5 Landscapes of Australia: their nature and evolution

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It is oft said that 'Australia is an old continent'. Certainly Australia has many ancient landscapes which have been exposed to the processes of weathering and soil formation for very long periods under very stable tectonic conditions. The results of this are that many of our landscapes have well-leached and infertile soils, a major factor in the evolution of the Australian flora. Having said that, it is not true that all Australian landscapes are ancient. Many are very young, and of course all our landscapes are still undergoing modification, albeit some very slowly. Many landscapes that were thought to be comparatively young, such as the Southeastern Highlands (Andrews, 1911; Browne, 1969; Hill, 1975), have recently been shown to be comparatively ancient (Wellman, 1987; Bishop, 1988; Taylor *et al.*, 1990*a*).

The Australian continent attained its present outline between 150 and 50 million years (Ma) ago (Wilford & Brown, Chapter 2, this volume), but many of our landscapes are even older. Comparison of the major landform regions (Figure 5.1) and the major geological structure of the crust or tectonic provinces (Figure 5.2) demonstrates this well.

The tectonic provinces of Australia can be divided into two along the Tasman Line (Figure 5.2; Veevers, 1984). West of this line the continent is dominated by Precambrian blocks and fold belts overlain by thin Phanerozoic basins, while to the east of it there are mainly Phanerozoic fold belts overlain by younger basins. Broadly these fundamental geological divisions correspond to landscape regions. The Precambrian blocks correspond to plateaux at elevations of up to about 500 m, the fold belts to upland areas up to 2000 m and the basins to lowland plains with elevations of generally less than 200–300 m (Figure 5.3). The distinction between these major landform regions is reflected in the present drainage networks. Most integrated drainage occurs along the coastal margins, particularly along the eastern Phanerozoic fold belt. The drainage systems in the western parts of the continent are, however, generally uncoordinated. The Eastern Highlands are wetter now than the western two thirds of the continent and Veevers (1984) pointed out that this has been a feature of the continent throughout the Cenozoic, although the abundance of lignitic sediments of early Tertiary age in the west, south and centre of the continent suggest that the Eastern Highlands were no wetter. Veevers also suggests that in general the present drainage systems reflect those of the Tertiary.

While it is difficult to speculate about the evolution of soils in Australia much before the Cenozoic, it is possible to reconstruct some soil history throughout the Cenozoic, as there are sufficient remnants of older soils to give some insight. The soils naturally reflect the interaction between

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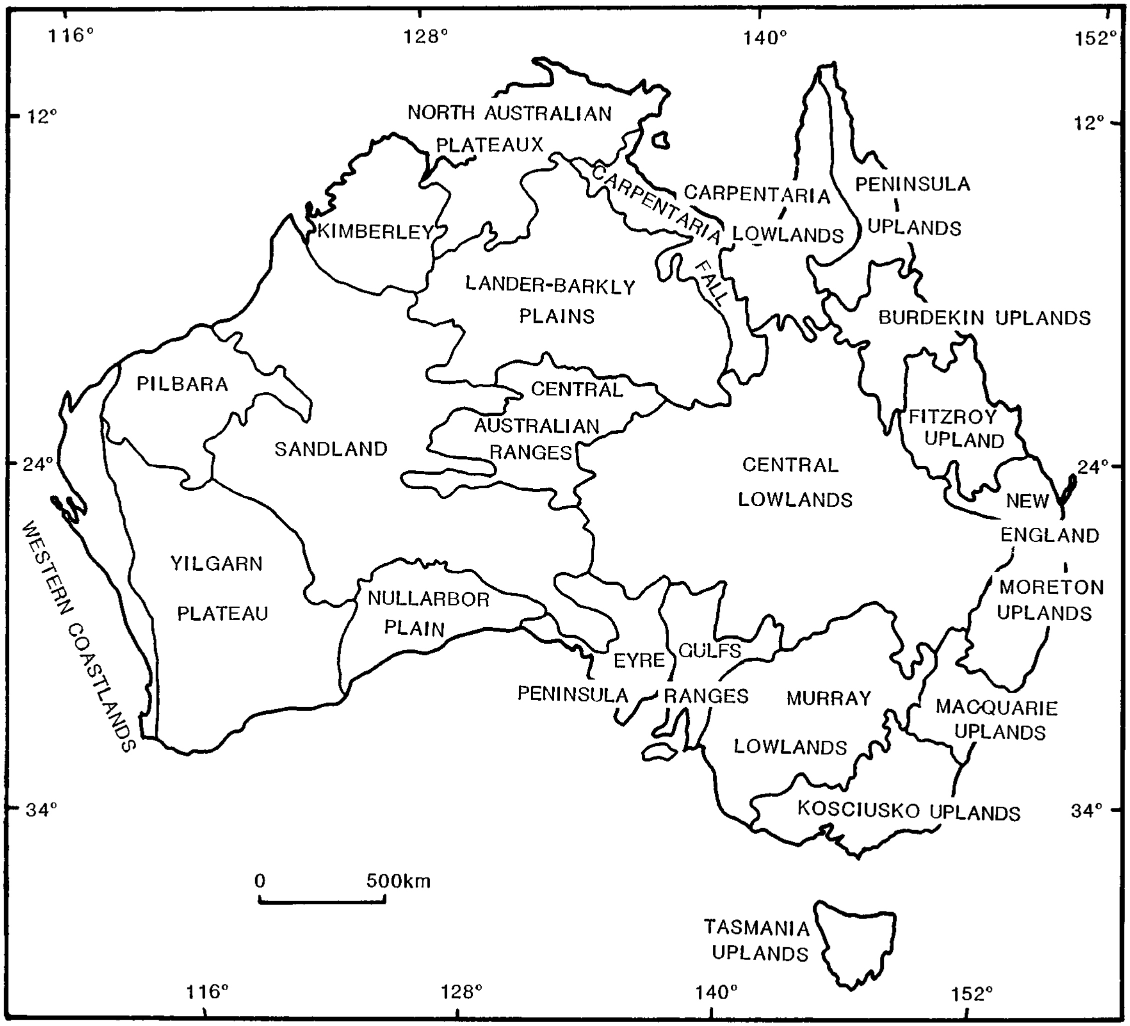

Figure 5.1 Australia's major landscape elements. The Kosciusko and Macquarie Uplands comprise what is referred to in the text as the southern sector of the Eastern Highlands, and the Moreton, New England, Fitzroy, Burdekin and Peninsula Highlands the northern sector. (Modified from Jennings & Marbutt, 1977.)

parent material, climate and rates of erosion or deposition, the last of these factors being generally tectonically controlled.

This chapter begins with the relationship between tectonic provinces and landscapes but because data from many regions are sparse the coverage is somewhat selective, concentrating on areas for which data are available. Towards the end of the chapter the evolution of regoliths and soils is discussed. Because the evolution of climate in Australia is discussed in detail by Quilty, (Chapter 3, this volume), it is not discussed here, except where climatic events are critical in landscape development.

