely sundered. However, western Tasmania and the northeastern part of Victoria Land in Antarctica, were sliding past one another along a fracture zone. Thus while some ocean may have intervened, a short migration path continued to exist until the close of the Eocene. In consequence, until this time animals and plants had a reasonable migration route from Australia to Antarctica, and vice versa. Thereafter the probability of migration decreased.

Cycle 3. Oligocene-Middle Miocene (Figures 13, 14)

In any discussion of Australian aridity, this interval is critical. The Middle Eocene rocks contain evidence of considerable river action, the antithesis of what would be expected from a major arid period. The modern arid zone can be said to have originated after the Middle Eocene (see also 7), and the Oligocene-Middle Miocene contains evidence of aridity perhaps more drastic than that of the present.

Sea level fell quite markedly very early in the Oligocene, perhaps as much as 200-250 m (107), and rose again towards the end of the Oligocene, leading to a major transgression. There was a short interval (1-2 m.y.) of lower sea level towards the end of the Early Miocene, but sea level rose again in the earlier part of the Middle Miocene to produce a transgression comparable in area with that of the Late Eocene, although probably not representing as high a sea level as that in the Late Eocene. These eustatic sea level changes have had a great effect on the distribution of sediment.

A clearly important factor whose impact is difficult to assess, is the radiation and geographic spread of the grasses. Little is known of the history of this group but grasses apparently became widespread in the Early Miocene in North America. Their history in Australia is poorly known but an Early Miocene spreading of this group would have had an inhibiting effect on sediment movement.

Other important changes occurred in the Middle Miocene and their effects were to be even more important in the next time interval. Australia and Asia collided, affecting the configuration of New Guinea and quite markedly altering geological patterns throughout northern Australia. This was the impetus for development of large surface anticlines in northwestern Australia and in part may have been responsible for the origin of the volcanic rocks of the northwestern Canning Basin. This was probably the time of major uplift of the Pilbara Block which then experienced rejuvenated drainage which in turn supplied some quartz sand to the ocean via the Fortescue and Ashburton river systems. Callen (20) suggested that formation of the Flinders Ranges was initiated in the Middle Miocene.

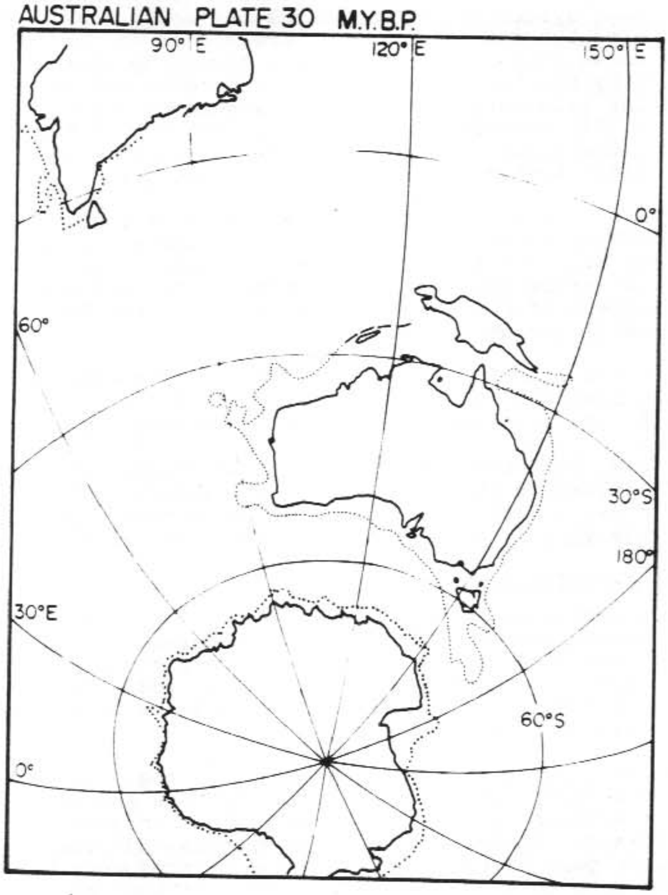

FIGURE 13. The location of Australia in the Oligocene (30 m.y.).

