Journal of the Royal Society of Western Australia, 89:57–82, 2006

Ancient weathering zones, pedocretes and palaeosols on the Australian Precambrian shield and in adjoining sedimentary basins: a review

J B Firman

14 Giddens Court, North Lake, WA 6163

Manuscript received June 2005; accepted May 2006

Abstract

A stratigraphic approach is used in this review of ancient weathering zones, mottled zones, pedocretes and palaeosols on the Australian Precambrian Shield and in adjoining sedimentary basins. Pedogenic features identified in the landscape during regional stratigraphic mapping have been traced along the western margin of the Australian Precambrian Shield. The weathered zones, pedocretes, mottled zones and palaeosols identified in South Australia and elsewhere have been extended into the Perth Basin where there are correlative conformities. The weathered zones, pedocretes, mottled zones and palaeosol units are described in a geochronological framework from Palaeozoic to Late Cainozoic. The weathering products of the Palaeozoic include the Playfair Weathering Zone. Mesozoic sequences include the Arckaringa Weathering Zone (a pallid zone in laterite profiles) and the San Marino mottled zone equivalent. The units taken together have been said by some authors to form "a distinctive basal horizon which underlies all true laterites". The laterite in this sense refers to the ferricrete forming a caprock on older materials. Early and Middle Cainozoic sequences include bauxite, the Greenmount Ferricrete and the Calingiri Silcrete. Late Cainozoic sequences contain the Jumperdine Ferricrete and the Karoonda Soil (which in some places is a syndepositional silcrete), and the mottled zones of lateritic podzolic soils. The weathered zones, pedocretes and palaeosols were formed under different climatic regimes. The study of weathering zones, pedocretes and palaeosols on the south-west margin of the Australian Precambrian Shield confirms the earlier conclusions derived from South Australia that sedimentary sequences are intercalated in the profiles between the Playfair Weathering Zone and the Arckaringa Weathering Zone, between the San Marino mottled zone equivalent and the Greenmount Ferricrete, and (after erosion of the ferricrete and formation of the Calingiri Silcrete) between the Playfair Weathering Zone and the younger Jumperdine Ferricrete. Sediments also are intercalated between the Jumperdine Ferricrete and the Karoonda Palaeosol.

The major implication of the work is that pedogenic features can be correlated Australia-wide on a morphological basis and according to their time of origin.

Keywords: weathering zones, pedocretes, palaeosols, stratigraphy, Western Australia, South Australia.

Introduction

The aim of this review is to place weathered zones, pedocretes and palaeosols on and around the Australian Precambrian shield in a stratigraphic setting, synthesising the information mainly from Western Australia and South Australia, but relating them to other sections in the eastern states where appropriate. Older pedogenic features are well preserved on the Precambrian shields, but they are down-faulted and buried by sediments in the marginal basins.

The location of weathering zones, pedocretes and palaeosols has been established on 1:250,000 geological maps compiled by the Geological Surveys of Western Australia, South Australia and the Bureau of Mineral Resources. The youngest substrate on which the material has been developed and the oldest unaltered rock or soil unit overlying it are identified. This procedure places the weathering zone, pedocrete or palaeosol in a stratigraphic position relative to other materials at the formation or stage level in the geological column for that area.

Each of the weathering zones, pedocretes or palaeosols serves to identify a bounding surface in sequence stratigraphy (Salvador 1994; Embry *in* Brakel 2003). These surfaces can be placed in the record of adjoining sedimentary basins according to their time of formation, a procedure that identifies sequences larger than a group or supergroup throughout the study area. The relevant basin stratigraphy has been described in the Perth area by Cockbain (1990) and Trendall & Cockbain (1990), and on the south-east margin of the shield by Firman (1975, 1980) and Drexel *et al.* (1993). The comments on basin sediments herein are summarized from these texts except where other references are given.

Although the ancient weathering zones, pedocretes and palaeosols could be as old as the sedimentary unit in or on which they have been developed, other evidence has been taken into account when suggesting the time of formation. In many cases, the age of the rock units with which they are stratigraphically associated is shown in the records of sedimentary basins and has been previously determined by palaeontological criteria (Cockbain 1990; Ludbrook *in* Drexel & Preiss 1995).

The pedogenic features described on the western margin of the shield have been matched to similar features on the south-east margin of the shield where they have been described and named (Firman 1994). The major implication of this work is that pedogenic features can be correlated Australia-wide on a morphological basis and according to their time of origin.

There are problems, however, with definitions of weathering zones, pedocretes and palaeosols, and for this reason some notes are provided here to clarify their use in this paper.

Soil consists of layers (horizons) developed below ground surface by soil forming processes operating in different ways at different times. All the layers, other than those relating to the modern environment are old. Assemblages of layers constitute soil profiles in the pedological sense (Firman 1969b, 1971).

Horizons of accumulation (B horizons) characterize particular profiles at the great soil group level. On the soil stratigraphic table (Fig. 1), surface soils are indicated by their B horizons and by the great soil groups with which they are associated. The soils overlie pedocretes and weathering zones commonly occurring in the Adelaide Region of South Australia. Similar soils in the Perth Region of Western Australia are described by McArthur & Bettenay (1960) and other soil scientists mentioned in this text.

Where a break in soil formation is followed by emplacement of younger material (either sediment or soil), a palaeosol may be recognized. Some soil profiles in the pedological sense are storied profiles and may include a number of palaeosols (Firman 1979, 1986; Yaalon 1971). The distribution of these soils has been outlined on maps of South Australia (*e.g.*, Firman 1986), and their evolution has been described in Firman (1988, 1994).

The term pedocrete is used to describe superficial materials that were originally weathering residues or sedimentary layers in soil profiles. These materials have undergone cementation by minerals precipitated from groundwater (*cf.* Netterburg 1985).

