## GEOLOGICAL HISTORY AND PALAEOCLIMATE

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This section of the chapter is a synthesis of the Tertiary geological record presented in a palaeogeographic and palaeoclimatic framework that incorporates the broader events affecting Australia, Antarctica and the Southern Ocean.

The general character of the early Tertiary Australian vegetation and the evidence it provides for palaeoclimate can be inferred from palynofloral and, to a lesser extent, macrofloral evidence. However, interpretations of past vegetation from fossil palynofloras suffer from a number of problems including uncertainties about affinities with modern species, the environmental tolerances of fossil taxa and the lack of quantitative data on fossil and modern pollen-spore spectra. In general, all the palaeoclimatic interpretations suffer from the lack of a complete record or from inadequate dating of the terrestrial record.

## CRETACEOUS-TERTIARY BOUNDARY: EARLY PALEOCENE (65-60 Ma)

At the beginning of the Tertiary, southern Australia lay in high latitudes (65-66°S) adjacent to a nascent, narrow Southern Ocean. There is no record in South Australia of marine transgressions during the earliest Tertiary (McGowran, 1991) and the Cretaceous-Tertiary boundary is an unconformity but the hiatus is of shortest duration in the offshore basins (Figs 10.2, 10.41).

The lack of marine sedimentation is in part a reflection of the huge eustatic fall in sea level from its maximum in the Maastrichtian. However, because of problems in defining the boundaries of palynostratigraphic zones, sediments assigned to the largely Late Cretaceous *Forcipites (ex Tricolpites) longus* Zone in the offshore basins may range into the Danian (earliest Paleocene). Thus, the age of the upper part of the Late Cretaceous Potoroo Formation in the Bight and Duntroon Basins and the upper part of the Sherbrook Group in the Otway Basin may extend into the earliest Paleocene.

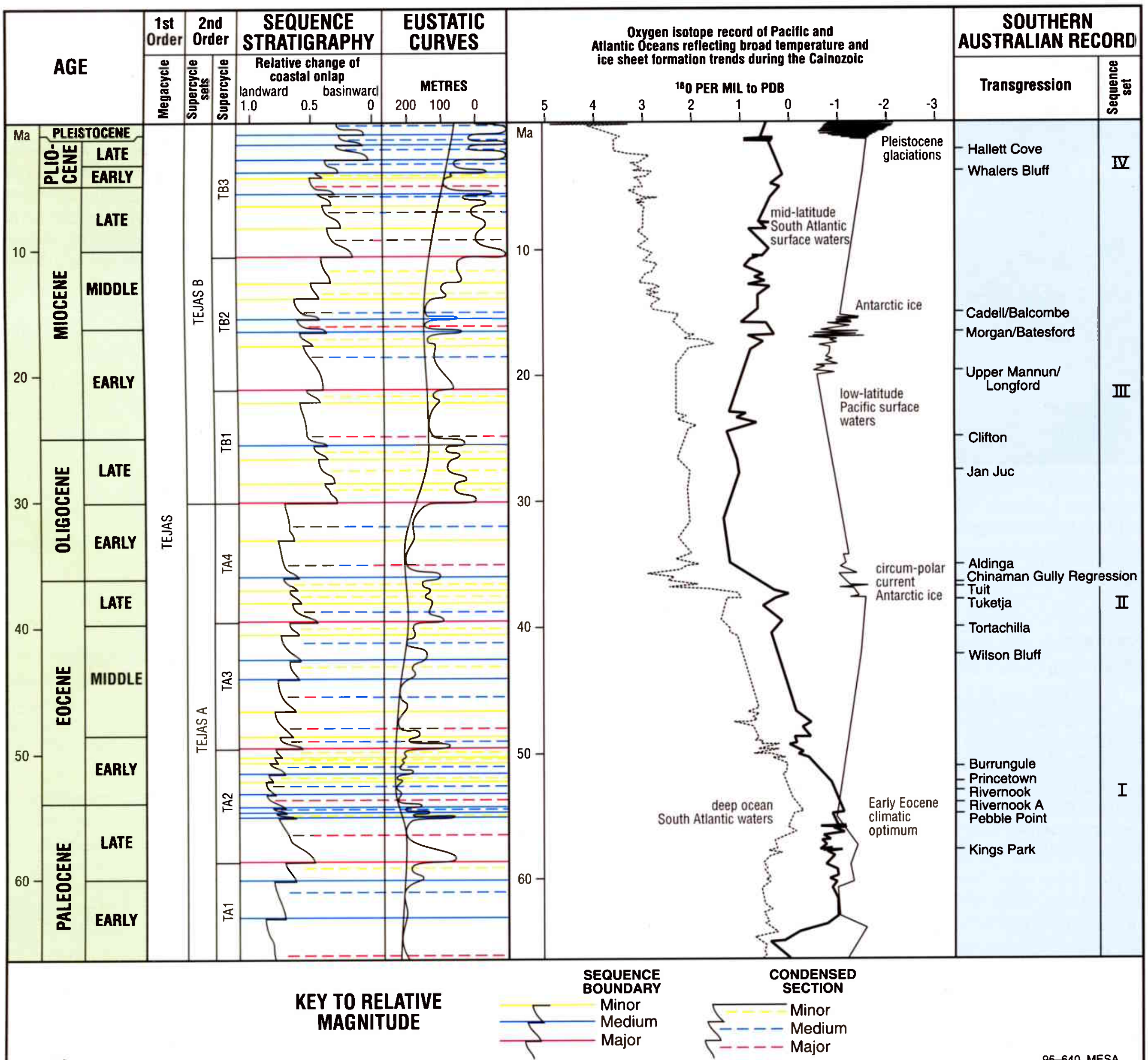


**Fig. 10.41** Tertiary sea-level curves, sequence stratigraphy (after Haq *et al.*, 1987b), oxygen isotope curves (after Shackleton, 1984) and South Australian sea-level events (McGowran, 1989; McGowran *in* Feary *et al.*, 1994).

Little is known about the topography at this time although the ancestral Mount Lofty and Flinders Ranges appear to have been subdued. Widespread plains existed in the interior and extensive deep weathering that commenced during the Mesozoic may have continued during the early Tertiary.

There is no onshore record in South Australia for the nature of the vegetation. However, palynological evidence from dredge samples in the Great Australian Bight suggests that vegetation in the south-central part of the continent was dominated by temperate (perhaps cool temperate) coniferous rainforests (Alley and Clarke, 1992). Like the great fall in global sea level, temperatures also had dropped from their high in the Cretaceous. This factor, along with southern Australia's position in high latitudes at this time, promoted the expansion of (cool) temperate rainforests. Podocarps were common, particularly the cool temperate species *Lagarostrobus (=Dacrydium)* cf. *L. franklinii* or huon pine, *Dacrydium* Group B spp., *Microcachrys* and *Podocarpus* spp., along with the araucarians. The forest association contained a well-developed understorey of ferns and mosses. Tree ferns were the most common and probably included species of Cyatheaceae and Dicksoniaceae along with *Osmunda*, Polypodiaceae, clubmoss, *Gleichenia* and peat moss (*Sphagnum*).