Spreading continued across the southern margin of Australia (Figure 13) and the South Tasman Rise had cleared northeastern Victoria Land so that there was free oceanic circulation between the two continents. This circulation probably reached full development late in the Late Oligocene after an earlier interval of lesser flow. It also meant that migration involved much longer distances over open ocean, a marked change from the earlier pattern. Details of Australia at the time are shown in Figure 14.

Across southern Australia, tectonic activity declined considerably. In southeastern Australia, deposition at one locality or another continued throughout the interval and both marine and non-marine sections are well represented. During intervals of high sea level, marine sedimentation was normal.

The story in southeastern Australia involves very complex facies relationships. In the Gippsland Basin and Victoria's Central Coast Basins, continental sediments with coal measures accumulated throughout the Oligocene and Miocene while marine sediments accumulated elsewhere in the same basins. The marine rocks throughout the Early and Middle and earlier part of the Late Oligocene consist of paralic sediments in the Murray Basin, and marl, and terrigenous units elsewhere. By the later Late Oligocene and into the Early and Middle Miocene, carbonate sediments became widespread in shallow water facies and their equivalents, marl and calcareous mud, were deposited in the deeper marine environment. An episode of basaltic volcanism was widespread about the Oligocene-Miocene boundary.

In Tasmania, the Tertiary marine rocks are restricted to the Early Miocene (99) and consist predominantly of calcareous sediments, especially in the later part of the Early Miocene.

In South Australia, the history is similar to that of Victoria except that a series of fault-bounded structures make generalisation difficult. However, the Oligocene to Middle Miocene sediments commonly are bryozoal limestone although thin and lenticular units of sand, marl and clay are quite common.

No definite Oligocene marine sediments are known from southern and southwestern Western Australia but the overlying Early and Miocene rocks are limestone(84, 101, 102) and the only evidence of terrigenous content consists of the areally small Colville Sandstone, an equivalent of the Nullarbor Limestone.

Along the northwest margin, dominantly biogenic carbonate sediments accumulated with the most marked prograding habit of any of the Cenozoic sedimentational cycles. Any trace of earlier basinal configuration has been obliterated and the 0 and 500 m isopachs are roughly parallel to each other and to the coastline. On the Rankin Platform over 1000 m of sediment accumulated. Sediments of this age are quite thick on the Sahul Platform, approaching 1000 m in thickness but thin over Timor which underwent a major orogeny at this time (28), although Carter, Audley-Charles and Barber (23) would place it a little later, in the Pliocene. Shallow water sediments contain an unconformity in the Early Miocene.

On the western side of Cape Range, and extending northeasterly offshore, is a narrow, poorly defined zone of quartz sand recognized in several oil exploration wells. The sand seems to be that of an old beach as the grains are well sorted, commonly frosted and contain large foraminifera.

In New Guinea, the earlier relatively simple transition from continent to deep sea gave way to a marked orogenic phase which continued into the Miocene. Epeirogenic uplift in the south led to widespread erosion and folding in orogenic style commenced farther northeast. Parts of New Guinea now became sediment source areas, and others deep basins, and terrigenous sedimentation with local source areas became widespread. Sediment thicknesses vary greatly but can reach 3000 m locally. The importance of this phase in New Guinea is that it marked the beginning of a continuing history of emergence. From the Oligocene onwards, an increasing proportion of the New Guinea area has been emergent.