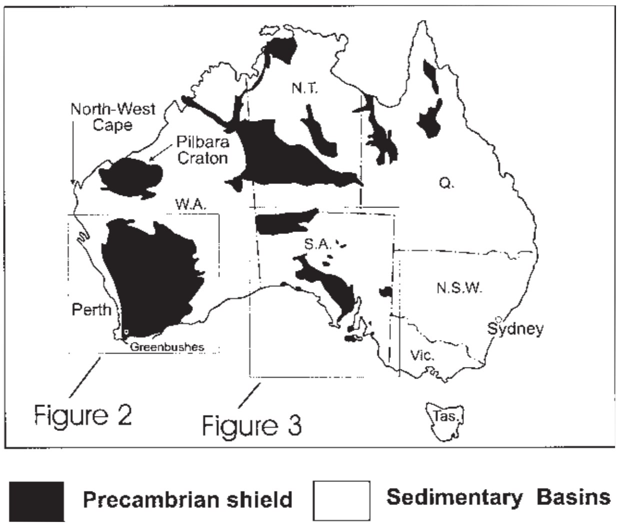

Figure 1. Map showing the Precambrian Shield, and insets of the Study Areas in Southwestern Australia and in South Australia.

Ironstone is an old term for ferricrete that indicates the cementing agent and the use of the metal as an ore. Ferricrete is commonly called laterite in early Australian literature, but the term is a misnomer derived from a supposed equivalence with clay used for brick-making in India. Ferricretes and silcretes have been called caprocks to emphasize their position in the landscape, and duricrusts to identify their hardness. Ferricretes and silcretes form the upper part of giant profiles overlying ancient weathering zones. These profiles are described as laterite and silcrete profiles in the Australian literature.

Where the parent material below a soil stratigraphic unit in Western Australia differs from that in a profile or section in South Australia another name is used. Although individual soils and pedocretes are stratigraphically associated with weathered rocks and surficial sediments in particular provinces or sedimentary basins where they were first described, they can be traced for great distances through different landscapes, into adjoining sedimentary basins, along the piedmont zones of mountain chains, river cliffs, and coastal margins.

The Australian Precambrian Shield

The Australian Precambrian Shield includes the Yilgarn Craton and the Pilbara Craton in the west and the Gawler Craton and Musgrave Block in the south-east. Proterozoic rocks which are shown north-east of the cratons (Figs 1, 2 & 3) are bounded by younger Phanerozoic rocks.

Much of the detailed evidence on ancient soils along the south-west margin of the Australian Precambrian Shield is derived from a narrow bench, described as a "laterite platform" and named the Ridge Hill Shelf by Woolnough (1918). The evolution of the shelf provides evidence important in the understanding of the regional stratigraphy of Phanerozoic sedimentary deposits and of associated weathering zones, pedocretes and palaeosols. The shelf, which is about 135 m below the top of the Darling Scarp and 80 m above sea level, is from one and a half to three kilometres wide and extends from Eneabba in the north to near Tutunup in the south – approximately a distance of 500 kilometres (Fig. 2). The shelf diverges from the Darling Scarp to the north and south to follow the western margin of Mesozoic sequences which on their eastern side are at much the same elevation as the shield itself.

The shield margin in the west is a fault zone across which the ancient shield rocks have been displaced over 15 km in the central Dandaragan Trough. The fault zone, which was named the Darling Fault (Saint-Smith *in* Jutson, 1934) is a N-S geofracture some 500 km in length, which separates Archaean and Proterozoic rocks of the Australian Precambrian Shield to the east of the fault – here represented by the Yilgarn Craton – from Phanerozoic sediments and volcanics of the Perth Basin to the west – here represented by the Dandaragan Trough and the Bunbury Trough which adjoins to the south.

Archaean rocks are part of the Yilgarn Craton, a stable nucleus composed of granites and gneiss enclosing a number of "greenstone belts" of metamorphosed layered