Flowering plants included a number of species with affinities to extant genera in montane and/or lowland rainforest in temperate to tropical areas, such as *Gevuina*, and/or *Hicksbeachia*, ?*Knightia* and *Macadamia*. The pollen of the rainforest taxa *Beauprea*, *Ilex*, *Trimenia* and *Gunnera* are recorded in very low frequencies. Rare pollen of *Nothofagus* are from the *Fuscaspora* group which is currently confined to cool temperate rainforests in Tasmania, New Zealand and Chile.

Thus, although evidence indicates that cool temperate rainforest was widespread in the southern part of South Australia, the flora includes minor frequency taxa of more tropical aspect. This mixture of apparently tropical through to subalpine plants growing in a lowland plain environment poses a dilemma in palaeoecological interpretation. However, the ecological tolerances of some or all of the species may have changed with time, and there may be no modern analogue for the fossils and therefore the fossil pollen with affinities to extant plants of megathermal aspect may have occupied different ecological niches during the early Tertiary. This problem is also true of palynofloral interpretations from the Paleocene up into the middle Tertiary.

## LATE PALEOCENE-EARLY EOCENE (60-53 Ma)

During the Late Paleocene and Early Eocene, fluvial and marginal marine, quartz-rich, terrigenous sediments were deposited in some interior basins and along the continental margin (Fig. 10.42). The volcanogenic zone which was active along the eastern part of the continent during the Mesozoic was no longer a major source of volcanic detritus (Veevers, 1984). Late Paleocene terrestrial sedimentation (Warina Sand) in the Murray Basin suggests blocking of westerly drainage from the eastern Australian highlands to the Eucla Basin by incipient uplift of the Flinders and Mount Lofty Ranges. This interpretation is supported by the deposition of very thin early Tertiary terrigenous sediments over thick Cretaceous sediments in the Eucla Basin, suggesting reduced sediment supply.

Although much of South Australia was undergoing erosion, the possible commencement of downwarping in the Lake Eyre Basin led to deposition of an extensive sand sheet in braided stream systems and finer grained, carbonaceous sediments in restricted swamps and lagoons. Similar sedimentary environments were confined to deeper parts of the Murray Basin. The absence of thick, extensive, fluvial conglomeratic facies and the lack of piedmont deposits flanking the ranges indicate subdued terrain. Recycled resistant quartz-rich lithologies at the base of the Eyre Formation in the Lake Eyre Basin indicate erosion of pebble lags from a stable, weathered landsurface. Colluvial to residual pebble-bearing sandstone may have been deposited on the Stuart Range and in the Billa Kalina Basin area.

At least five successive marine transgressions from the Indian Ocean penetrated along the opening southern continental margin (Fig. 10.41; Deighton *et al.*, 1976; Davies *et al.*, 1989; McGowran, 1991). The transgressions were characterised by restricted, marginal marine planktonic and arenaceous foraminifera (*Cyclammina* biofacies). The oldest transgression recognised in South Australia (Pebble Point Transgression) is within the Pebble Point Formation in the Gambier Basin (McGowran, 1991).

Palynofloral evidence indicates widespread rainforest over much of the continent which, together with depositional environments in the Lake Eyre Basin, implies a very wet climate (Truswell and Harris, 1982; Sluiter, 1991; Macphail *et al.*, 1994; Alley and Sluiter, in prep.).

Data interpreted from Harris (1965) suggest that Late Paleocene vegetation along the south-central margin of the continent, like that of the earliest Paleocene, was dominated by coniferous rainforests in which podocarpaceous types were common, including high-rainfall, cool-temperate species. The araucarians and diverse proteaceous forms were also well represented but *Nothofagus* was uncommon, although a number of species of the *Brassospora* and *Fuscaspora* groups were present. The forest contained a well-developed understorey of moisture-loving ferns and mosses.

Quantitative data (Sluiter, 1991; Alley and Sluiter, in prep.) and general descriptions of palynofloras (Wopfner *et al.*, 1974) from the lower part of the Eyre Formation in the Lake Eyre Basin indicate that vegetation in the northern part of the State was significantly different from the south. The vegetation mosaic within the basin varied from angiosperm-dominated (usually Cunoniaceae) with modern temperate rainforest affinities to gymnosperm-dominated and mixed angiosperm-gymnosperm rainforest assemblages, all with a diverse fern and moss understorey. This implies that northern South Australia was warmer than the south, an interpretation supported by the presence of pollen with affinities to a number of modern subtropical to tropical (megathermal) plants, including *Anacalosa*, Cupanieae, *Beauprea*, *Santalum*, *Ilex* and common Trimeniaceae.

Since the Eyre Formation was deposited on an extensive flood plain containing swamps, shallow lakes and peat bogs, the environment was ideal for the spread of *Sparganium* (bur-reed), the first Australian record of which is from the Eyre Formation, and the herb *Gunnera* which currently grows in wet, boggy conditions. Areas of open water are indicated by abundant freshwater microplankton.

Similar rainforests may have persisted through the Early Eocene, although vegetation is interpreted to have become a Myrtaceae-dominated complex notophyll vine forest in the Lake Eyre Basin (Sluiter, 1991). However, some drillhole data in the Lake Eyre and Torrens Basins indicate continuing dominance of Cunoniaceae in some localities, but Myrtaceae in others (Alley and Sluiter, in prep.). Likewise, the Casuarinaceae (probably *Gymnostoma*), araucarians and podocarps, although well represented in some parts of the basins, were less common elsewhere, suggesting a variable rainforest mosaic.

Plants of megathermal aspect were still present along with palms, Euphorbiaceae and *Gevuina/Hicksbeachia* of the Proteaceae. The proteaceous component of the vegetation is diverse and includes the sclerophyllous *Xylomelum occidentale* which, along with the sun-loving Malvaceae, suggests drier and/or more open parts of the forest existed. This interpretation is supported by a great decline in the importance of fern spores which are locally common at some sites in the Lake Eyre Basin but rare in the Torrens Basin. Data interpreted from Harris (1965) in the Gambier Basin indicate a high frequency of gymnosperm pollen with temperate to cool-temperate rainforest affinities which is in agreement with the more cool-temperate aspect of the vegetation.