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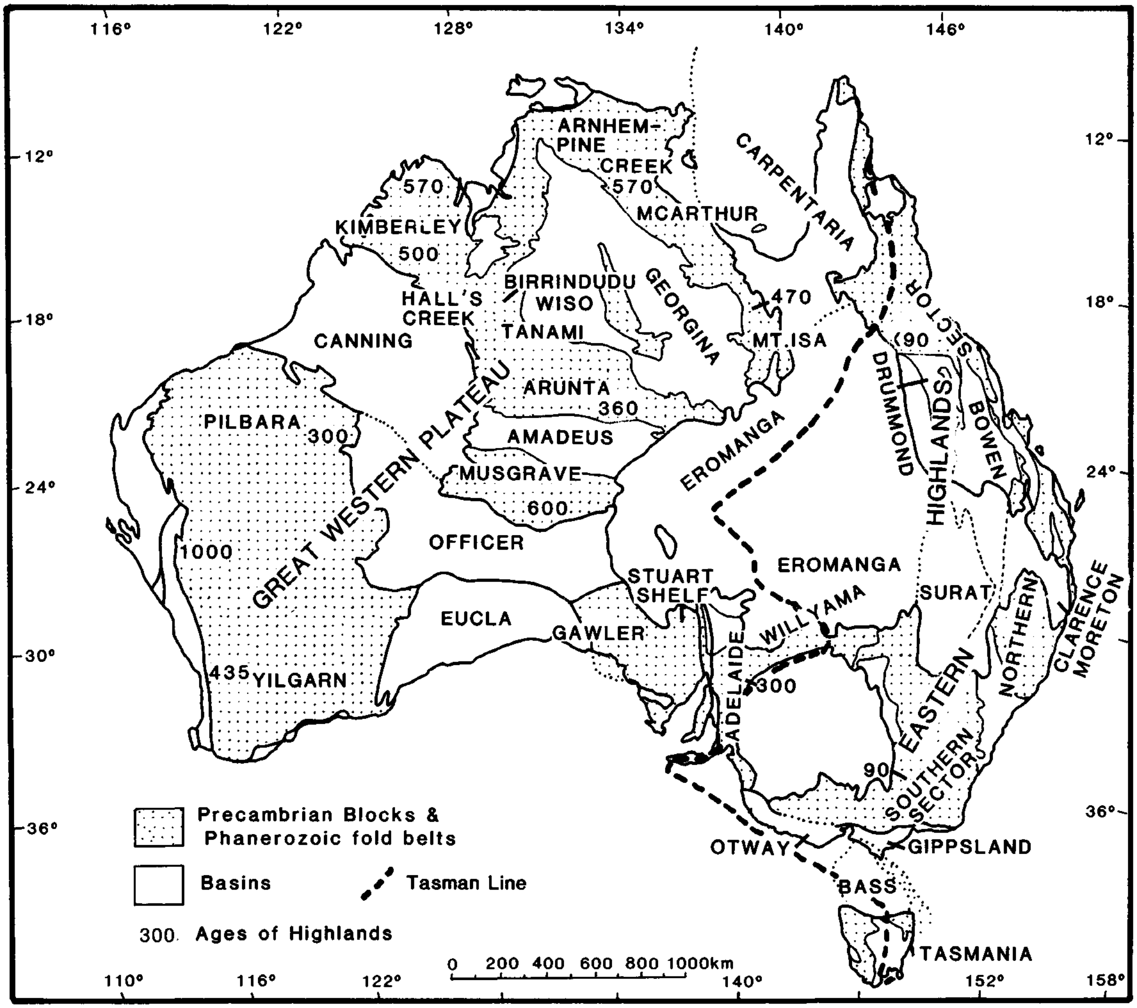

Figure 5.2 The major tectonic provinces of Australia, showing the major lowland depositional basins, Palaeozoic accretionary terrains (separated from the cratonic blocks to the west by the Tasman Line), and the cratonic blocks which make up much of the Great Western Plateau. The ages of the highland and cratonic blocks are from Veevers (1984) and Taylor. (Modified from Veevers, 1984.)

GEOLOGICAL EVOLUTION AND LANDSCAPE REGIONS

The geological (or tectonic) evolution of Australia is closely related to the nature and age of the major landscapes. The division of the continent into two along the Tasman Line is a convenient division between the older landscapes of the western two thirds of the continent and the younger higher-relief eastern third. In both the eastern and western regions the older rocks are partly covered by comparatively thinner and younger sedimentary basins, which form the major lowland landscapes. It is convenient to maintain these major subdivisions of the continent in the discussion that follows.

The maximum possible age for landscapes is determined by the 'age of exposure' of the rocks

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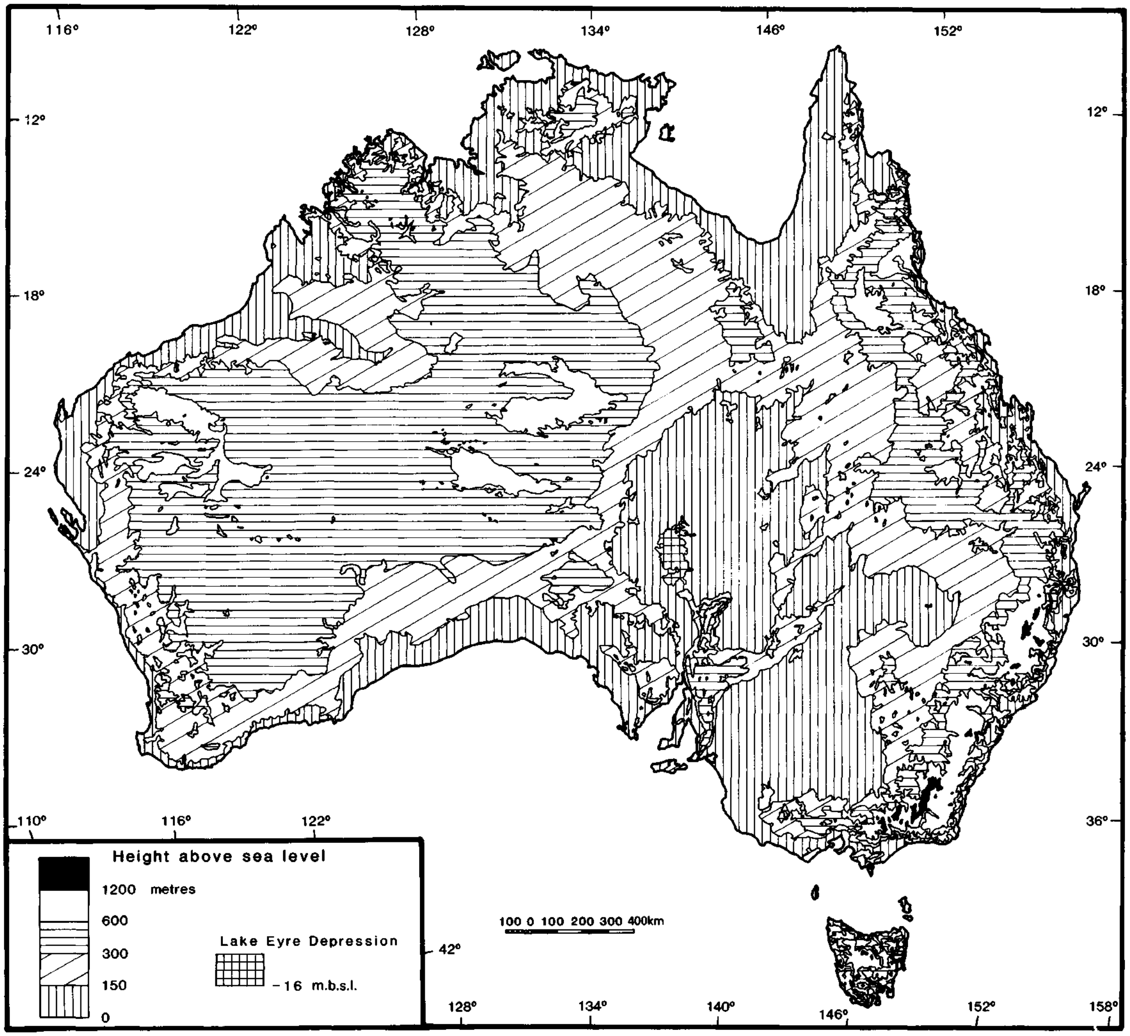

Figure 5.3 A topographic map showing how the topography generally follows the major tectonic provinces. m.b.s.l., metres below sea level.

to terrestrial processes or when major episodes of terrestrial sedimentation ceased. Figure 5.4 is a map of the 'age of exposure' compiled by Beckmann (1983). This map does not give the age of the landscape because after exposure the original surface may be partially or wholly stripped by erosion and there may be multiple erosional or depositional surfaces of varying ages in the landscape. None the less the map does reflect the gross geology and landscape ages of Australia.