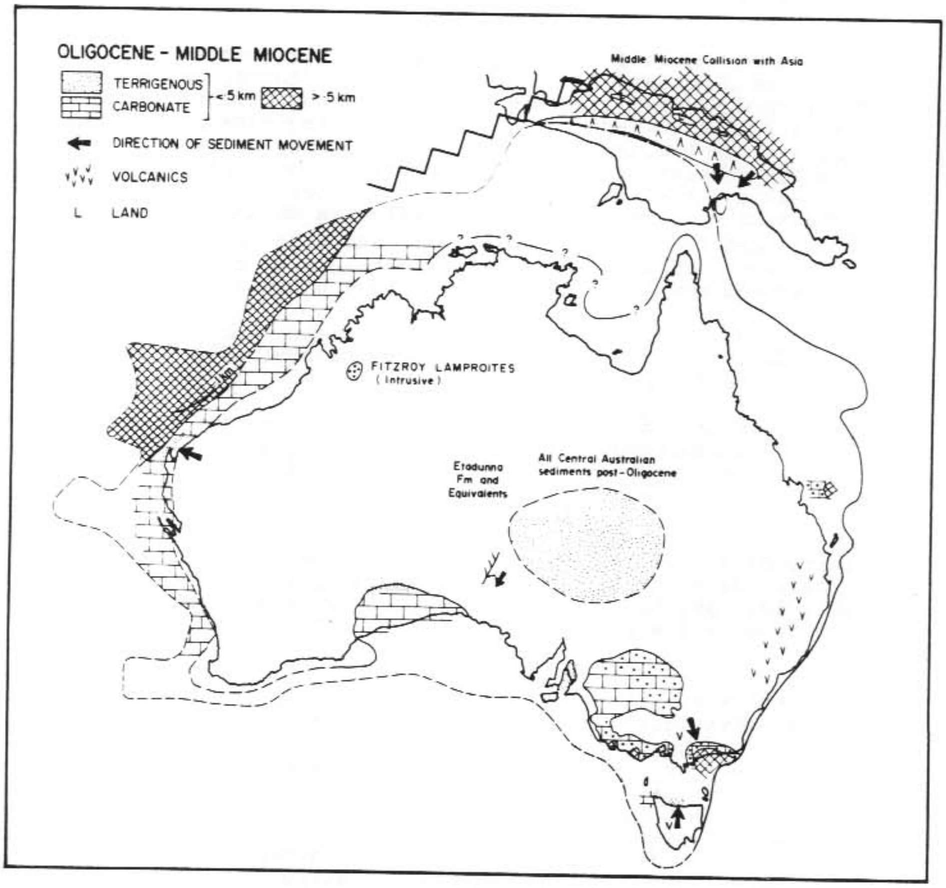

FIGURE 14. Oligocene-Middle Miocene palaeogeography of Australia.

Little is known of the marine Cenozoic of Queensland but both Palmieri (93) and Hekel (73) have produced data for wells in the Capricorn Basin. About 1000 m of rocks of this age are known from Aquarius No. 1, consisting mainly of biogenic carbonate with varying amounts of fine terrigenous material.

In Central Australia, the Oligocene apparently is not represented by clastic sediments but the formation of surface silcrete, initiated in the

Eocene, continued (141, 21). The Etadunna Formation and equivalents were deposited in the Miocene and consist of chemical limestone and ferruginous and clayey sandstone with primary dolomite. Rocks of this sequence contain rich vertebrate faunas, the study of which was initiated by Stirton, Tedford and others.

The phase of silcrete formation seems to coincide with the main period of ferruginous lateritisation in Western Australia (73, 111). Davies et al. (33), have suggested a worldwide arid interval at this time but some seasonal humidity would be expected for Australia.

Palaeogeography

The Oligocene and Early Miocene seem to be the only time intervals during which direct migration paths to Australia from other continental masses were absent. Before the Oligocene, there was some form of contact with Antarctica, and since the Middle Miocene, with Asia. Thus it seems that the earliest known Australian marsupials (diprotodonts from the Geilston Travertine in Tasmania,(123)) of Late Oligocene or older age, represent a group that entered not by Asia, but perhaps by Antarctica, or even originated here and migrated elsewhere, at least initially, via Antarctica.

Groups of terrestrial organisms which migrated to Australia via Antarctica can be expected to be represented in rocks of all ages but can also be expected to have diverged from their coeval Antarctic cousins, particularly since the Late Eocene-Early Oligocene. Forms which originated in Asia cannot be expected in rocks older than Middle Miocene, suggesting that the marsupial migration path (whether to or from Australia) was through Antarctica.