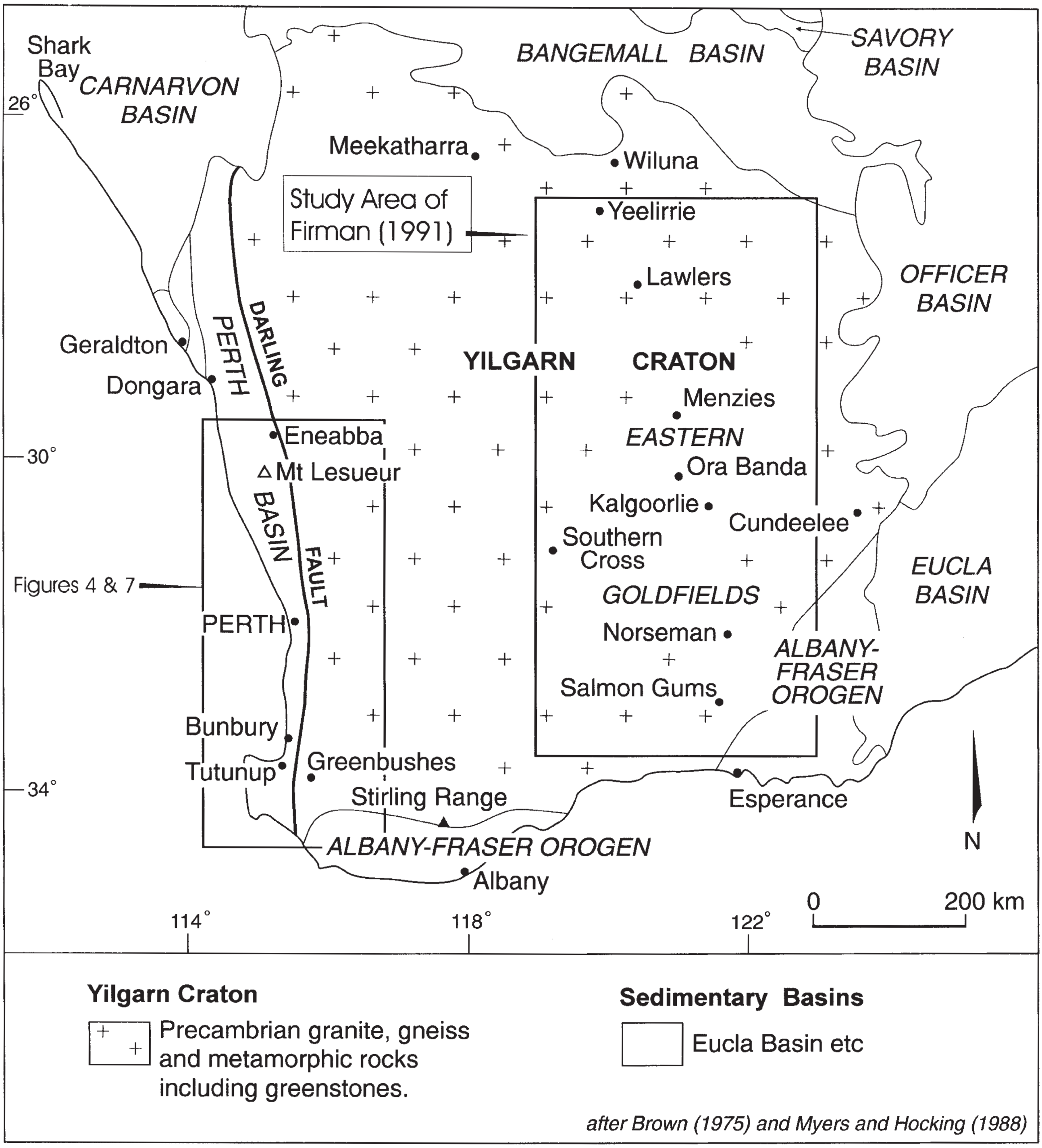

Figure 2. Location of the south-west margin of the Australian Precambrian Shield, the Yilgarn Craton, Pilbara Craton and adjoining sedimentary basins. The figure indicates the area along the Darling Fault where palaeosols, pedocretes, mottled zones and weathering zones are extended into parts of the Perth Basin where there are correlative conformities. The boxed area centred over Kalgoorlie is the study area presented in Firman (1991).

rock. The basement rocks on the western margin of the shield are part of the Western Gneiss Terrain, the most western unit defined within the Yilgarn Craton by Myers 1990 (see Granitic Rocks in Fig. 4).

Proterozoic rocks are Middle Proterozoic according to Myers & Hocking (1988). They were part of the extensive cover of sedimentary rocks containing stromatolites and trace fossils, which are now exposed over a wide area in northern Australia, and in erosional remnants of rocks containing an Ediacran fauna in the Stirling Range in the south and the Ediacra Range in South Australia.

Tholeiitic quartz dolerite dykes intrude all the Precambrian rock-types including the Proterozoic. Giddings (1976) reports six episodes of dyke intrusion, ranging from the Archaean to Late Precambrian. The dykes which cut the Cardup Group (Cardup Series of Prider 1943), are presumed to be Late Proterozoic or younger. They are the youngest crystalline basement