Geological evolution and landscape ages of the western plateaux

The cratonic blocks that so dominate the western region of the continent are all made up predominantly of Precambrian granitic, metamorphic and sedimentary rocks that comprise the Yilgarn–Pilbara, Kimberley, Arnhem–Pine Creek–McArthur–Mt Isa and the Musgrave–Amadeus–Arunta Blocks (Figure 5.2) and

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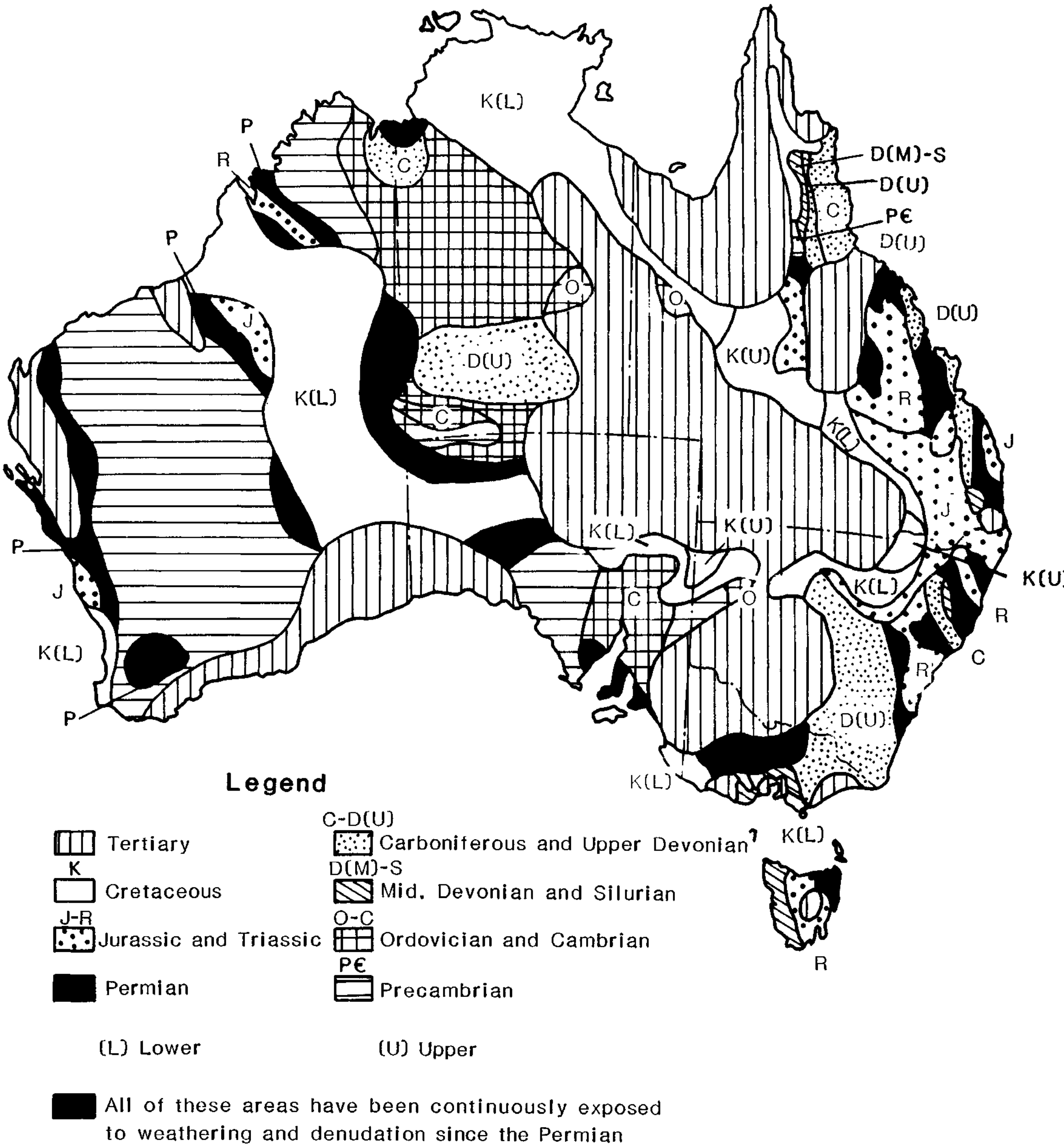

Figure 5.4 A map portraying the 'age of exposure' to weathering of the continent. While this does not include Tertiary and Quaternary volcanics it gives a good general idea of the maximum age of the landscapes of Australia. The solid tone includes areas of Permian rocks and areas known to have been exposed since the Permian but not on Permian rocks. (Modified from Beckmann, 1983.)

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which correspond to major landscape provinces (Figure 5.1). These regions have been prominent landscape elements for most of the Phanerozoic, forming important sediment sources for the Phanerozoic basins which surround them.

Since their exposure the landscapes of the western region blocks have been substantially modified. The Yilgarn–Pilbara Plateau has been degraded by 600–700 m or more throughout the Phanerozoic (Veevers, 1984), probably a substantial portion of this during the Late Carboniferous and Permian, when glaciers swept across the plateau from south to north. Veevers & Wells (1962) reported glaciated pavements from this time exposed in the Pilbara region, where relics of glacially carved valleys can still be seen, and Butt (1989) reported Permian glacial deposits in valleys on the northern Pilbara. Substantial sediment was also shed west into the Perth Basin between the Permian and Cretaceous, although much of the Mesozoic sediment may be derived from uplifted parts of the basin. Van de Graaf (1981) calculated rates of denudation of between 4.5 and 5 m per Ma, which suggests that considerable uplift must have occurred during the Phanerozoic. It is unlikely that little if any significant uplift occurred after the Permian glaciation, as tills of that age remain on the surface. Jackson & van de Graaf (1981) argued that the relict drainage of the Yilgarn, now represented by chains of lakes, developed between the late Mesozoic and Eocene and involved some 100 m of erosion, but R. P. Langford, G. E. Wilford & E. M. Truswell (unpublished data) date the drainage as Permian, which is in accord with other data. Van de Graaf (1981) suggested that, during the late Cenozoic, erosion has been only a few centimetres per Ma. The Yilgarn–Pilbara Plateau has therefore been uplifted and eroded significantly during the Palaeozoic – early Cenozoic but since then it has been extremely stable.

The Kimberley and Northern Australian Plateaux and the Carpentaria Fall are underlain by the Kimberley and Arnhem Blocks, the Pine Creek Inlier, McArthur Basin and Mt Isa Block, which collectively consist largely of geosynclinal sediments and metamorphic and granitic rocks of Precambrian age, and have formed landscapes throughout much of the Phanerozoic (Veevers, 1984). Again these ancient high landscapes have been uplifted through much of the Phanerozoic, providing sediments for their marginal basins (Figure 5.2). The present coastline of this area approximates closely to that which has existed through much of the Phanerozoic, except during the Early Cretaceous, when the sea swept briefly across the Pine Creek Inlier and Daly and McArthur Basins, leaving a quartzose sheet sand that has since been substantially removed (Skwarko, 1966). This indicates the long-term lateral stability of these cratonic areas over the last 500 Ma or so. Permian glacial debris in the Fitzroy Trough includes material derived from the Kimberley Plateau to the north, showing that, during the late Carboniferous and Permian the plateau, like the Yilgarn, underwent some glacial erosion. Young (1986) demonstrated that, in addition to physical removal of detritus, the effects of solution weathering can be substantial in Devonian quartz sandstones of the Ord Basin, and it would be surprising if similar chemical effects were not just as prominent in landscape denudation on the adjacent cratons.

The Central Australian Ranges (Figure 5.1) have the highest elevation of any of the Precambrian cratonic areas of the western region, with some peaks reaching 1500 m. The ranges are made up of three major geological entities: the Precambrian Musgrave Block, the Arunta Block and the late Proterozoic–Palaeozoic Amadeus Basin (Figure 5.2). To the northwest these regions are connected to the Kimberley Block by the Tanami Block, Birrindudu Basin and Hall's Creek Province. All these are composed of sedimentary, metamorphic and granitic rocks. The Central Australian Ranges are overlain around the margins by Phanerozoic sediments of younger sedimentary basins and partially divided by Palaeozoic sediments in the Amadeus Basin (Figure 5.2). Cambrian and Devonian sediments of the marginal basins lap on to the Arunta Block (Veevers, 1984), indicating that it was a feature of some relief during the Cambrian and that its uplift was complete by the Devonian. Both blocks acted

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as sediment sources for their surrounding basins. Glacial pavements in the highlands and glaciogene sediments in the surrounding basins indicate that glaciers eroded the Central Australian Ranges. Erosion during the late Mesozoic and early Cenozoic etched a southeasterly drainage network that is now partially filled with sediments (Twidale & Harris, 1977). It is this drainage that established features such as Uluru and the Olgas, proving the antiquity of such landscape elements. Minor fault-bounded Cenozoic basins occur within the Central Australian Ranges, illustrating the continued role of tectonism in these landscapes.