The Oligocene-Middle Miocene includes in its products little evidence of active drainage, perhaps even less than would be expected from today's drainage. In the Late Oligocene-Early Miocene in particular, marine sediments are predominantly biogenic carbonates, to a degree much greater on a continent-wide scale than at any other time in geological history. This suggests that rivers were carrying very little sediment to the sea other than along the northern margin in the New Guinea region. As in earlier Cenozoic intervals the pattern is in marked agreement with that discussed by Davies et al. (33) who speculated that it might indicate a worldwide period of great aridity at the time.

By Middle Miocene times, the climate had changed dramatically and the rocks containing the vertebrate faunas of Central Australia show evidence of large lakes and wooded areas with eucalypts (118,20), suggesting more hospitable conditions there than at present. Callen (20) further suggested seasonal aridity and generally low relief. The fossils recorded by Lloyd (81 , 82) could be regarded as compatible with a more humid phase.

Seas around Australia were warm, perhaps even tropical. Australia had moved considerably north of Antarctica, the circum-Antarctic current was properly developed and by late in the Early Miocene, faunas of large foraminifera occurred as far south as Tasmania (99).

Planktonic foraminiferal faunas from western and northwestern Australia show marked tropical affinities. This is also true of those from New Guinea and Queensland. Southeastern Australian faunas are considerably less diverse and suggest some lower general surface temperature of ocean waters, with the exception late in the Early Miocene of warm water Batesfordian faunas. Palmieri (93) noted some affinities of the Queensland Oligo-Miocene with the southeastern faunas. Dorman (40) estimated palaeotemperatures based on oxygen isotope data but the data now seem too few, and these palaeotemperatures, while in general agreeing with the faunal evidence, are based on averages, not the preferable minimum values. Thus although they support the faunal evidence, not much reliance should be placed on them.

Data from the New Zealand region are better based and have been reviewed by Hornibrook (66) and supplemented by the oxygen isotope data of Shackleton and Kennett (112). These data probably are very relevant to the history of southeastern Australia. The data of Shackleton and Kennett (112) indicated a marked cooling of surface waters which then remained approximately constant throughout the Oligocene, Early Miocene and up to the early Middle Miocene after which there was another marked general decrease. Also, a prominent feature arising from Shackleton and Kennett's data is the continuing decline in temperature of deeper water, even though surface temperatures remained fairly constant. The Early Oligocene temperature decrease is in agreement with the interpretation of Edwards (46) based on calcareous nannoplankton. Australian benthic faunal evidence, and also much evidence from New Zealand given by Hornibrook (66) indicated very warm conditions toward the later part of this interval.

To these data must be added the information summarised by Hayes and Frakes (62), Kemp (76), and Kemp and Barrett (77) on the onset of Antarctic glaciation, based on analysis of ice rafted detritus, sedimentation rates and palynology. Glaciation seems to have become widespread in the Late Oligocene and to have removed effectively all vegetation from Antarctica. The last phases of vegetation survived in an "alpine temperate-type of glacial environment" (76). In Early and Middle Miocene times, glaciation expanded and covered essentially all of Antarctica but extensive ice shelves did not develop.

The rapid deterioration in climate and the extent of the Late Oligocene icecap probably meant extinction for most of the Antarctic terrestrial flora and fauna and probably also destroyed most evidence of the earlier biota.

<u>Cycle 4. Late Miocene-Pleistocene</u> (Figure 15)

In this time interval, Australia evolved the features of its present shape and topography. The pattern of collision with Asia continued, allowing for land path migration of terrestrial fauna and flora. Folding of Tertiary rocks continued in northwestern Australia, and the Flinders Ranges seem to have been elevated. The Kosciusko Uplift may have been most active in this interval.

There is usually an unconformity between marine sediments of Cycle 3 and Cycle 4, reflecting a significant sea level drop and rise, and coinciding with the Messinian salinity crisis (1). As a generalisation, much less of the continent was covered by marine conditions during this interval than during any other Tertiary cycle of high sea level. Later in the interval, the well known glacially controlled eustatic cycle began. Other sea level fluctuations, possible tectonically controlled, have been detected in other parts of the world, particularly during the Pliocene, but studies of the phenomena associated with these fluctuations are in their infancy in Australia.