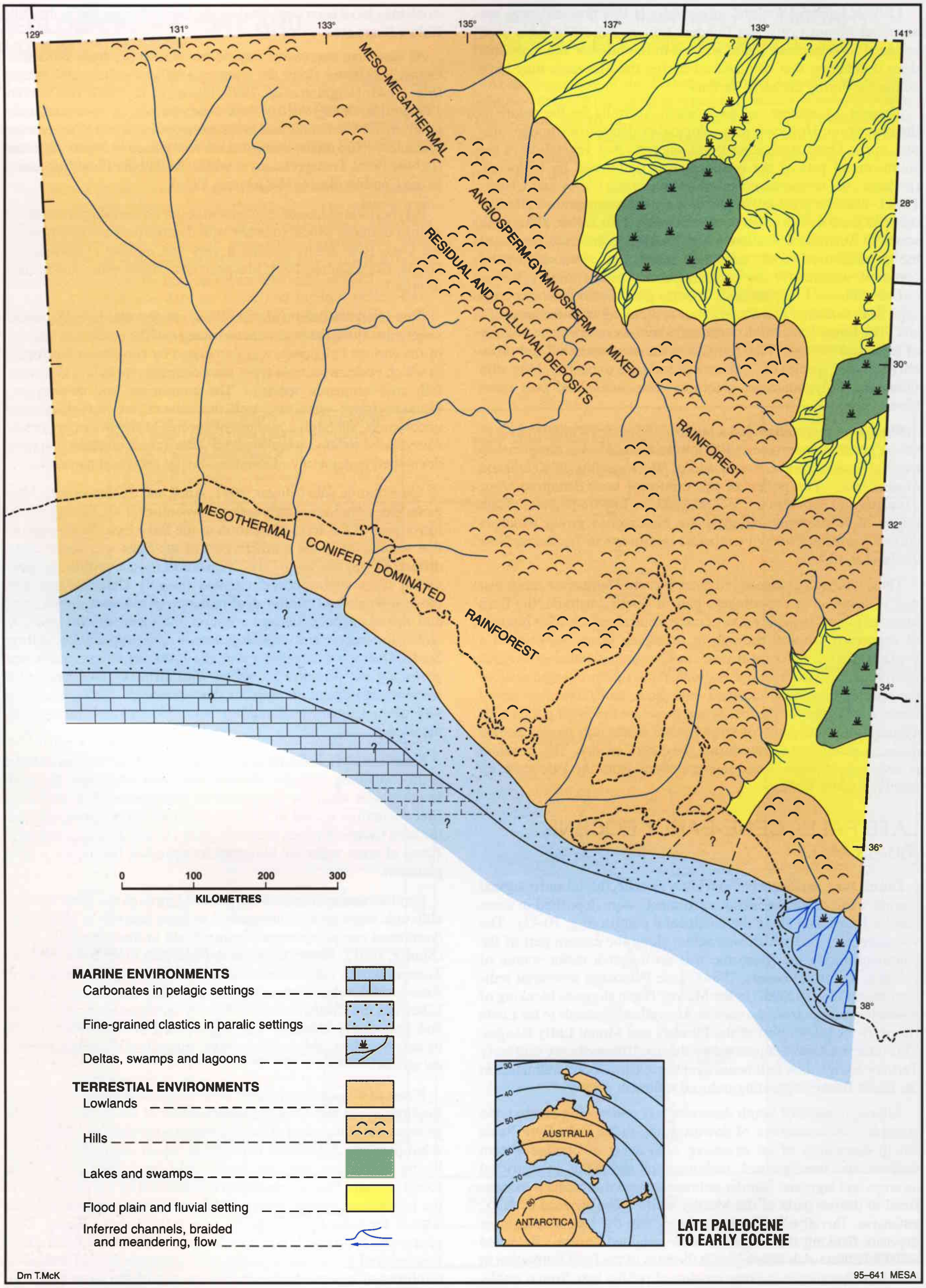


**Fig. 10.42** Late Paleocene-Early Eocene palaeogeography of South Australia.

## EARLY TO MIDDLE EOCENE (53-44 Ma)

There is almost no record of sedimentation during the late Early to early Middle Eocene (McGowran, 1989), the time of the first major cooling in the Tertiary as indicated by an increase in oceanic $\delta^{18}O$ (Fig. 10.41; Shackleton and Kennett, 1975). Cooling is also inferred from oceanic micropalaeontological evidence (McGowran and Beecroft, 1985).

The only palynofloral evidence for the character of Early Eocene vegetation and climate comes from the Gambier, Lake Eyre and Torrens Basins. Although sedimentation continued in the Murray Basin, the facies are not suitable for the preservation of palynomorphs. Data from the other areas, however, show that conditions established in the earliest Eocene persisted through the Early Eocene (Macphail *et al.*, 1994).

## MIDDLE TO LATE EOCENE (44-36 Ma)

Southern Australia was at relatively high latitudes (50-55°S) when widespread deposition began in the late Middle Eocene. The Southern Ocean had widened significantly, allowing extensive flooding of the continental margin during at least three transgressions correlated with eustatic sea-level rises (Johnson and Veevers, 1984; McGowran, 1989, 1991; McGowran *et al.*, 1992).

Uplift of the ancestral Mount Lofty and Flinders Ranges and downfaulting within and adjacent to the ranges probably resulted from compressional reactivation of meridional to northeast-trending Delamerian structures. Deposition of terrigenous, non-marine and sometimes paralic sediments began in the St Vincent, Pirie and Torrens Basins adjacent to the uplands and in the intramontane Willochra and Walloway Basins.

Deposition which commenced in the Paleocene in the Lake Eyre Basin, and perhaps in the Billa Kalina Basin, continued in the Middle Eocene. The later phase, however, was interrupted by an hiatus in the Early Eocene in the Lake Eyre Basin and by uplift and erosion along the Stuart Range-Billa Kalina Basin axis. This was probably the cause of a reversal of drainage direction in the Billa Kalina Basin from channels flowing towards the Eucla Basin to those flowing northwards to the Lake Eyre Basin. The appearance of recycled Cretaceous palynomorphs in the Middle Eocene part of the Pidinga Formation in the Eucla Basin may be coincident with uplift and erosion in the headwaters of the palaeochannels (Alley and Beecroft, 1993). This phase of deposition in some areas and erosion in others suggests widespread tectonic movements, especially along the Torrens Hinge Zone.

At commencement of the Wilson Bluff Transgression in the late Middle Eocene, deposition of extensive neritic carbonates began in platform settings around the continental margin (Fig. 10.43). Bryozoal meadows thrived on the platform while pelagic limestone accumulated in deeper water; clastic sediments were deposited in coastal and paralic environments.

Terrigenous sedimentation in the west was confined to the margin of the Eucla Basin and its palaeodrainage system, and estuarine conditions migrated up into the channels. Seaward migration of a high-energy, siliciclastic shoreline and the formation of an extensive coastal dune complex marked the end of deposition on the emergent part of the Eucla Basin, possibly in the Late Eocene (Benbow, 1990a). This may be part of the Aldinga Transgression which may correspond to a warming of oceanic water along southern Australia (Benbow, 1990a; McGowran, 1986). Moderate intensity prevailing westerly winds are inferred from the formation and orientation of coastal dunes in the Eucla Basin (Benbow, 1990a).

Terrigenous sediment throughout the eastern coastal basins was mostly derived from the eastern Australian highlands. In the Murray Basin, deposition of bryozoal limestone, confined to the southwestern region, commenced in the Late Eocene. The Padthaway Archipelago acted as a barrier to open marine conditions in the eastern Murray Basin (Brown and Stephenson, 1991). In the Gambier Basin, neritic bryozoal limestone was not deposited until the latest Eocene or earliest Oligocene.