The Precambrian Gawler and Willyama Blocks, with the Adelaide Fold Belt and Stuart Shelf (Figure 5.2) make up the core of the Eyre Peninsula and Gulf Ranges landscape region (Figure 5.1). These regions are made up of volcanics, metasediments, flat-lying and folded sediments, and granitic rocks surrounded by basins of Phanerozoic sediments that lap on to the older cratonic platforms. This region has formed high ground on and off since the late Carboniferous (Veevers, 1984), but parts of the area formed highlands well before this. This high ground provided sediments to the marginal Phanerozoic basins (Figure 5.2) since their inception. Glacial activity during the Permian significantly eroded the highlands. Renewed late Cenozoic faulting in the Gulf Ranges region produced their present form (Callen & Telford, 1976).

Geological evolution and landscape ages of the Eastern Highlands

The Eastern Highlands of Australia, a complex landscape region (Figure 5.1) about 400–500 km wide, extends from Tasmania to North Queensland. It is a relatively high region with average elevations in excess of 500 m and large areas in excess of 1000 m. An obvious feature of the highlands is the asymmetric drainage, with short, steep, east-flowing networks and very long, low-gradient, westerly drainage with long sedimentary records in the basins flanking the inland margin of the highlands.

The Eastern Highlands are dominated by Early to mid-Palaeozoic geosynclinal deep and shallow marine sediments and granitoids with abundant Cenozoic basalts. Some Mesozoic and Cenozoic basins also occur within the highlands. They are flanked by sedimentary basins that lap on to the Palaeozoic rocks of the highlands. The highlands have been providing sediment to these basins throughout the Cenozoic.

The date of formation of the highlands is a matter of considerable debate. Early workers (Andrews, 1911; Browne, 1969; Hill, 1975) believed most of the uplift was comparatively recent (since the Late Miocene). These workers based their conclusions primarily on the southern highlands; however, more detailed work in the highlands and flanking basins has shown that considerable differences may exist between the histories of the northern (Queensland and northern New South Wales) and southern (southern New South Wales, Victoria and Tasmania) highlands. Wellman (1987) reviewed the erosional and uplift history of the whole highlands and Bishop (1988) provided a similar review, predominantly of the southern portion.

Ollier (1977) showed that, in the southern sector, the highlands had a relief of at least 600 m in the Eocene and Taylor *et al.* (1985, 1990*a*) demonstrated a relief of at least 500 m and probably 800 m by the Paleocene. Further studies of the marginal basins (Macumber, 1978; Wooley, 1978; Veevers, 1984; Brown, 1989) show that sediments derived from the southern highlands began depositing during the late Mesozoic in the Gippsland and Otway Basins and during the Paleocene in the Murray Basin. Nott *et al.* (1991) and Young & McDougall (1982) showed that the southern New South Wales coastal strip was established by the mid-Tertiary and probably earlier. Williams (1989) recorded Late Cretaceous and Paleocene sediments in basins along the northern coast of Tasmania. These data clearly show that the southern sector of the highlands was uplifted sufficiently by the earliest Tertiary or Late Cretaceous to provide a major sediment source for the flanking basins. There is now a general consensus that the uplift of the

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southern sector is at least late Mesozoic, but there is little evidence to suggest how much older it may be. The absence of sediment in the flanking basins older than late Mesozoic suggests the major uplift dates from about 95 Ma, as suggested by Jones & Veevers (1982) and favoured by Wellman (1987). Lambeck & Stephenson (1986) however, argued on the basis of a passive isostatic rebound model that the highlands date from the late Palaeozoic and have risen more or less continuously since, in response to erosional unloading. In contrast Jones & Veevers (1982) argued for periodic uplift through the Cenozoic, associated with volcanism and accompanying sedimentation/sea level fluctuations in the flanking basins. The Tasmanian segment of the highlands possibly began to develop its present form in the Triassic and the present configuration was well established by the Late Cretaceous (Williams, 1989). Whichever is the correct model, the southern sector of the highlands was certainly well established by the Cenozoic.

The northern sector of the Eastern Highlands has Mesozoic sediments preserved on the highland summit, which suggests uplift was after the Early Cretaceous in Queensland and after the Triassic near Sydney (Wellman, 1987). The presence of abundant andesitic debris in sediments as young as Cenomanian (90 Ma) in the Eromanga Basin along the western highland flanks but derived from volcanoes east of the present coast (Veevers, 1984) shows that the highlands did not exist until after this time. The presence of quartzose sediments overlying the deeply weathered Late Cretaceous–Paleocene surface (Doutch, 1976) suggests that by the Eocene the highlands were shedding sediment into the flanking basins. Grimes (1980) identified three periods of uplift and basaltic volcanism, during the Paleocene–Eocene, Late Oligocene to mid-Miocene and Pliocene–Quaternary, similar to those in the southern sector identified by Jones & Veevers (1982). He also notes that Quaternary uplift with basaltic volcanism occurred as recently as 13 ka ago in northern Queensland. In the Ebor area of New England, retreat of the Great Escarpment must postdate the formation of the Ebor Volcano 18.5 Ma ago (Gleadow & Ollier, 1987). Elsewhere Ollier (1982) argued that uplift in this region postdates 18 Ma. Schmidt & Embleton (1976) suggested that the Sydney Basin was uplifted and eroded between 100 and 180 Ma.

The southern sector of the Eastern Highlands is probably older in general than the northern sector but both contain landscapes of considerable antiquity with superimposed younger landscapes in many areas. There is the unifying feature of widespread occurrence of basaltic landscapes, which, although highly dissected, frequently preserve the topography and soils over which the lavas flooded (Bishop, 1988). These basalts range in age from Holocene in Victoria to Late Cretaceous in central Queensland and northern New South Wales. The overall rate of eruption was more or less constant through the Cenozoic. Lava field volcanism dominated until about 35 Ma, while after that time most activity was associated with central volcanic eruptions (Wellman & McDougall, 1974).

History of landscapes in the basins flanking highland regions

While many of the sedimentary basins which flank the highland regions (Figure 5.2) have histories which extend well back into the Palaeozoic, most were inundated by the sea during the Early to mid-Cretaceous (Figure 5.5). During this period sedimentation alternated between marine and terrestrial due to global sea level changes (Morgan, 1980) or to uplift of the newly formed continent (Veevers, 1984; Wilford & Brown, Chapter 2, this volume). During the marine phases the highland areas were separated by shallow seaways, which Wasson (1982) suggested would have increased spatial and habitat diversity on the continent. Certainly the shallow seas in which sea levels oscillated would have led to a diversity of marginal marine habitats through this period. On the retreat of the Cretaceous seas during the late Aptian, the basins generally had a low relief surface, which, because of limited post-Cretaceous tectonism, was retained through most of the Cenozoic. There are remnants of this mid-

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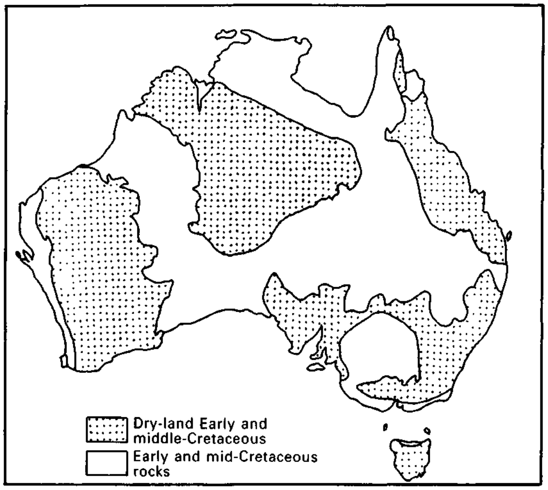

Figure 5.5 The extent of the marine inundation of the continent during the Cretaceous. (From Wasson, 1982.)