Throughout southeastern Australia, with the exception of the offshore Gippsland Basin, there is a considerable part of the Middle and Late Miocene for which there is no record of sedimentation. Sediments formed were mainly terrigenous, often paralic and with evidence of marine pulses. The sediments usually are thin and there is no evidence of deep water sedimentation.

In the offshore Gippsland Basin, there is an almost complete record of sedimentation through this interval but there was a very pronounced change to shallow water marine sedimentation with widespread deposition of shoreline to nearshore marine sediments (Abele <u>et al</u>. <u>in</u> 44). Carbonate sediments accumulated in the shallow marine environment, contrasting to events in western Victoria and South Australia. Eventually, in the Late Pliocene, conditions changed to entirely continental ones. Again, sediment thickness is quite low.

Offshore across southern Australia, sediments probably are carbonate sands, but details are unknown.

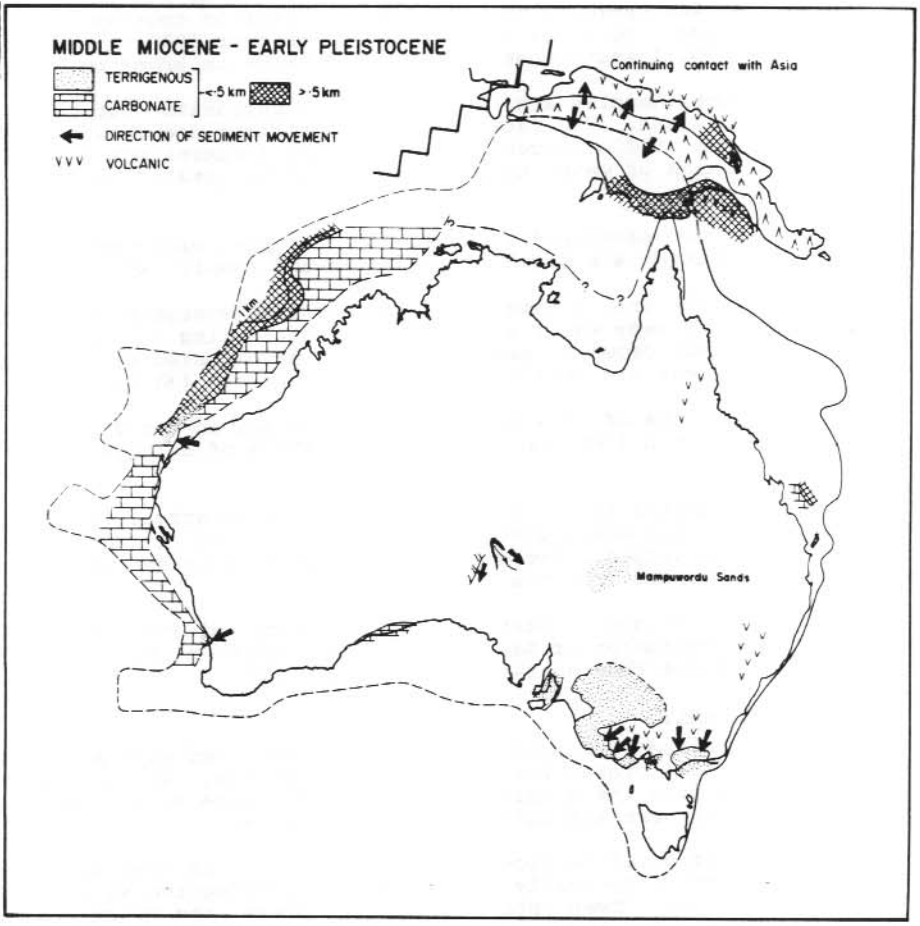

FIGURE 15. Middle Miocene-Pleistocene palaeogeography of Australia.

Quilty (106) has recorded marine carbonate sediments offshore from Perth and Quilty (101, 102) recorded personal communications from A. Beu and G.W. Kendrick mentioning Pliocene molluscs from sandy sediments. The carbonate sediments recorded from oil exploration wells offshore probably eventually will be shown to be quite extensive. Maximum known thickness is about 200-250 m. The absence of terrigenous sediment in Late Miocene rocks and its presence in the Pliocene and younger rocks suggest rejuvenated drainage activity in the Pliocene.