Widespread rainforest persisted over much of the continent. A major floral change occurred with *Nothofagus* and conifers becoming important, whereas proteaceous types dwindled in frequency (Macphail *et al.*, 1994). However, the relatively high frequencies of pollen with affinities to temperate to mesothermal rainforest types, along with megathermal rainforest elements, still represent a dilemma to palaeoclimatic interpretation. This palynofloral association occurs throughout the South Australian Middle to Late Eocene sedimentary basins, even in areas where there is no evidence for any uplands high enough to have supported cool temperate rainforest. Thus, the vegetation may have been a rainforest mosaic with no modern analogue. In southern South Australia, the rainforest in many localities included a dense understorey of ferns and mosses.

Middle Eocene palynofloras from the Torrens and Lake Eyre Basins indicate that the structure of the vegetation continued to differ from that of the southern continental margin. Pollen of rainforest types such as *Nothofagus* and the Podocarpaceae generally form only a minor part of the spectra. Because *Nothofagus* produces vast quantities of wind-transported pollen, it is commonly over-represented in modern and fossil palynofloras. The low frequency of *Nothofagus* pollen may imply that the genus formed only a very minor part of the vegetation or, more likely, that the pollen was transported considerable distances from the ancestral Flinders and Willouran Ranges.

The Myrtaceae are relatively common with up to 2% *Eucalyptus* pollen and, in the Torrens Basin, up to 10% *Myrtaceidites parvus*. The Cunoniaceae are very patchily distributed, with the highest recordings in a few drillholes in the southwestern Lake Eyre Basin but are virtually absent from the Torrens Basin. Although pollen of the Proteaceae are numerically low, species diversity is relatively high. The subaquatic families Cyperaceae, Sparganiaceae and Restionaceae are locally common, indicating the presence of wet areas in the basins. Although grass was established in the interior its pollen was very minor.

The low frequency of pollen from rainforest plants, in association with high Casuarinaceae (highest in the Torrens Basin) and diverse and reasonably well-represented proteaceous pollen, suggests restriction of rainforest to moister valley floors while more sclerophyllous vegetation dominated the drier hinterland.

Middle Eocene macrofloras in the North Maslin Sand (St Vincent Basin) contain abundant and diverse leaves, fruits and flowers including *Lygodium* (a climbing fern), the conifers *Podocarpus* and *Retrophyllum* (Podocarpaceae), *Brachychiton* (Sterculiaceae; bottle trees or kurrajong), *Banksieaephyllum* (affinities to *Banksia* and/or *Musgravea*), *Myrtaciphyllum* (Myrtaceae; affinities to *Syzygium* or lillypilly), and the families Araliaceae (umbrella trees), Elaeocarpaceae (quandong), Lauraceae and Arecaceae (palms; Maslin Bay only). The majority of leaves have affinities with extant plants in mesothermal-megathermal rainforests (Lange, 1970, 1982; Christophel and Blackburn, 1978; Blackburn, 1981; Christophel and Greenwood, 1989; Greenwood, 1994), consistent with the presence of epiphyllous fungi on leaf cuticles (Lange, 1969). *Nothofagus* pollen, a high-rainfall indicator, is abundant in Middle to Late Eocene sediments, but macrofloral remains are absent.

Macrofloras of the Lake Eyre and Billa Kalina Basins contain abundant conifer shoots with affinities to the families Araucariaceae, Cupressaceae (*Papuacedrus*) and Podocarpaceae (*Dacrycarpus* and *Dacrydium*; Offler, 1969, 1984; Callen *et al.*, 1986). Rare fruits of *Eucalyptus* are probably the earliest record of this genus (Lange, 1978, 1982). *Banksieaeformis* (Proteaceae), *Brachychiton* (Steruliaceae), abundant leaves of Myrtaceae (*Eucalyptus* and/or *Melaleuca*), and cones of *Gymnostoma* and *Casuarina* are also present (Greenwood *et al.*, 1990; Christophel *et al.*, 1992).

The mean size and morphology of leaves of macrofloras in the North Maslin Sand are characteristic of mesothermal-megathermal