Cretaceous surface preserved throughout many of the major basins, particularly in the Eromanga, Officer and Canning Basins. Much of the Cretaceous surface is covered or partially covered by Cenozoic sediment, particularly in many of the eastern and southern basins. Each major basin is examined in turn and correlations are shown in Figure 5.6.

Post mid-Cretaceous deposition began in the Murray Basin during the Paleocene and continues today. Jones & Veevers (1982) suggested that sedimentation was initiated by the uplift of the Eastern Highlands and concomitant subsidence of the basin. Three major depositional cycles separated by erosional intervals occurred during the Paleocene–Early Oligocene, Oligocene–Middle Miocene, and Late Miocene–Pliocene. Marine incursions occurred during each cycle, with the most extensive during the Late Miocene. During each cycle a wide spectrum of environments existed, from shallow marine carbonate platforms through lagoonal, tidal and deltaic regions to riverine plains with lakes (Figure 5.7). The cause of these depositional cycles is not certain, but Brown (1983, 1985, 1989) attributed them to sea level changes accompanied by basinal isostatic adjustment. The effects of these sea level variations were restricted to the basin, but stream valleys on the margins of the Eastern Highlands eroded deeper during lower sea levels, were backfilled during high sea levels as a result of diminished erosion potential (Macumber, 1978). The final regression of the sea from the Murray Basin during the Late Miocene – Early Pliocene formed a prograding series of beach ridges and intervening fluvial and estuarine quartz sands (Parilla sand). These ridges form prominent landscape features in the western parts of the basin. Since the final regression of the sea, the basin has been dominated by alluvial, lacustrine and aeolian activity under oscillating cold and warm conditions that characterise the last 2.5 Ma. During this period the availability of water has varied, but not in any systematic way with regard to temperature (Bowler, 1978), except that at this time generally arid conditions prevailed in contrast to the generally humid conditions which had persisted since the Late Cretaceous.

The Eucla Basin was dominated by limestone deposition during the Eocene and Miocene. Rivers draining from the Yilgarn and Musgrave Blocks into the Eucla Basin were established after the withdrawal of the Cretaceous seas. During high sea levels in the Eocene, these channels were inundated by the sea and alluviated with the deposition of sands, lignite, spongolite and limestones across the southeastern Yilgarn (Jones, 1990). Across the Officer and southwestern Eromanga Basins these channels were filled with quartzose alluvium (Lampe Beds) and alluvium and marginal marine sediments (Pidinga Formation: Benbow *et al.*, 1982). These palaeochannels now form chains of playas on the Yilgarn and across the Officer and southwestern Eromanga Basins. After deposition of the Miocene limestone, the Eucla Basin was uplifted and the sea withdrew, leaving the flat surface of the Nullarbor Plain exposed. Minor alluvial and lake deposits in shallow drainage lines separated by low hills of deeply weathered Cretaceous rocks form the only Tertiary record in the Canning Basin. Longitudinal dunes, formed during the Quaternary, overlie these old drainage systems. The Eromanga Basin, the largest of the flanking basins, saw the deposition of the Winton Formation after the retreat

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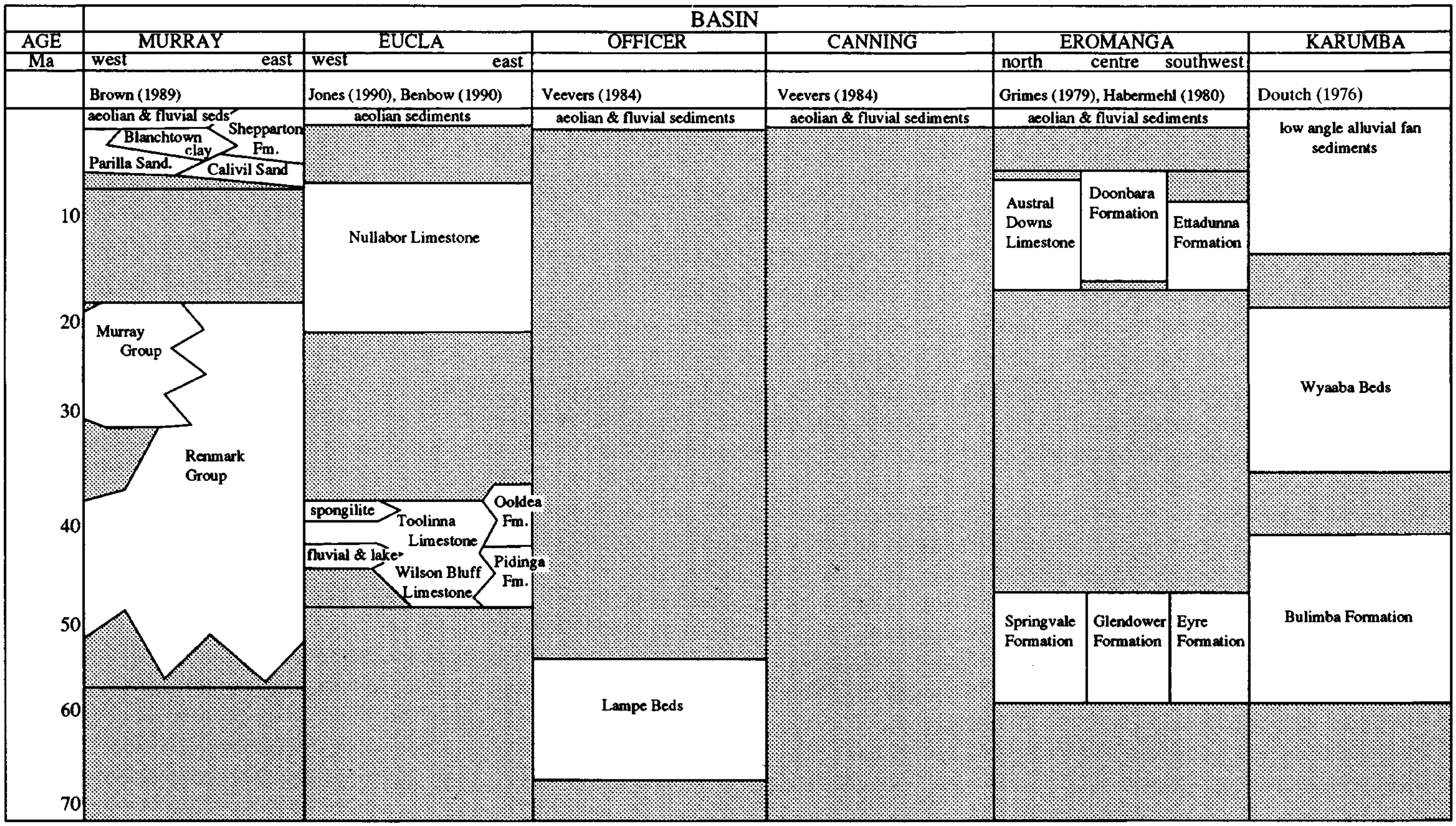

Figure 5.6 Correlation of formations, weathering events etc. acrosss the Murray, Eucla, Officer, Canning, Eromanga and Karumba Basins. Fm, Formation. (Karumba Basin from Doutch, 1976; Grimes, 1979; Veevers, 1984.)