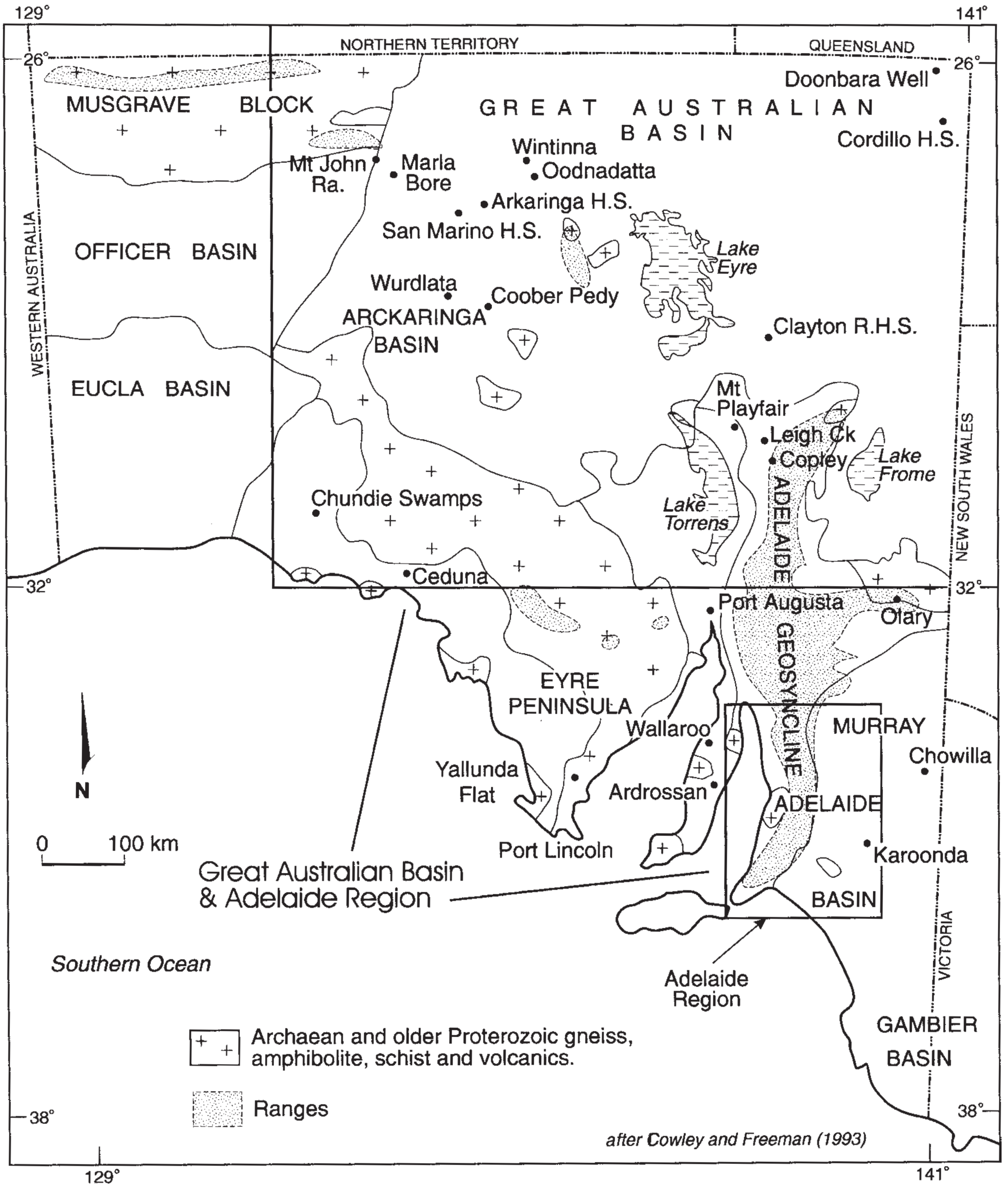

Figure 3. Important localities on the south-east margin of the Australian shield in South Australia. The boxes show areas where studies of soil – geology have been made and palaeosols, pedocretes, mottled zones and weathering zones have been mapped at 1:250,000 scale. For details of the Adelaide Region see Firman (1986, 1988). For details of the Great Australian Basin area see Firman (1980).

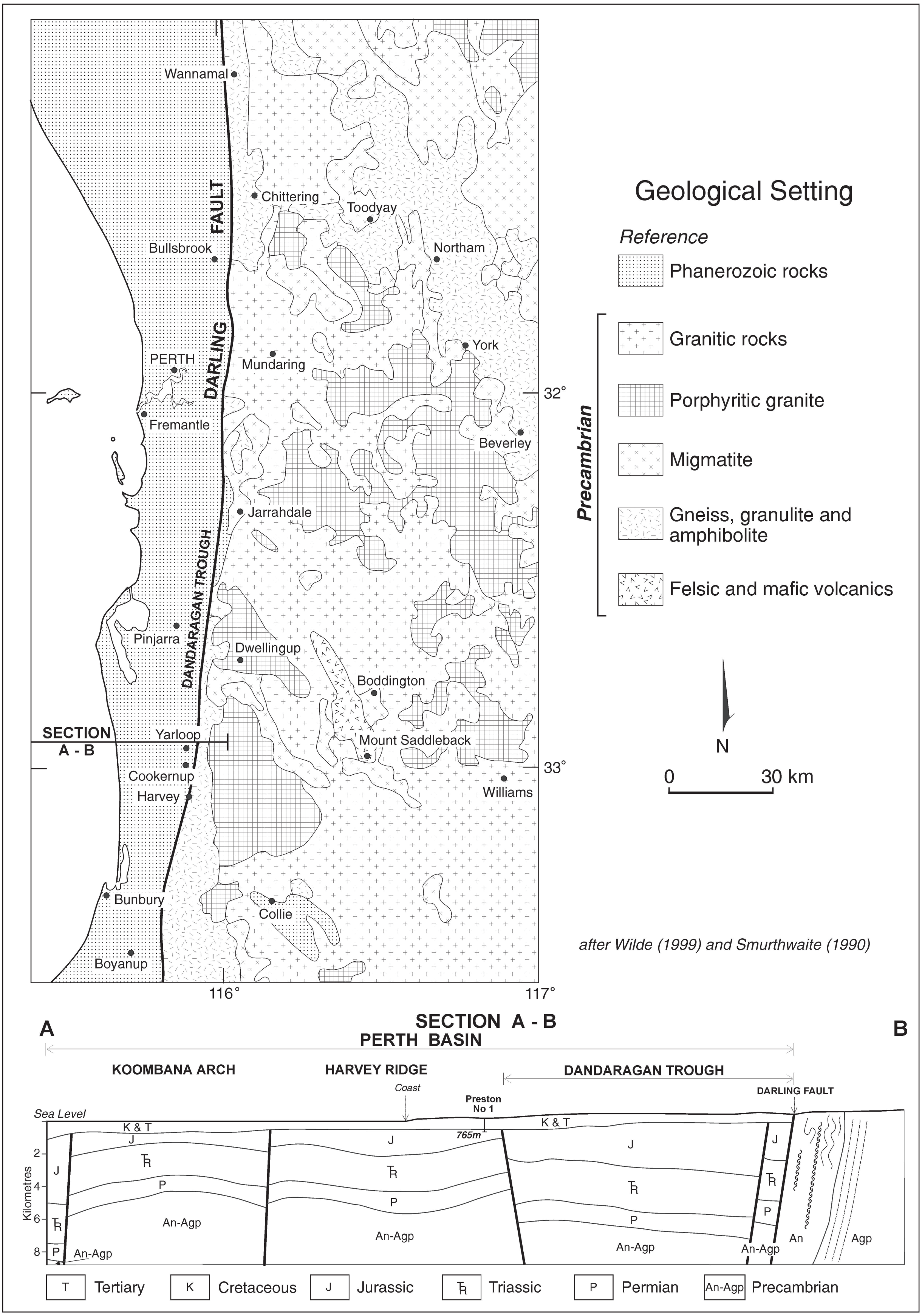

Figure 4. The geological setting of the south-west margin of the shield. Precambrian rocks east of the Darling Fault Zone and Phanerozoic sediments of the Perth basin to the west. Map supplied by Professor Simon Wilde.

rocks on the margin of the shield affected by the oldest weathering zone at the base of laterite profiles.

The Precambrian on the south-east margin of the shield is described in relation to morpholithological features relevant to this study by Firman (1975) and in more detail by Drexel *et al.* (1993).