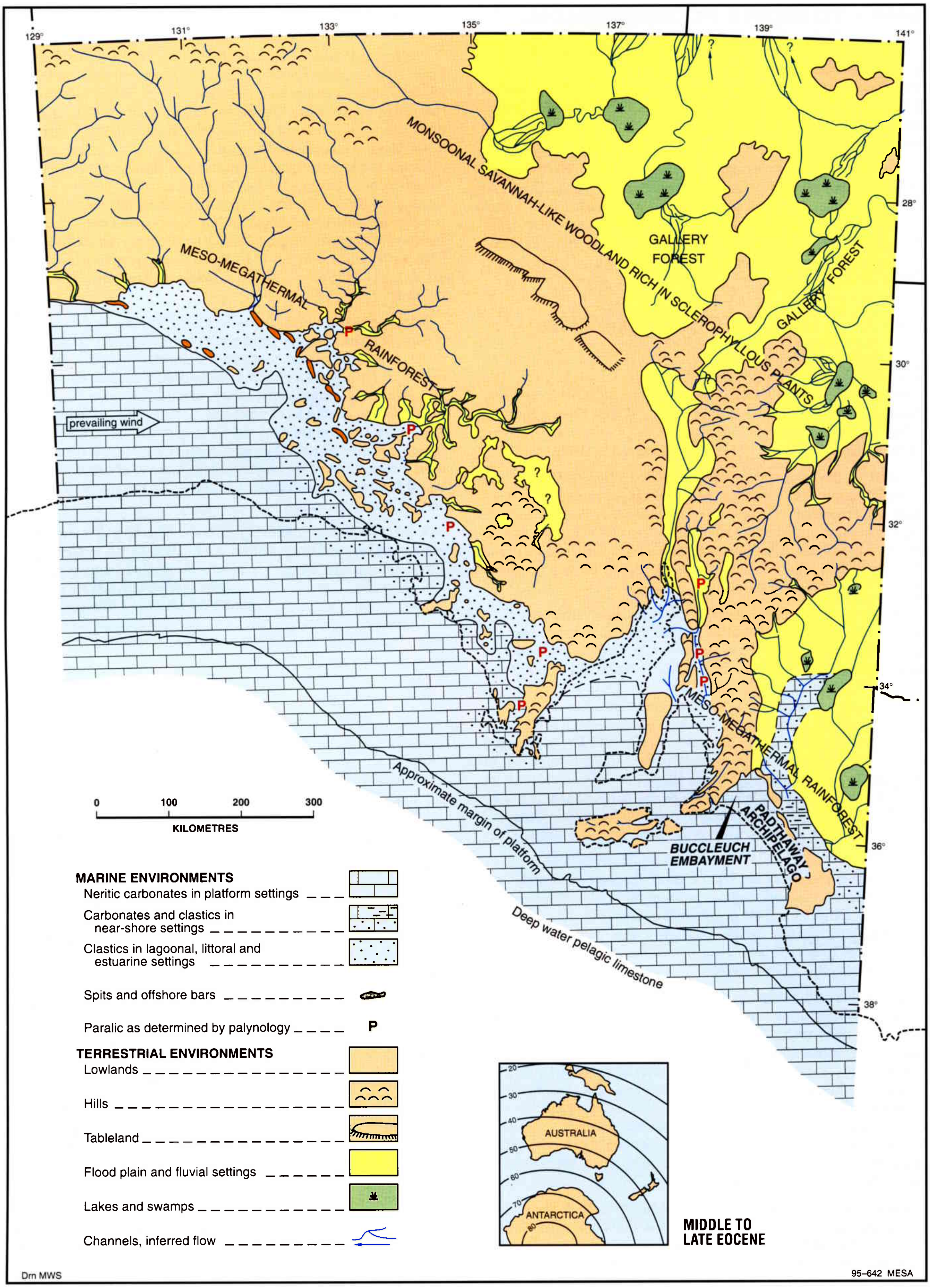


**Fig. 10.43** Middle to Late Eocene palaeogeography of South Australia.

rainforests (Christophel and Greenwood, 1989; Greenwood, 1994), whereas the same characteristics of the silcrete floras suggest the presence of rainforest and sclerophyllous vegetation (Greenwood *et al.*, 1990; Greenwood, 1994). This association might imply a monsoonal inland climate, with rainforest plants forming gallery forests along permanent water courses. Alternatively, the presence of sclerophyllous leaves may indicate areas of low soil fertility in a humid climate (Lange, 1980, 1982; Christophel and Greenwood, 1988, 1989; Greenwood *et al.*, 1990). Thus, by the Middle Eocene there is some evidence from the palynofloras and macrofloras for latitudinal climatic zonation in southern Australia. Based on the correlations between leaf morphology and climate in modern vegetation, the Middle Eocene macrofloras indicate mean annual temperatures of ~18°C in the south (e.g. Golden Grove) and ~21°C in the southern Lake Eyre Basin (Greenwood, 1994).

Additional evidence for palaeotemperature during the Middle-Late Eocene is provided by the marine platform limestones typical of modern temperate-water limestones being deposited south of the 18° isotherm at about 30°S latitude (Lees and Buller, 1972). This apparent contradiction with the botanical record may reflect lowering of ocean salinity in a region of high rainfall. For example, extensive temperate-water carbonate (foramol) assemblages occur offshore from wet, tropical southeast Asia (Lees, 1975; Nelson, 1988). However, similar limestones continued to be deposited in the southern Australian marine basins after a major cooling and relatively arid phase around the Eocene-Oligocene boundary.

The presence of the foraminifera *Halkyardia*, *Linderina* and *Hantkenina* is evidence of the southward expansion of warm ocean waters (McGowran, 1979). The rare occurrence of *Truncorotaloides spinulosus* in the unnamed basal glauconitic member of the Wilson Bluff Limestone is interpreted as an important indicator of warm-water influence (McGowran and Lindsay, 1969). On the other hand, the environment was not tropical because of the rarity of the keeled *Globoratalia*-like tests, the relative abundance of spinose, acarininid tests, and the absence of true tropical indicators. The very low diversity of larger foraminifera, compared to their high diversity in lower latitudes during the Middle to Late Eocene, indicate marginally warm or temperate water along the southern Australian coast.

Oceanic temperatures are interpreted as significantly lower later in the Eocene, although short-lived warmer episodes were superimposed on the overall cooling trend (Fig. 10.41; Shackleton and Kennett, 1975; Shackleton, 1984, 1986a) and can be matched with several of the later Eocene transgressions (McGowran, 1989; McGowran *et al.*, 1992). The cooling trend is reflected in the oxygen isotope record and probably indicates growth of the Antarctic icesheet during this time (Barrett *et al.*, 1987; Mathews and Poore, 1980).

## EOCENE-OLIGOCENE BOUNDARY AND THE EARLY OLIGOCENE (36-30 Ma)

Major changes in oceanic biota around the Eocene-Oligocene boundary have been referred to as the 'Terminal Eocene Event'. However, the boundary does not seem to mark an abrupt major evolutionary break but is part of an episodic or gradual change which started in the Middle Eocene and continued into the earliest Oligocene (Pomerol and Premoli-Silva, 1986). This conclusion is supported by accelerated overturn of much of the marine biota, a significant decrease in temperature, and development of the modern two-layered structure of the oceans. Oxygen isotope studies show that this climatic change followed rather than preceded the biostratigraphic events, thus precluding a causal relationship (Shackleton, 1986a).

In the St Vincent Basin, foraminiferal studies show that there was no catastrophic change in the local inner-neritic community (Lindsay and McGowran, 1986). The rate of arrival of new species appears to have increased during each of the Eocene transgressions whereas the greatest increase in disappearances occurred at the Chinaman Gully Regression.

Although widespread deposition continued into the Early Oligocene in the Murray, Gambier, St Vincent, Pirie and Eucla Basins, the later Early Oligocene stratigraphic record in South Australia is relatively restricted. Deposition of carbonates continued in the St Vincent and offshore basins; in the Murray Basin, carbonates passed landwards to fine-grained fluviolacustrine sediments.

Palynological evidence from the Murray, St Vincent and Pirie Basins shows continued decline in angiosperm diversity matched by increasing dominance of *Nothofagus* and *Gymnostoma*. *Nothofagus* pollen was dominated by the *Brassospora* group with minor *Fuscaspora* and rare *Lophozonia*. Rainforest gymnosperms, largely of cool temperate aspect, occur with lower frequency than earlier in the Tertiary, although a single taxon may be relatively high in some palynofloras. The Myrtaceae and Proteaceae are greatly diminished and Cunoniaceae is very rare or absent in many palynofloras. Ferns and mosses formed a minor part of the vegetation. The semiaquatic Cyperaceae, Sparganiaceae and Restionaceae are consistently present, being relatively common in the northern St Vincent Basin and northwestern Murray Basin; they indicate extensive marsh conditions.

Thus, in the southern part of the State at least, latest Eocene to Early Oligocene vegetation was largely *Nothofagus*-dominated, cool temperate rainforest. This floral change was probably related to a global cooling trend (see above).

The end of deposition in the late Early Oligocene coincided with a fall in global sea level of ~125 m and a phase of icesheet development in Antarctica (Haq *et al.*, 1987a; Shackleton, 1986a). In the deeper Gambier Basin, however, deposition was continuous across the Early-Late Oligocene boundary (Lindsay, 1985).

Extensive silcrete on the Cordillo Surface and in the southwestern part of the State may have formed during the Oligocene.

## LATE OLIGOCENE-MIDDLE MIOCENE (30-14 Ma)

The Early Oligocene regression was followed by a rapid transgression which initiated deposition of widespread neritic limestone on the platforms, in newly formed embayments in the St Vincent and western Murray Basins, and in a number of small intramontane basins of the southern Mount Lofty Ranges area (Fig. 10.44). At least six transgressive episodes are marked by Late Oligocene intercalations of glauconitic Ettrick Formation within the marginal marine Geera Clay of the Murray Basin and by Early to Middle Miocene horizons containing warm-water, extra-tropical, large foraminifera, *Lepidocyclina* and *Austrotrillina-Marginopora-Flosculinella*.