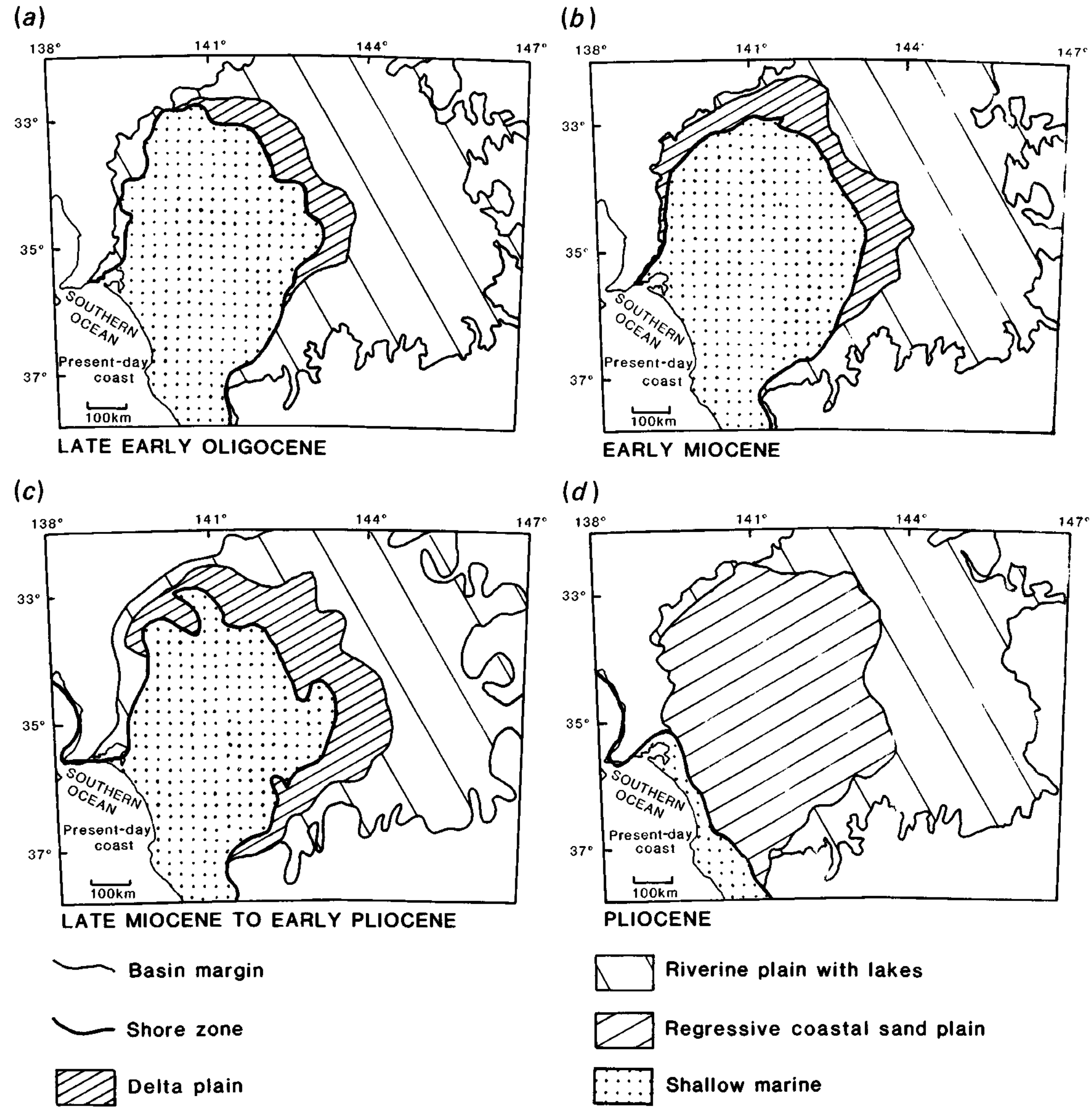

Figure 5.7 (*a*) to (*d*) An example of the evolution of a basin fill during the Tertiary. This much simplified example is for the Murray Basin in southeastern Australia. (Modified from Brown, 1989.)

of the sea during the Albian (95 Ma). This is a terrestrial sheet of volcanogenic sandstone, shale and coal deposited between about 95 and 90 Ma. This low relief surface was deeply weathered during the ensuing 20–30 Ma (the Mornay Profile of Idnurm & Senior, 1978). This phase of weathering was terminated by the deposition of the quartz-rich fluvial Eyre Formation and its equivalents during the Paleocene and Eocene. Another break in deposition allowed time for the development of further weathering and the formation of silcrete (the Cordillo Silcrete of Wopfner, 1974; and the Cordillo Surface of Doutch, 1976). Post Eyre Formation warping and uplift during the

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Oligocene produced the major landscape elements within the present basin. It also caused subsidence of the Lake Eyre and Lake Frome depressions with sedimentation in substantial lakes during the Miocene. The depressions elsewhere in the basin were the locus of deposition of the Etadunna Formation (and its equivalents). The Etadunna is a sequence of muds, carbonates and evaporites deposited in streams and lakes. Warping continued after the deposition of the Etadunna, and the surface was once again deeply weathered (the Canaway Profile and its equivalents, Curalie and Strathgordon; Doutch, 1976). The warped areas continued to be the locus of fluvial and lacustrine sedimentation. The Cooper Syncline beneath the channel country of Cooper Creek and Lake Yama Yama are examples of this, as are many other drainage lines of southern Queensland (Senior *et al.*, 1978). Sedimentation in these loci consists of up to 160 m of quartz sandstones and conglomerates, mudrocks and thin gypsum layers, above the Etadunna Formation. These drainage lines are still the centres of fluvial and lacustrine sedimentation. They are separated by low ridges and mesas of deeply weathered and silcreted Cretaceous rocks and Eyre Formation. As fluvial and lake sedimentation continued through the Quaternary, dune fields swept across the interfluves, particularly in the southwest in the Simpson and Strezlecki Deserts. Evaporites and clastics accumulated in the lakes and muds and sands in the rivers during drier and wetter phases, respectively.

Other similar flanking basins such as the Gippsland, Otway and Perth Basins have post-Cretaceous records of marine and terrestrial sedimentation punctuated by tectonically or eustatically induced breaks.

REGOLITH AND SOILS OF THE CONTINENT

Regolith is a term used to encompass all the fragmental earth materials, residual or transported, that overlie bedrock and usually forms the surface of the land (Ollier, 1988). Soil forms the uppermost part of the regolith.

From the earlier parts of this chapter it is clear that much of the continent has elements of its landscape that are very ancient whereas other elements are comparatively young. The nature of the regolith depends primarily on climate, time, rate of stripping (erosion) and the type of rock or sediment on which it has developed.

The last major glaciation to occur in Australia was during the late Carboniferous and early Permian. These glaciers produced pavements and valleys still preserved in some of the old plateaux of Western Australia and in the Eastern Highlands of Victoria (Craig & Brown, 1984). After this glacial episode, conditions suitable for abundant plant growth persisted until the Jurassic, even though southern Australia was in a high latitude position. The climate began to dry about 160 Ma ago, but at about 140 Ma it again became humid. This humidity persisted and with it the landscapes became forested (Frakes *et al.*, 1987). There is some debate about temperatures during the Mesozoic. Frakes *et al.* (1987) suggested that the Jurassic was generally temperate but that in the Early Cretaceous there were 'cooler than expected' temperatures. This is supported by Francis (1990) for the southwestern Eromanga Basin. This is not surprising, since between 175 and 40 Ma much of Australia lay within the Antarctic Circle (Wilford & Brown, Chapter 2, this volume). Taylor *et al.* (1990*b*) also provided evidence for cool climates in the southern sector of the Eastern Highlands during the Late Paleocene.

Frakes *et al.* (1987) noted three warm to cool cycles throughout the Tertiary: Late Cretaceous–Middle Eocene, Middle Eocene–Early Oligocene, and Early Oligocene–Late Miocene. These broad climatic cycles gave way to more arid climates during the period between mid-Pliocene and the start of the Quaternary, when temperatures oscillated between warm and cold on an about 100 ka cycle, during which time water availability also varied, but not necessarily in consort with temperature (Frakes *et al.*, 1987). Throughout this time the history of groundwater is intimately related to regolith development (see e.g. Butt, 1989; Brown, 1989). The groundwater conditions are largely related to climate and geology.

Variations in rock type across the continent

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have dramatically affected the nature of the landscape and regolith. Regions with rocks containing labile minerals (igneous rocks and volcanogenic or feldspathic sedimentary rocks) tend to have generally deep regoliths, whereas those on quartzose sedimentary rocks or limestones tend to have thin regoliths and soils.

Minor tectonic activity has occurred in parts of the continent from the Late Cretaceous. When combined with sea level changes during this period (Frakes *et al.*, 1987) their effect has been to cause much of the regolith to be stripped from the cratonic blocks and the Eastern Highlands, or to promote deposition in the flanking basins and on to the margins of the cratonic blocks.