Palaeozoic – sedimentation and weathering

The geological history of the Australian Precambrian Shield subsequent to its early development is recorded in important stratigraphic sequences on the margins of the shield where they are exposed by exoreic drainage. Within these sequences, stratigraphically associated or

SOIL STRATIGRAPHIC TABLE

Palaesols Pedocretes and weathering zones (Age)	Great soil groups	Lateritic podzolic	Solodic	Red-brown earth	Solonized brown soil	Black earth, terra rossa and rendzina[d]	Red and yellow podzolic	Solonchack	Siliceous and calcareous sand	Skeletal soil
Sandy A horizons etc.		+	+	+	+	+	+	+	+	+
Alluvial and estuarine soils								+		
Peebinga Soil	1				+					
Loveday Soil					+		+			
Callabonna Soil	2			+		+	+			
"Wilkatana" soil				+						
Bakara Soil	3				+	+				
Ripon Calcrete					+					
Ardrossan Soil	4			+	Older					
Older structured clays			+	+						
Denison gypcrete				Older						
Karoonda Soil	5	+								
Jumperdine Ferricrete[a]	6	+								
Calingiri Silcrete[b]	7	+								
Greenmount Ferricrete[c]	8	+								
San Marino mottled zone	9	+								
Arkaringa Weathering Zone	10	+								
Playfair Weathering Zone	11	+								

Soil profiles

S.A. examples
a. Ferricrete on Loxton Sand
b. Clayton River Silcrete
c. Yallunda Ferricrete
d. Black earths and red-brown earths

Figure 5. The diagram shows the relative stratigraphic position (youngest at the top to oldest at the bottom) of palaeosols, pedocretes, mottled zones and weathering zones found in surface soils and substrates in an around the Australian Precambrian Shield. The crosses record the presence of master horizons in soils at the great soil group level and of pedocretes, mottled zones and weathering zones encountered in this study. Note that some soils are multi-storied. The numbers in the age column indicate geological time as follows: 1. Recent; 2. Late Pleistocene; 3. Medial Pleistocene; 4. Pliocene- Pleistocene; 5. 2.5 m years +; 6. Pliocene; 7. Miocene; 8. Eocene- Miocene; 9. Late Cretaceous - early Eocene; 10. Late Cretaceous; 11. Palaeozoic. Numbers 1– 4 are from Firman, 1988. Numbers 5 – 11 are from the present text and are supported by palaeontological studies quoted herein and by palaeomagnetic dating (Idnurm & Senior, 1978). Lower horizons and weathered substrates are omitted from the table.

as companion materials, weathering zones, pedocretes and palaeosols were developed which individually and as assemblages of layers and horizons record the history of weathering and of soil formation since the Proterozoic. Soil stratigraphic units, and their stratigraphic context are shown in Figures 5 & 6). On the south-west margin of the shield, the geological record east of the Darling Fault can be interpreted in part from Proterozoic rocks preserved in scattered outcrops at a high level along the Darling Scarp, and Permian, Mesozoic and Cainozoic rocks exposed by the erosion of fault blocks or preserved in grabens, deep embayments and ancient valleys (Playford *et al.* 1975; Hocking & Cockbain 1990).

STRATIGRAPHIC TABLE

		Perth Basin	Darling Range & Eastern Goldfields	S. E. Shield Margin
Cainozoic	Pleistocene *	Mottling Guildford[1] Formation	Valley Fill Menzies Fm.[1]	Ardrossan Soil Blanchetown Clay[1]
	Pliocene *	Karoonda		Soil
		Guildford Fm[3]		Blanchetown Clay[2]
			Sands and gravels	Avondale Clay
		Yoganup Fm.		Parilla Sand etc
	*	Jumperdine Ferricrete	Ferricrete[2]	Ferricrete[3]
		Ascot Formation	Sandy valley fill	Loxton Sand
	Oligocene-Miocene *	Stark Bay Fm		Etadunna Formation[4]
			Calingiri Silcrete	Clayton River Silcrete
			Fluvial sediments[3]	Waste mantle
	Eocene-Miocene *	Greenmount[4]	Ferricrete	Yallunda Ferricrete
	Paleocene-Eocene	Kings Park Fm.	Darling Range Bauxite	Pidinga Formation[5]
Mesozoic	*	San Marino mottled zone.[5]	San Marino mottled zone	
	*	Arckaringa	Weathering	Zone
		Sandstone[6]	Ridge Hill Sandstone	Winton Formation
				Bulldog Shale
Palaeozoic		Permian sediments		
	*		Playfair Weathering Zone	
				Cambrian and Ordovician sediments
Precambrian		Basement Rocks		Basement Rocks
* Weathering zones, pedocretes and palaeosols		1. Upper beds 2. Lateritic Podzols 3. Lower beds 4. Plateaux (Mooliabeenie, etc) 5. Poison Hill 6. Coolyena Grp	1. Yeelirie (lower beds) 2. Mulline Fm.	1. and Hindmarsh Clay 2. Lower beds 3. "Gun Emplacement" 4. also Nullarbor Ls. 5. Eyre Formation Inland

Figure 6. The stratigraphic table shows sedimentary units that bracket the weathering zones and pedogenic units in different profiles. Note the alignment of duricrusts and the alternation of iron and silica deposition. For the south-east margin of the shield, the names of sedimentary units down to Pidinga Formation relate to southern basins. Many of the names of units listed below the Clayton River Silcrete – with the exception of the Yallunda Ferricrete and Pindinga Formation – are found in or on the margin of the Great Australian Basin.