Significant warming of the sea is interpreted from the decrease in oceanic and shelf $\delta^{18}O$ (Dorman, 1966; Shackleton and Kennett, 1975; Shackleton, 1986a). The skeletal composition of the Nullarbor Limestone and the more widely spread and diverse larger foraminifera along southern Australia indicate that early Middle Miocene shelf seas were warmer than at any time in the Tertiary (McGowran, 1979; Adams *et al.*, 1990). Warm-water coralline algal *Archaeolithothamnion* facies were widespread in the Eucla, Pirie and Murray Basins. However, the absence of extensive coral reefs, calcareous cyanobacteria and chemically precipitated ooids indicates that true tropical conditions were not attained.

In the Murray Basin, shallow platform limestones passed shorewards into terrigenous sediments deposited in restricted marine lagoons, interdistributary bays and tidal flats. The coastal plain merged eastwards with alluvial plain, fluvial and lake environments. In contrast, carbonates of the Eucla and St Vincent Basins were rimmed by very narrow terrigenous clastic shorelines.

Relief amplitude of part of the ancestral highlands was generally similar to the present. However, in the southern Mount Lofty Ranges, the difference in height between the base of Oligocene-Early Miocene limestone in the Myponga and Hindmarsh Tiers Basins, and the top of the adjacent hills, implies local relief of

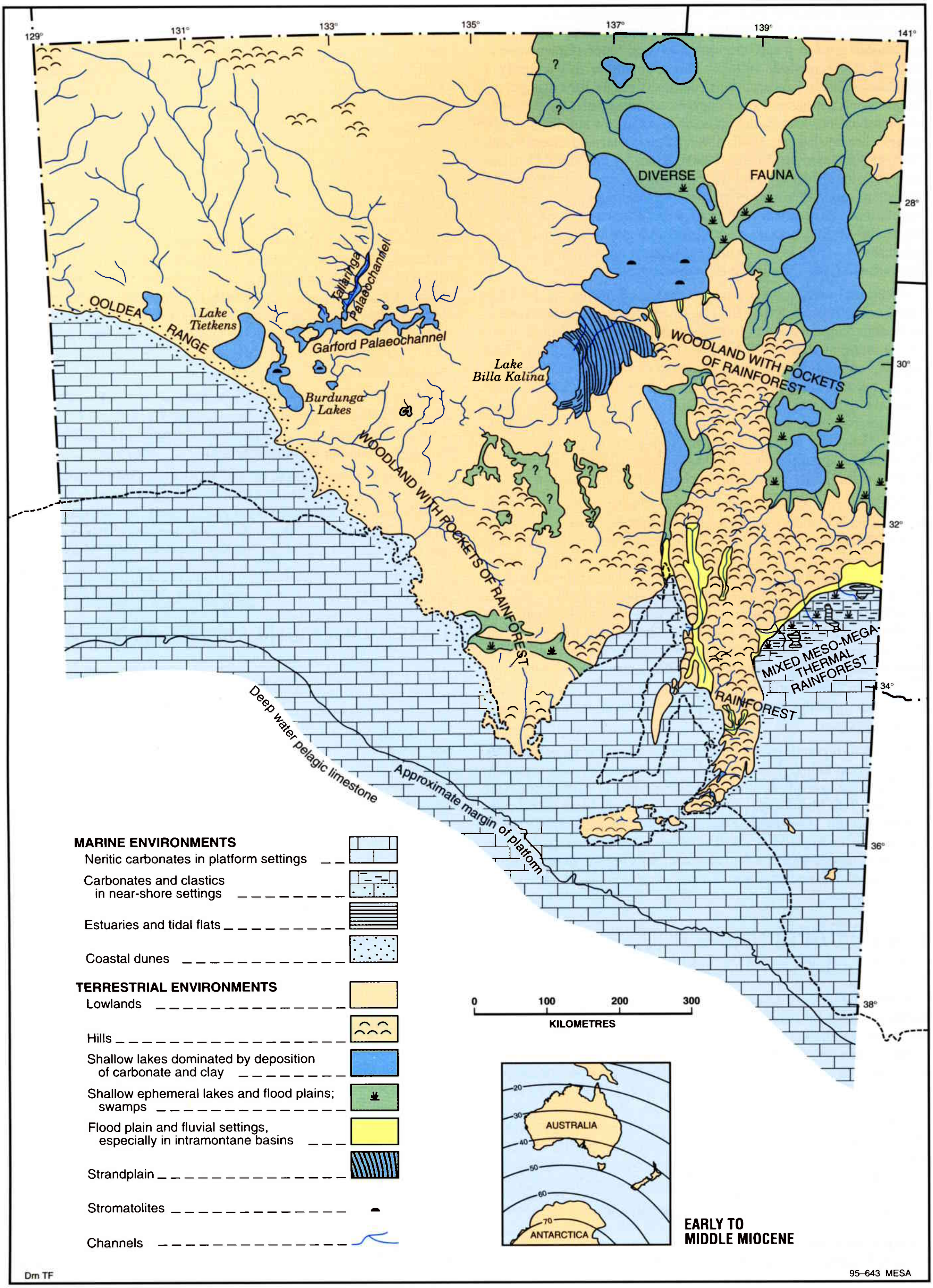


**Fig. 10.44** Early to Middle Miocene palaeogeography of South Australia.

250-430 m, which is greater than at present. Similarly, in the ranges south of Leigh Creek, the difference in height between the base of the middle Tertiary Neuroodla Formation and the ridge tops indicates local relief amplitude of ~350-450 m, considerably more than the modern landscape. Piedmont fans along the eastern margin of the intramontane Barossa Basin provide evidence of uplift of this part of the Mount Lofty Ranges during the Oligocene-Middle Miocene.

The inland non-marine basins and palaeodrainage systems contained extensive, shallow, alkaline lakes in which argillaceous and calcareous and dolomitic mudstones were deposited (Krieg, Callen *et al.*, 1990; Benbow, in prep.). Centres of deposition were controlled by local epeirogenic movements in the Tirari Sub-basin (Wopfner, 1974) and by already established palaeochannels in the Callabonna Sub-basin and Eucla Basin. These inland sediments remain poorly dated, but maximum deposition may have occurred around the Early-Middle Miocene boundary, more or less contemporaneously with maximum deposition over the marine platforms.

Although the inland climate was significantly wetter during the Early-Middle Miocene than today, the presence of extensive dolomite indicates evaporative conditions, and the local presence of ooids and stromatolites implies warmth as well as shallow water (Krieg, Callen *et al.*, 1990; Benbow, in prep.). Decreasing carbonaceous sediments and increasing dolomite towards the northwest suggest increasing relative aridity in that direction.