While there are undoubtedly regolithic materials which pre-date the Late Cretaceous (e.g. Permian glacial materials and pavements), well-documented examples are rare. The majority date from the time of the regression of Cretaceous seas. Two major regolith-forming episodes can be identified since this time. The first, from the Late Cretaceous to the Late Miocene, gave rise to deep lateritic weathering under humid and most would argue warm (e.g. Frakes *et al.*, 1987; Butt, 1988; Ollier, 1988), conditions, although cooler phases are recognised (Frakes *et al.* (1987) summarised the evidence) based on micropalaeontological records both onshore and offshore and on $\delta^{18}O$ values. The second began about 10–6.5 Ma, when there was a rapid reduction in sea level brought about by expansion in the Antarctic ice sheets. By 2.5 Ma the Tertiary seas had retreated and the climate was altered to cyclical repetitions of cold (glacial) and warm (interglacial) periods in which warm periods were wetter than the cold periods and winds periodically became more intense. During this last 2.5 Ma, the acidic deep weathering environment gave way, at least in central and southern Australia, to alkaline weathering conditions with the production of widespread evaporites and calcareous regoliths.

Deep weathering

Many Australian land surfaces are covered by deeply weathered *in situ* or sedimentary materials. Doutch (1976) showed multiple 'periods' of ferruginisation in the basins of Eastern Australia as did Frakes *et al.* (1987) and Grimes (1980).

Such 'weathering events' are easily recognised in depositional terrains, where the various 'events' are, at least in part, separated by intervening sedimentary events. It would be reasonable to assume that under the generally tectonically stable conditions that existed through the period between 90 and 6.5 Ma, intense weathering would be continuously occurring, but Frakes *et al.* (1987) correlated the deep weathering events with the warmer parts of their three Tertiary climatic cycles, which also happen to coincide with the uplift pulses of Jones & Veevers (1982) in the Eastern Highlands. The evidence of Francis (1990), Taylor *et al.* (1990*a*,*b*), Bird & Chivas (1988) and the postulation of cooler Late Cretaceous climate in Frakes *et al.*'s paper suggest, however, that the widely accepted belief that deep weathering needs warm climates may not be true. Recent evidence from Iceland (Gislason *et al.*, 1990) shows clearly that very rapid chemical denudation is possible in cool to cold climates as also suggested by Reynolds (1971). The idea of continuous weathering is certainly supported when the ages of deep weathering for the whole continent are plotted (Figure 5.8). Even considering the inaccuracies in the dating of weathering profiles, the stratigraphic and palaeomagnetic control is sufficient to place some value on the data.

The deeply weathered profiles generally grade upwards from parent rock through a zone of increasingly kaolinite-rich saprolite (rock weathered *in situ* that retains the original rock fabric), which becomes increasingly palid upwards. This is overlain by a mottled zone consisting of a white or pale-coloured matrix containing ferruginous red mottling and an uppermost ferruginous crust (ferricrete, laterite or bauxite). This is the classical 'laterite' profile originally described in Western Australia by Walther (1915).

These deeply weathered profiles show considerable variability. Many have transported upper horizons that are not related to the underlying saprolite (e.g. Churchward & Bettenay, 1973; Milnes *et al.*, 1985; Taylor & Ruxton, 1987).

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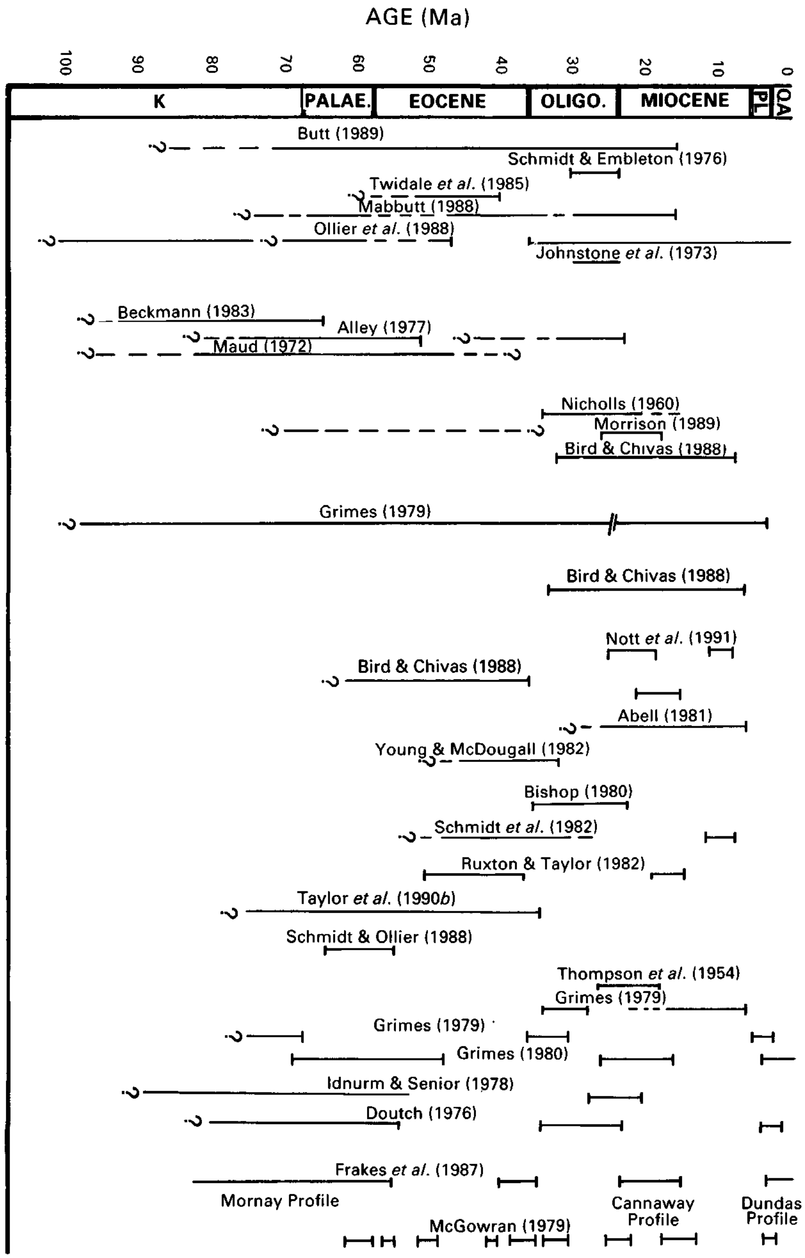

Figure 5.8 A time plot of some 'weathering events' as recorded in the Australian literature on weathering. Clearly, this plot shows there to be little cyclicity in these events, but it should be added that the data presented here are shown without critical review of their reliability. PALAE, Palaeocene; OLIGO., Oligocene; K, Cretaceous; PL, Pliocene; QA, Quaternary.

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Some are stripped, with the upper zones removed (e.g. Senior, 1979; Butt, 1989; Ollier *et al.*, 1988), others have silicified upper zones (e.g. Ollier *et al.*, 1988) or are partially stripped with a silcrete in the pallid zone (e.g. Senior, 1979; Ollier, 1988) or capped by silcreted sediments unconformably overlying stripped profiles (e.g. Senior, 1979; Taylor & Ruxton, 1987; Ollier *et al.*, 1988).

These highly leached deep weathering profiles cover much of Australia, from east coast to west and from Tasmania (where they are less common) to Cape York. In places they are relatively thin (e.g. Monaro, where they vary from 2 m on basaltic lavas to tens of metres on surfaces exhumed from beneath early Tertiary basalts); in others very thick (e.g. southwest Queensland where they exceed 100 m; Senior, 1979). Most of these deeply weathered landscapes have been eroded into a series of mesas and low plateaux, protected somewhat by caps of ferricrete and/or silcrete, separating broad valleys cut into the weathered rocks. The cause of this erosion is tectonic, eustatic or due to climatic change or a combination of these. The products of the erosion (mainly kaolinite and quartz) are deposited in the lower parts of the landscape, particularly in the valleys, but some products occur as widely distributed sheets of alluvial sediments (e.g. Eyre and Glendower Formations). Some areas of the cratonic blocks, most notably the Yilgarn, are covered by sandplains. These are thought to originate by solution of kaolinite from the deep weathering profiles, leaving a lag of the solution-resistant quartz sand (Butt, 1985).