The best known post Middle Miocene is from offshore northwestern Australia. It is clear from Quilty (101, 102) and from information available in Oil Search Subsidy data that the sediments of this age thicken with increasing distance from the coast at a rate greater than for any other rocks in the Tertiary. Sedimentation rates documented for North Tryal Rocks No. 1 (101, 102) are much faster than for earlier intervals and these data combine to suggest a marked increase in the rate of depression of the continental shelf. The reason for increase in sedimentation rate or continental shelf depression is unknown. Rocks of this interval are over 1000 m thick in the North Tryal Rocks No. 1 section and over 2000 m thick in areas on Timor.

The sediments usually are marine biogenic carbonate, but some sections do contain a little sand. The facies generally reflect deeper water than during the Oligocene-Middle Miocene so that larger foraminifera are absent; consequently knowledge of water temperature cannot be obtained by this technique.

On Timor there developed a series of small post orogenic basins whose geology and distribution are shown by Crostella and Powell (29).

The New Guinea area became progressively more emergent during this interval, the zone of deep water sedimentation contracting northward. Thick sediments accumulated, often in small basins and accompanied by volcanism. The progressive changes are well illustrated by Harrison (61).

Marine sediments of this age in Queensland are so far documented only from the Capricorn Basin (93 , 64) where up to 800 m of calcareous mudstone occur.

In Central Australia the interval began with relatively widespread wet conditions (20) but these contracted markedly in the Pliocene as the modern Lake Frome developed. Overall, the area of aqueous conditions seems to have been much reduced from the Middle Miocene.

The mountain ranges of eastern Australia were uplifted, at least in part, after the extrusion of basalt in the Mt. Tomah-Mt. Wilson areas of New South Wales and are thus post-Middle Miocene (137).

Palaeogeography

A land migration route was by now well established with Asia but other contacts had been broken for a considerable period. It is therefore to be expected that from the Middle Miocene onwards, some Asian influence should be seen in northern Australia's fauna and flora.

The distribution of terrigenous sediments suggests that drainage systems were ineffective generally, though not as ineffective as in the Late Oligocene-Early Miocene. Even into southeastern areas, the volume of sediment transported seems quite small, especially when the uplift of the Flinders Ranges and Kosciusko areas was active. Thus even as relief increased in southeastern Australia, drainage became less effective suggesting much increased aridity as Australia evolved into modern conditions. This contrasts with the picture in southwestern Australia where effective drainage became established in the Miocene, even as relief remained approximately constant.

Shackleton and Kennett (112) show that there was a marked sea water temperature decrease commencing in the Middle Miocene (approximately 12 m.y.). This change was dramatic in both surface and deep waters south of New Zealand, and reflects the increase of glacial activity on Antarctica. The effects of this change become most obvious in the Late Pliocene when the major worldwide glacial period seems to have begun. The correlation in this time interval between sea level and glacial activity is obvious but glacial activity should not be used to explain all sea level fluctuations mentioned earlier; many may have been tectonically controlled.

There is ample evidence that these glaciation-controlled temperature changes had an influence on Australia.

From southeastern Australian molluscs, Dorman (40) presented oxygen isotope data. His interpretation of the results has been questioned above because average values rather than minima were used. Use of the minimum value makes the Late Pliocene temperature reduction more dramatic than Dorman envisaged. If the stratigraphic data from Singleton, McDougall and Mallett (113) is incorporated into Dorman's work, it seems that this marked change occurred in approximately Late Pliocene (N20) time. The change is marked not only by oxygen isotope changes but also by decreased planktonic foraminiferal diversity, reflecting decreasing temperature.

The only other area of Australia where comparable information is available is from northwestern Australia. Quilty (101, 102) mentioned briefly results based on studies of planktonic foraminifera from WAPET's North Tryal Rocks No. 1 which was sampled with sidewall cores through a Late Miocene - Pleistocene carbonate section. The comparison with southeastern Australia is very interesting.