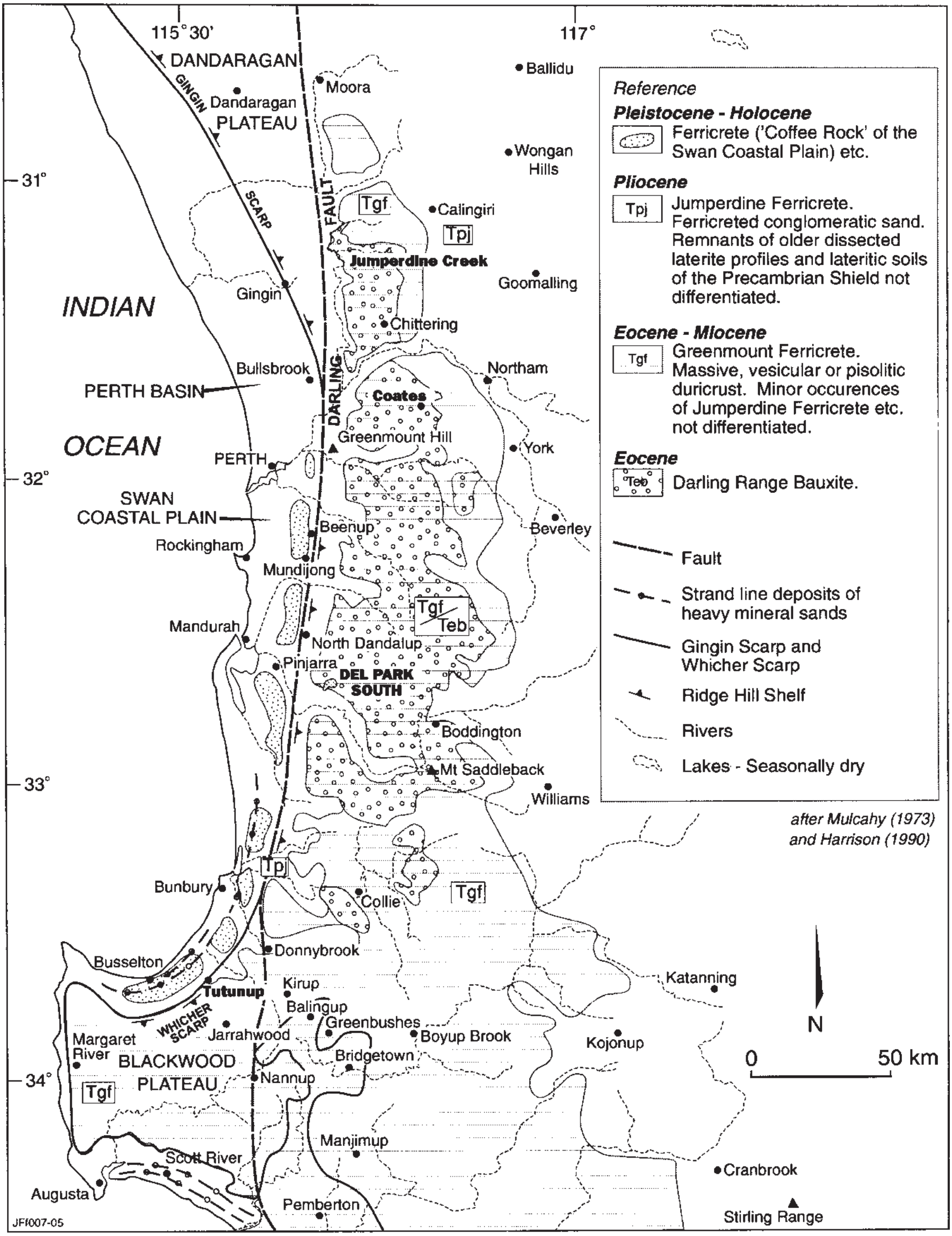

Figure 7. Geological map showing the distribution of ferricrete and bauxite on the western margin of the Precambrian Shield. Note that Greenmount Ferricrete also occurs to a limited extent on the Dandaragan Plateau, in the Gingin area near Poison Hill and at Mooliabeenie.

The Playfair Weathering Zone

In Western Australia, a polygenetic Palaeozoic erosion surface is postulated by Fairbridge & Finkl (1978). They state that the primordial surface on which the Playfair Weathering Zone was later developed may be traced back to post-Archaean/Early Proterozoic peneplantation visible in unconformities in the Stirling Range south-east of the study area.

The Playfair Weathering Zone is exposed in deep open pits in the Eastern Goldfields (Fig. 2), notably at the Agnew gravel quarry, and the Black Flag, Kanowna Belle and Panglo gold mines. In the Lawlers district of the Eastern Goldfields (Fig. 2) at the Genesis gold mine a Permian fluvioglacial palaeochannel is incised into the top of the Playfair Weathering Zone (Anand 1993a, 1993b). Along the western edge of the shield the zone is exposed by excavation of dams – the Serpentine Dam is a good example – and on the valley walls of streams incised through the Darling Scarp near Perth (Figs 2, 7 & 8).

Important sequences have been described near Yeelirrie in the Eastern Goldfields (Fig. 2), by Glassford (1987). The oldest named unit, Westonia Formation, is easily confused with *in situ* weathered Precambrian basement rock (Glassford 1987; de Broekert 2003). The presence of the formation between weathered basement and overlying "sandy lateritic to bauxitic duricrust" of uncertain age is incompatible with the notion of a direct genetic correlation between the weathered basement and the duricrust, the ferricrete of this study.

The Playfair Weathering Zone is named after Mount Playfair north-west of the type section, which is 2 km SSE of Copley in South Australia (Fig. 3). The unit is subhorizontal and has been developed on folded rocks of Precambrian, Cambrian and Ordovician age in the Mount Lofty and other ranges in South Australia, and on rocks of the Precambrian Shield on the margins of late Palaeozoic and Mesozoic basins elsewhere. It is characterized by large irregular red, yellow and white patches up to 10 m across. Thickness varies, but zones 100 m thick are common. The reader is referred to Firman (1994), and to the earlier work quoted therein showing important sections.

Near Adelaide, the palaeosurface on which the Playfair Weathering Zone was developed post-dates the folding of Proterozoic, Cambrian and Ordovician rocks along the Adelaide Geosyncline in the Delamerian Orogeny. In the north of South Australia, a similar weathering zone was developed near Marla, west of Oodnadatta (Fig. 3) possibly as early as the exposed erosional surface on the Cambrian Trainor Hill Sandstone (Firman 1980; Gravestock *et al.* 1995). Covering sediments are not present and the age of the weathering may be younger.