Soils formed on the deeply weathered materials and on sediments derived from them are highly leached and acid, and consist largely of kaolinite, quartz and sequioxides. The types of soil commonly associated with these parent materials are shown in Table 5.1. The parent materials for these soils are, in general, old (Figure 5.8), and it is likely that many of these leached acid soils have formed the substrate for vegetation in Australia since the early Tertiary. Indeed because of their significant erosion during the later Tertiary and Quaternary and their partial burial during the Quaternary they were more widespread than at present and as a consequence would have played a major part in the evolution of our flora.

Table 5.1. *Soil parent materials and soils resulting largely from Tertiary deep weathering*

Soil parent materials	Soils
Kaolinite, laterite, bauxite, silcrete, mottled and pallid zone materials, and deeply kaolinitised rock	Massive red and yellow earths (Gn2) and the associates the earthy sands (Uc5.2), earthy loams (Um5.3, Um5.5), the gravels and possibly the red siliceous sands (Ucl.23), red structured earths (Gn3)

The notations in brackets are Northcote's soil forms.

Deep weathering in landscapes underlain by quartzose or limey sediments has not produced a thick regolith. In quartz sandstone terrains (e.g. eastern Kimberley, Arnhemland Plateau) the predominant form of weathering has been solution, resulting in the development of karstic landscapes dominated by solution channels along structural weaknesses in the rocks. In extreme cases, such as the Bungle Bungle Ranges (Young, 1986) and Ruined City of Arnhemland (Jennings, 1983), tower karst landscapes have been produced. Soils are minimal in these landscapes, except in some valleys that contain infertile quartz sand soils. The Nullarbor Plain is underlain by Miocene marine limestones, and, although it has only been exposed to terrestrial weathering for a comparatively short time, it has karstic landforms and discontinuous drainage typical of limestone terrains. Soils here are thin calcareous loams with extensive calcrete development (Northcote & Wright, 1982).

Regoliths and soils of the Quaternary

The growth of the Antarctic ice sheet near the end of the Miocene and the associated sudden decrease in sea surface temperatures resulted in an intensification of atmospheric circulation, initiating conditions, similar to those of the present day, that control the distribution of the mid-latitude dry deserts. For the next 3 Ma, landscapes and vegetation underwent the transition from

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those of the humid Tertiary to those of the more arid Quaternary (Frakes *et al.*, 1987). There is widespread evidence of predominantly alkaline weathering, associated with the post-Tertiary drying at about 2.5 Ma. Since then, oscillatory warm and cool climatic phases have been associated with widespread alluviation, lacustrine sedimentation and aeolian activity, with hillslope instability, erosion and valley alluviation in highland areas.

The Quaternary record for Australia prior to the last glacial–interglacial cycle, which began about 120 ka ago, is poor, but a good record for the last cycle is preserved. The development of the landscape and regolith during this phase was well described by Bowler (1982), Wasson & Clark (1987) and Frakes *et al.* (1987), so only a brief summary is included here.

Between 120 and 60 ka, at the start of the last cycle, landscapes and climates were very similar to those of the present. Inland Australia was dominated by stabilised longitudinal dunes (Frakes *et al.*, 1987). Major westerly flowing streams drained the Eastern Highlands, carrying fine sediments out across the Murray Basin. Dry lake beds were scattered across the landscape. About 60 to 36 ka, as the build-up of ice began in the northern hemisphere, runoff from the Eastern Highlands increased, rivers transported coarser sandy sediment across the Murray Basin, and the inland lakes filled (Bowler, 1978). A brief drying at this time reactivated the longitudinal dunes (Bowler & Wasson, 1983) but wetter conditions rapidly returned and persisted until 25 ka, when cooler, dryer conditions became dominant.

During the glacial maximum from about 30 to 15 ka, glaciers covered much of central and western Tasmania and a small area near Mt Kosciusko, leaving behind them glacial landscapes and moraine when they retreated. In the inland areas available precipitation decreased (Bowler & Wasson, 1983). High wind velocities enabled longitudinal dune fields to be reactivated and develop to their present dimensions. Source-bordering dune fields developed downwind of major streams (even in the highlands, e.g. Canberra), and lunettes of clay-rich materials formed on the leeward side of inland lakes and in Tasmania (Frakes *et al.*, 1987). The dune fields in many coastal regions also developed during this time in Tasmania. Inland lake systems dried, depositing increasing amounts of salt and gypsum, which, with clays, were deflated and deposited in the lunettes. During this same arid phase, dust and salts were carried downwind and deposited as blankets across much of Australia. Many of the desert loams and parna (loess) were formed during these arid climatic episodes and in the highlands, where they accreted in soil profiles (Walker *et al.*, 1988).

In the Eastern Highlands the cool, dry periods were marked by widespread hillslope erosion, formation of alluvial fans and valley alluviation with gravels and sands (between about 30 and 15 ka), followed by relative hillslope stability and the accumulation of fine alluvium in valley bottoms (Walker & Butler, 1983). The sand and gravel and the fine alluvium typically have red to yellow podzolic and earth soils and prairie soils, respectively developed on them.

This arid phase (and those of previous Quaternary cycles) generally produced alkaline weathering conditions in the arid areas. Increased quantities of expanding clays with high cation exchange capacity, eroded from weathering profiles formed under changed conditions in the Eastern Highlands, were deposited on the adjacent lowlands. These produced soils such as the alkaline, saline and cracking clay soils so typical of much of inland Australia (Table 5.2). The dune sands produced uniform red siliceous sands. This dramatic change from leached acid soils to the more alkaline, carbonate- and salt-rich soil of the Quaternary must have had a significant impact on vegetation, particularly when the climatic instability and changes in availability of water are considered.

Associated with the Quaternary climatic oscillations were sea level oscillations of 100 to 120 m. These changes in sea level resulted in the complex set of coastal environments and landscapes of the present. Many of the large coastal plains were built during this period, indeed many since the last glacial maximum. Complex coastal dune systems with complex soil landscape patterns

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Table 5.2. *Soil parent materials and soils resulting from Quaternary arid weathering*

Soil parent materials	Soils
Sediments of Quaternary age, and all fresh rocks and sediments exposed by erosion of the deep weathering profile, or else always protruding above it	Calcareous earths (Gc soils), crusty and hard red duplex soils (Dr1, Dr2), saline clays and cracking clays (Uf1, Ug5), shallow sands (Uc), shallow loams (Um), shallow calcareous loams (Um5.11) and saline loams (Um1)

The notations in brackets are Northcote's soil forms.

developed during this period. Land-bridges between the mainland and Tasmania and New Guinea have formed and been severed on numerous occasions and the coastal plains around much of the continent have expanded and contracted with sea level change.

The cool to cold, windy and dry conditions which characterised the last glacial maximum gave way to present conditions *ca* 10 ka ago, and sea levels stabilised at about their present level *ca* 6 ka ago.

CONCLUSION

The interdependence of climate, vegetation and landscape is well known. This chapter has briefly examined the evolution of landscapes and the regoliths and the soils developed on them. Many of the landscapes of the Great Western Plateau have developed their present character since the region was swept by Permian glaciers. The retreat of the Cretaceous seas shaped the landscapes of the basins in this region. The Eastern Highlands, although their age is uncertain, were uplifted before the late Mesozoic. Hence all the major landscape elements have existed for at least 90 Ma, and are certainly ancient compared to those in most other continents.

Since the retreat of the Cretaceous seas, the continent has been tectonically quiet, with only minor uplift and sagging having any influence on landscapes. Climatic changes during this interval have, however, had a profound effect on the landscapes and their regoliths. The period from the Cretaceous to the Pliocene was predominantly humid, causing widespread deep weathering and leached acid soils. The onset of arid conditions about 2.5 Ma dramatically altered the weathering regimes to predominantly alkaline, leading to salt- and carbonate-rich soils. Intensified winds during this phase built the extensive aeolian landscapes that characterise much of the interior and coastal landscapes.

These dramatic shifts in landscape and soil development over a long time have caused equally dramatic shifts in vegetation, from humid forests during much of the Tertiary to the flora of today. Equally it is likely that earlier changes in vegetation can be viewed in the same way, although data on earlier landscape evolution and soil development are sparse.

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