Vertebrate fossils, particularly in the upper green clay and channel sands of the Etadunna Formation, have aided reconstruction of palaeoenvironments and understanding of the evolution of Australian faunas (see Callen, 1990, for a summary of the main groups). The faunas contain numerous birds, including many aquatic species, land-dwelling marsupials characterised by browsing types, fish, lungfish, dolphins, large crocodiles and turtles, indicating warm conditions and the existence of a substantial body of permanent water (Archer and Clayton, 1984). The presence of dolphins indicates an exorheic drainage system while koala-like animals, phalangers, possums and native cats suggest that trees grew in the area.

Although trees grew around lakes and rivers, the vegetation record is poor. The few sparse palynofloras from the Lake Eyre Basin contain relatively common *Podocarpus* and *Nothofagus* (Callen and Tedford, 1976) implying rainforest elements. A palynoflora from near the base of the Namba Formation in Wooltana 1 is dominated by Restionaceae, growing as swamp plants, with lesser conifers and *Casuarina*, minor *Nothofagus* (*Brassospora*) and very rare grass pollen (Martin, 1990). Thus, widespread interfluvial grasslands had not yet developed in central Australia, an interpretation supported by the preponderance of browsing marsupials.

Around the Murray Basin, mixed rainforest prevailed, dominated by myrtaceous genera (possibly *Syzygium*, *Acmena* and *Tristania*) and *Nothofagus* (*Brassospora*), although the latter are much lower in frequency than in the Gippsland area (Victoria; Truswell *et al.*, 1985). These rainforest trees are associated with significant *Gymnostoma* and lesser Cunoniaceae and gymnosperms, including consistently present *Araucaria*, *Dacrycarpus*, *Dacrydium* Section B and *Podocarpus*, and very minor *Lagarostrobus* and *Microcachrys*. There is uncertainty about the palaeoclimatic significance of this rainforest assemblage, but the preponderance of Myrtaceae may be in response to seasonally drier conditions (Truswell *et al.*, 1985).

Palynofloras from the intramontane Barossa Basin contain high frequencies of *Nothofagus* pollen, mainly *Brassospora* but with significant *Fuscaspora*, in association with common *Casuarina*, very variable Myrtaceae and podocarps. These spectra indicate rainforest similar to that of southeastern Australia, perhaps growing in locally suitable sites such as uplands surrounding the basin.

Palynofloras from the eastern Eucla Basin imply drier conditions on Eyre Peninsula. *Casuarina* dominated the vegetation with reduced *Nothofagus* (*Brassospora* the most common) and podocarps. The Proteaceae were very poorly represented and *Acacia* was present. The lack of grass indicates that woodland and/or forest, rather than grassland, extended across the peninsula.

Palynofloral evidence suggests significant regional and perhaps even local variations in vegetation during the Oligocene to Early Miocene in response to a shift to drier conditions, with greater impact on inland areas.

## MIDDLE TO LATE MIOCENE (14-6 Ma)

The major increase in $\delta^{18}O$ values in the South Tasman Rise area during the Middle Miocene reflects an increase in the size of the Antarctic Ice Sheet and not so much a decrease in ocean temperature (Shackleton and Kennett, 1975; Mathews and Poore, 1980). This icesheet greatly influenced atmospheric and oceanic circulation patterns in the Australasian region and patterns were most likely similar to those of today (Kemp and Barrett, 1975; Kemp, 1978).

The regression that followed deposition of extensive marine limestones in the Middle Miocene was accentuated by uplift of the southern trailing plate margin. Despite falling sea level, deposition of neritic carbonates continued in the Gambier Basin and outer Eucla Basin platform well into the Late Miocene (Fig. 10.45; Abele *et al.*, 1976, 1988; Apthorpe, 1972).

Mild epeirogeny during the Late Miocene resulted in gentle warping, small-scale faulting, weathering, erosion and formation of low-angle unconformities in the St Vincent and Murray Basins. Uplift of the Eucla Basin platform and Gambier Basin resulted in cessation of deposition and a change to subaerial exposure and development of karstic features. Limestone of the Eucla Basin may have been reworked and thus been a major source of bioclastic sediment, perhaps being eroded from the newly formed Bunda Cliffs. Further doming of the Cordillo Surface with major subsidence in the Lake Eyre and Torrens Basins may have occurred at this time.

The change in atmospheric circulation brought about by the Antarctic Ice Sheet and the lack of widespread Late Miocene deposits inland suggest increasing aridity at this time (McGowran, 1987; Truswell and Harris, 1982). In the eastern Murray Basin, cessation of deposition of carbonaceous sediments and the decreasing proportion of *Nothofagus* pollen indicate diminishing precipitation by the end of the Middle Miocene (Martin, 1977). In the southeastern part of the continent wet conditions with rainforest persisted into the Late Miocene (Kemp, 1978). Similar conditions prevailed in the Barossa Basin area where *Nothofagus*-dominated rainforest (mainly *Brassospora*) varied in time and space with vegetation assemblages dominated by podocarps and occasionally Casuarinaceae.

The immaturity of karst development on the Nullarbor Plain and the intact preservation of palaeodrainage and coastal dunes of the Eucla Basin suggest aridity here for much of post-Miocene time (Jennings, 1967; Van de Graaff *et al.*, 1977; Benbow, 1990a).

## PLIOCENE (6-1.6 Ma)

The Pliocene was an interval of widespread deposition of largely terrigenous sediments in non-marine and paralic to shoreline settings. The record of marine transgressions is best known in the St Vincent and Murray Basins but dating is not precise enough to distinguish closely spaced global eustatic peaks. Little is known of the marine carbonate record of the continental shelf.

In the Murray Basin, deposition began with latest Miocene to Early Pliocene extensive, shallow marine platform marl in the western part; eastwards, these sediments passed into sand deposited in shoreface, deltaic and alluvial plain environments (Fig. 10.45). During subsequent progradation, an extensive strandplain with arcuate beach ridges formed under the influence of a westerly wind system which produced a southwesterly swell and longshore current regime (Belperio and Bluck, 1990). Large quantities of sand were supplied from the Eastern Highlands. In contrast, the Early Pliocene transgression(s) left a restricted clastic record in the St Vincent