In the type section south of Leigh Creek (Fig. 3) 2 km south-east of Copley in South Australia (Firman 1980), the zone is overlain by Jurassic sediments. At Leigh Creek, coal measures of Middle Jurassic to Triassic age overlie the zone. Triassic and Permian sediments in adjoining basins are weathered, but do not show the thick, deeply weathered Playfair Weathering Zone. Another section, which is a possible supplementary section, occurs at Warramboo (Heath 1962) .

A similar weathering zone has been noted on early Palaeozoic rocks in New South Wales by the writer and in Victoria by Dr W V Preiss (per comm, 2002). A post-Ordovician/pre-Permian age is suggested for the Playfair Weathering Zone.

Younger Palaeozoic sequences

Much of the younger geological record is missing from the terrain east of the Darling Fault. A Silurian sequence is identified in the northern part of the Perth Basin. It includes quartz sandstone, carbonate rocks and evaporates (including tidal red beds). A Devonian – Carboniferous sequence is identified from reworked microfloras in Cretaceous and Permian rocks (Mory & Iasky 1996). A Late Carboniferous and Permian sequence was deposited by intermittent transgressions of a sea from the north. Continental sedimentation extended onto the Yilgarn Craton and coal-bearing sediments were deposited in the Collie, Wilga and Boyup basins. The lowest part of the Permian sequence is glacigene. In the north the Irwin Coal Measures and the Wagina Sandstone contain a well-developed Glossopteris fauna. There was a short-lived marine transgression in the Perth Basin during the Late Permian followed by uplift and erosion.

Mesozoic – sedimentation, weathering and development of the San Marino mottled zone

Weathering events during the Mesozoic on the Australian Precambrian Shield are not separately recorded in the literature, but the sedimentary record itself provides an indication of weathering and erosion in the provenance areas.

A Triassic sequence up to 3000 m thick is identified when the Perth Basin was again a rift valley which opened to the sea in the north. The base of the sequence is marked by a widespread unconformity. The main rock unit laid down as a result of tectonism, the Lesueur Sandstone, was probably deposited in a series of fans along the fault scarp. A Jurassic and Early Cretaceous sequence, which records the post-Gondwana phase of continental break-up, began when Australia and the rest of Gondwana separated and plate-margin settings became important.

The Bunbury Basalt, a vesicular porphyritic basalt, occurs near the base of the sequence. The basalt erupted at 123 and 130 m.y. (Wilde 1999). During the Cretaceous the geometry of the basin changed from a broad rift valley to a wide marine gulf and subsequently to a continental margin as pull-apart took place. The early Cretaceous consists of the lower South Perth Shale and the overlying Leederville Formation of interbedded sandstone, shale, siltstone and claystone, with minor conglomerate.

North of Perth the Leederville Formation is overlain by the Dandaragan Sandstone. An outcrop too small to map, which is possibly Leederville Formation, overlies conglomerate north-west of Walyunga (Wilde & Low 1978) and Fig. 9. Fluvial conditions persisted onshore and include the Bullsbrook Formation which was laid down