Many species of planktonic foraminifera show differences in direction of coiling (sinistral-dextral) depending on water temperature. The underlying control is not known. Globorotalia cultrata (d'Orbigny) is sinistrally coiled in the Late Miocene, changes to dextral (indicating warming in the earliest Pliocene - almost exactly the reverse of the pattern expected from Shackleton and Kennett's curve) and changes back to sinistral (implying cooling), late in the interval P19/20, certainly before P21 (Late Pliocene). To the degree that the comparable change could be detected in southeastern Australia from the information available, the cooling in southeastern and northwestern Australia seems contemporaneous.

Immediately after cooling in northwestern Australia, there is a marked decrease in planktonic content of foraminiferal faunas, indicating a significant decrease in water depth. In my 1974 paper I assumed that this meant the prograding continental shelf edge passed over the location of the well at that time. As an alternative interpretation, it may represent a fall in sea level due to glacial control. The coincidence with the base of the Pleistocene is persuasive.

In earlier time intervals, particularly Late Eocene-Middle Miocene, it has been simple to use the presence of large foraminifera as an index of warm water (subtropical or warmer). This use is by analogy with the distribution of modern larger foraminifera. In the Late Miocene-Pliocene, there is very little evidence of larger foraminifera in most areas studied, suggesting that conditions were generally cooler than earlier. This evidence agrees with the oxygen isotope studies but cannot be regarded as conclusive because the facies accumulated do not appear to be ideal for the existence of large foraminifera.

In summary, though the data for this time interval are sparse, it seems that the Late Miocene-Pliocene was generally a time of increasing aridity and generally cooler sea water temperatures, decreasing markedly at the end of the interval as the Pleistocene glacial period got under way. The suggestion of generally increasing Australian aridity is in marked contrast to the suggestion by Davies <u>et al</u>. (33) for increasing drainage activity worldwide during this interval although their general trend may be in keeping with the data from southwestern Australia. This is the only Cenozoic interval in which the Australian picture is at variance with that elsewhere.

SUMMARY

From the Triassic, Australia became progressively more detached from other elements of Gondwana until the Miocene, when it collided with Asia. As part of the breakup sequence, the continent underwent predominantly tensional tectonics at its margins. In consequence, margins of the continent have generally had a higher elevation than central Australia and this has led to long term drainage over low gradients to central Australia, a pattern that exists today.

The continent seems generally to have been arid during the early Triassic with rivers periodically carrying sediment through an arid landscape. Aridity may also have been a feature of the early Jurassic in the Perth Basin and there seems to have been a gradient from cool to warm temperature in southeastern Australia to warmer and more arid to the west and northwest.

In the Early Cretaceous, Australia was inundated by marine conditions, divided into a series of islands and underwent generally humid conditions. With the withdrawal of the sea, effective drainage seems to have ceased and very little terrigenous sediment to have made its way to the sea. This lack of sediment has meant that clean carbonate sediments accumulated in a warm marine environment. This change from terrigenous to carbonate marine sediments marks a change to less humid conditions, a change which initiated the present cycle of predominantly carbonate sediments in the marine realm. Australian aridity stems from this time.

Since the mid Cretaceous, the Australian margin, other than in the southeast where tectonic factors have influenced climate and runoff, has accumulated carbonate sediments, attesting to reduced effective drainage (probably reflecting increased aridity). The Paleocene-Eocene and Middle Miocene seem to be periods of considerably more humid conditions reflected in the distribution of terrigenous sediment.

The Middle Eocene was the last time in Australian history that extensive river systems operated and the Middle Miocene is the last interval in which humid conditions seem to have prevailed. Late Eocene to Early Miocene carbonate sediments suggest very ineffective drainage in keeping with worldwide patterns at the time (33).

The Miocene collision with Asia coincides with considerable changes in Australia's elevation with uplift common in northwestern and southeastern Australia. This uplift seems to correspond with a period of decreasing effective drainage.

The marked cooling of ocean waters associated with the onset of major glaciation can be recognised in faunas in southeastern and northwestern Australia.

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