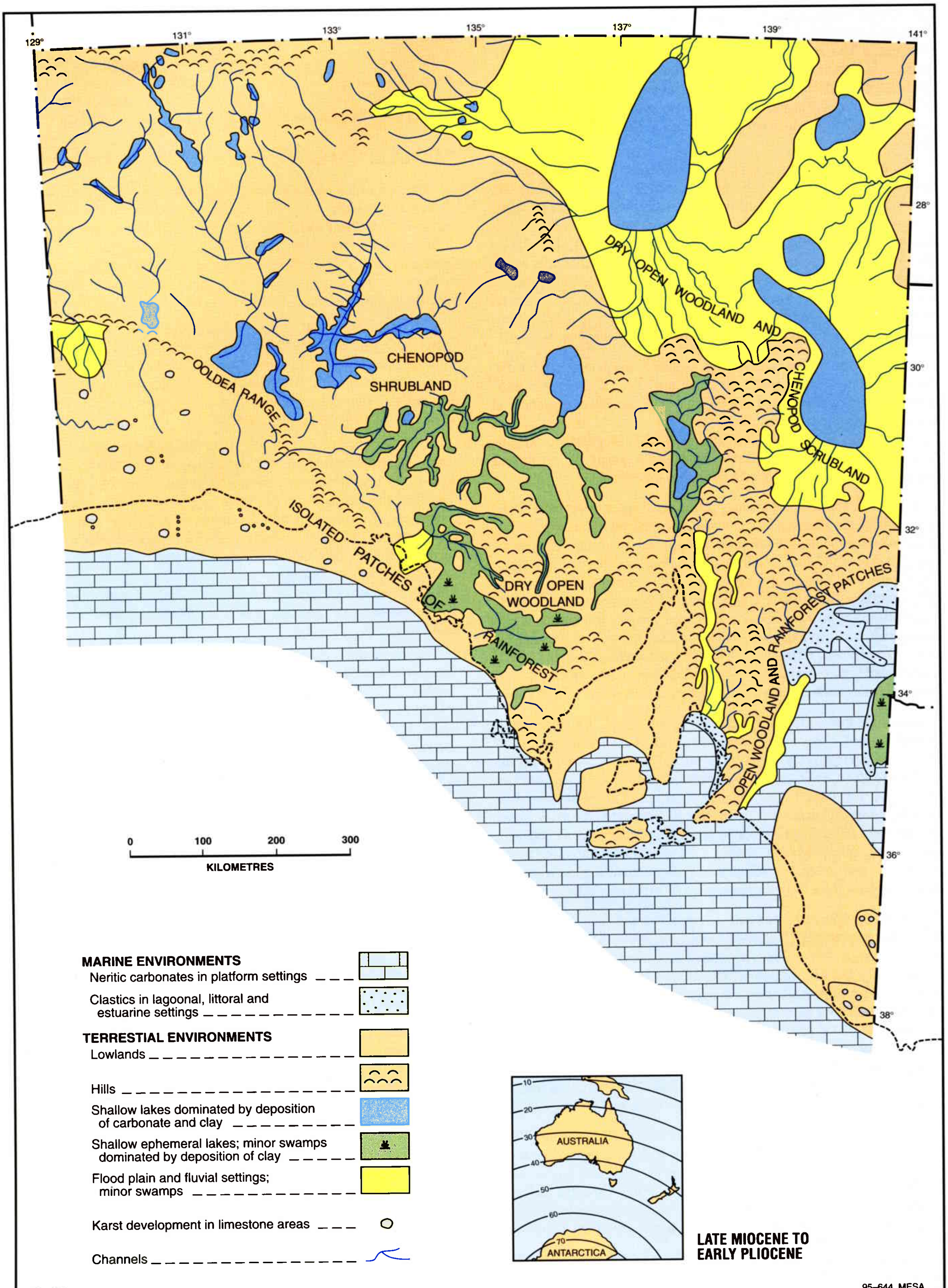


**Fig. 10.45** Late Miocene to Early Pliocene palaeogeography of South Australia.

Basin, probably as a result of limited sediment supply from adjacent uplands.

During the Early Pliocene (and/or possibly Late Miocene) there was very extensive fluvial and lacustrine sedimentation along palaeochannels around the Eucla Basin, in the Lake Eyre Basin and elsewhere. Thick and extensive argillaceous and minor calcareous Early Pliocene mudstone on northern Eyre Peninsula possibly correlates with the uppermost part of the vertebrate-bearing Etadunna and Namba Formations, which may extend into the Early Pliocene (Martin, 1990). The Serpentine Lakes Palaeochannel on the Bunda Plateau was reactivated, leading to deposition of a broad alluvial fan (M.C. Benbow, MESA, pers. comm., 1994). Clastic sediments in the Hamilton Basin were deposited in flood-plain and piedmont settings marginal to the Musgrave Ranges. The presence of crocodile remains suggests that conditions were warm and wet in this area.

The record of late Cainozoic development of aridity is unfortunately very meagre. Superimposed on this overall trend of increasing aridity were warm, wet episodes in the Pliocene. Open vegetation growing in a climate more arid than that of the Middle Miocene has been inferred from the presence of grass, composites and Chenopodiaceae pollen on northern Eyre Peninsula (Truswell and Harris, 1982). *Casuarina* is abundant and *Eucalyptus* is present in these assemblages. The presence of *Dacrydium*, *Podocarpus*, *Phyllocladus* and very rare *Nothofagus* (*Brassospora*) pollen indicate rainforest in edaphically suitable sites (Truswell and Harris, 1982; N.F. Alley, unpublished information). These assemblages are also present in the Early Pliocene of the Narlaby Palaeochannel, along with significant frequencies of Restionaceae (rather than grass) and *Micrantheum*, in association with *Acacia*, Cupressaceae (probably *Callitris*) and sedges, both the latter being locally common. The occurrence of open woodland containing pockets of rainforest accords with the interpretation of Late Miocene to Early Pliocene vegetation in the eastern Murray Basin by Martin (1973a, 1978).

Ferricrete, and subsequently extensive silcrete, formed across the inland during the Late Pliocene. Epeirogenic uplift of the Flinders and Mount Lofty Ranges to near their current altitude culminated at about this time, and flanking fans (Willawortina Formation and Hindmarsh Clay) were formed. These movements may have been responsible for the folding of silcrete marginal to the northeastern Flinders Ranges although no major displacement occurred across faults.

In the closing stages of the Tertiary, clay was deposited in extensive shallow lake systems. In the Murray Basin this resulted from tectonic damming and/or damming by coastal barriers of streams following regression of the sea. Lake Bungunnia occupied much of the western Murray Basin between 2.5 and 0.7 Ma, with its northern and eastern margins surrounded by wide alluvial plains (Bowler, 1980; Stephenson, 1986; Stephenson and Brown, 1989).

Widespread carbonate deposition took place in coastal and offshore environments during a period of higher sea level near the Pliocene-Pleistocene boundary. Sheltered estuaries and bays of Gulf St Vincent passed to more energetic sandy and rocky bays and headlands around Kangaroo Island (Milnes *et al.*, 1983; Ludbrook, 1983). Coastal dunes formed from shelf-derived calcarenites, which became a feature of southern Australia during the Quaternary, were established along part of the coastline in the Late Pliocene, as indicated by dated basalt interbedded with aeolianite near Warrnambool in Victoria. Saline and carbonate facies in the Murray Basin, other inland basins and palaeodrainage of the Eucla Basin indicate the drying of lakes and general climatic warming and/or drying in the late Tertiary and Quaternary.

The processes of erosion and deposition that shaped the late Tertiary landscape continued during the Quaternary; these are described in the following chapter. The lack of later widespread tectonic uplift and absence of Quaternary glaciation, such as characterised Europe and North America, has resulted in the preservation of many Tertiary sediments, landforms and weathering horizons in the modern landscape.