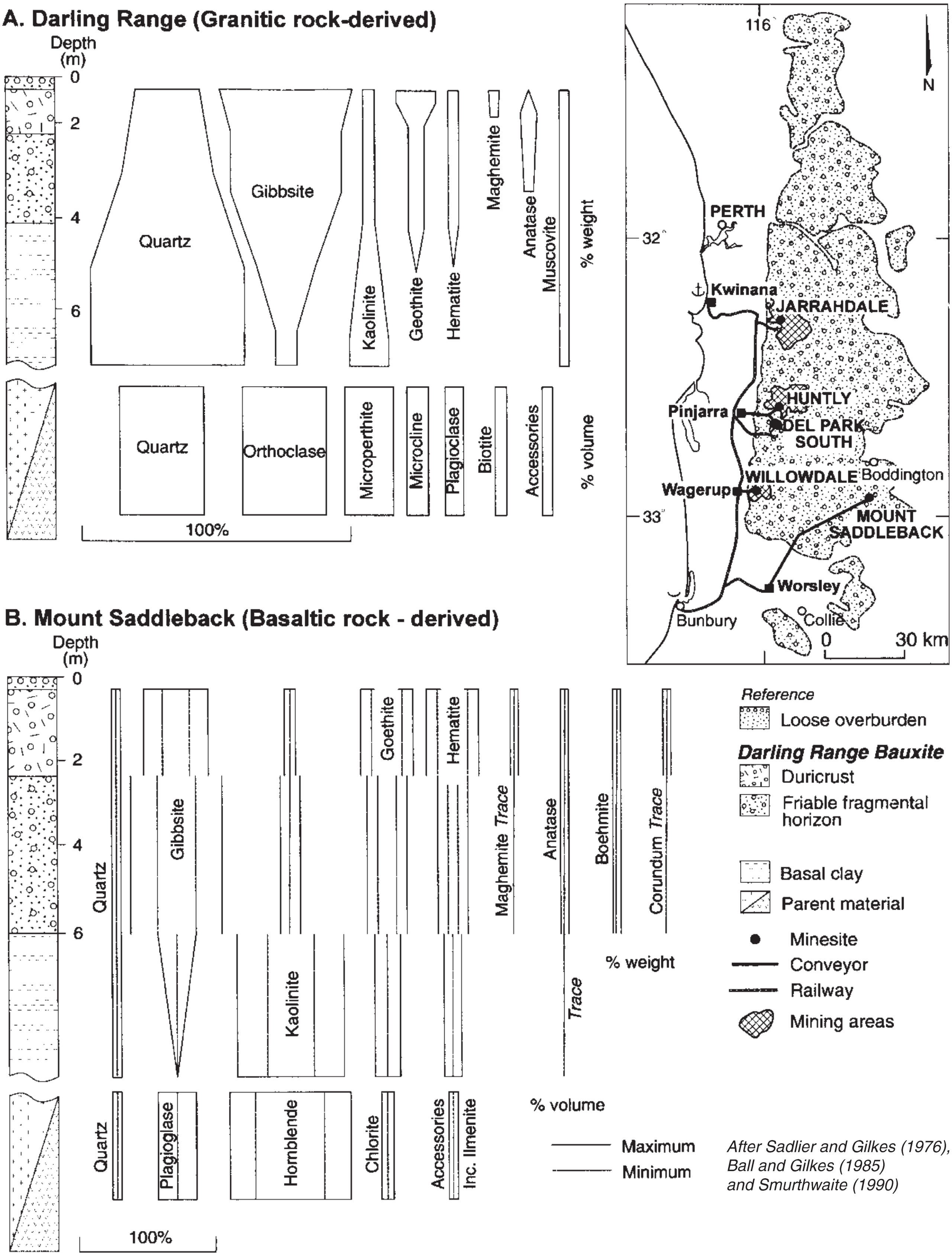

Figure 8. Locality map and typical profiles (from Sadlier & Gilkes 1976 and Ball & Gilkes 1985) through the Darling Range Bauxite.

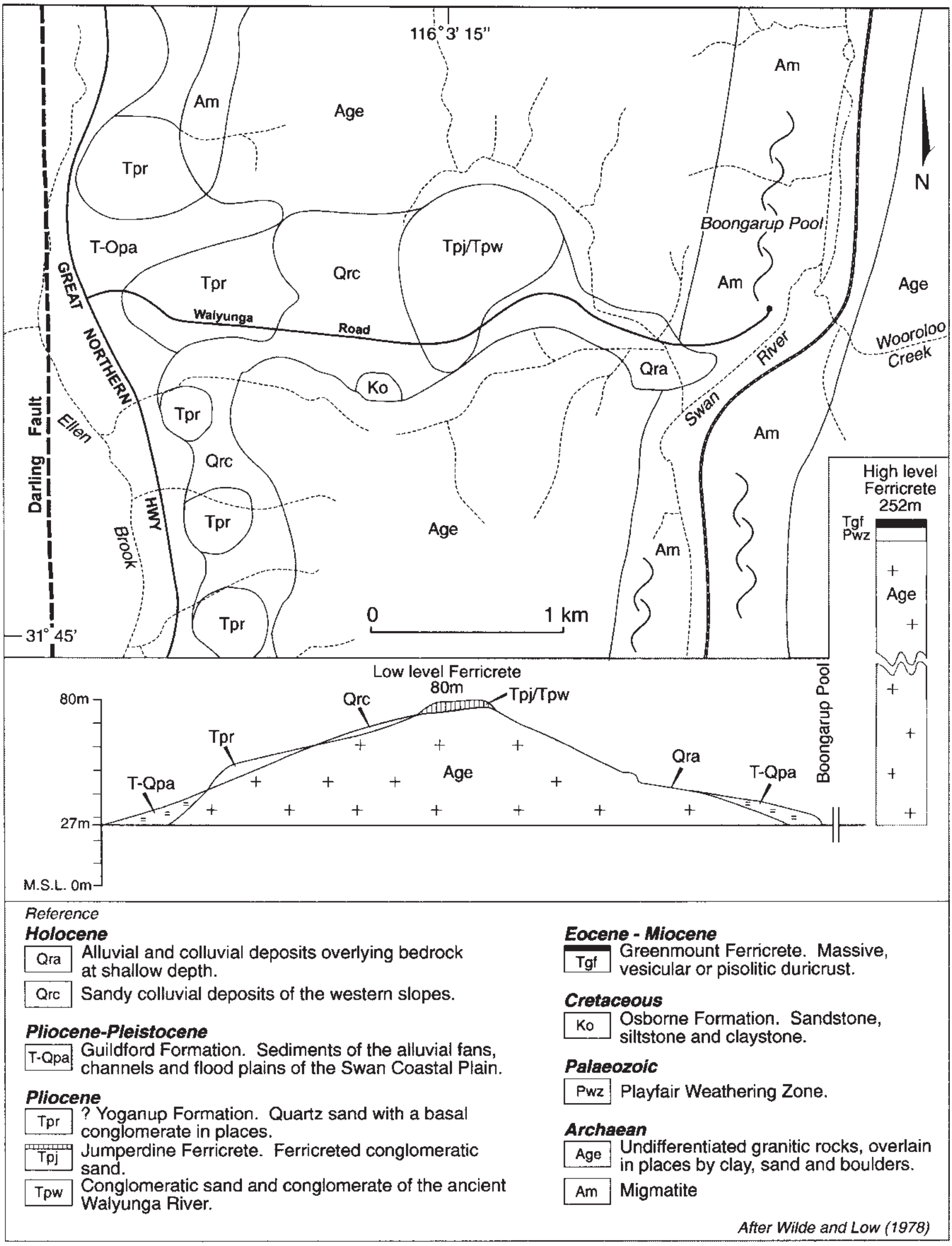

Figure 9. The two classes of laterite (ferricrete), high-level and low-level, near Walyunga south-east of Bullsbrook. The east-west section follows Walyunga Road. The high-level ferricrete occurs across the Swan River at the Lookout.

in valleys cut into the Darling Scarp, as was the Donnybrook Sandstone to the south. After a brief regression, the sea returned to the Perth Basin and shallow-marine conditions prevailed for the remainder of the Cretaceous. Marine glauconite-bearing formations are predominantly Late Cretaceous. Movements on the Darling Fault ceased at this time, as Cretaceous rocks crop out a short distance east of the Darling Fault and in places may cap the Darling Fault itself.

South of Perth, Mesozoic units crop out on the Blackwood Plateau (Fig. 7). The "Maxicar Beds" (Lowry 1965; Playford & Low 1972) consist of 9 m of poorly sorted, ferruginous, feldspathic sandstone. Some sections are cross-bedded. Exposures of white claystone, siltstone and fine-grained sandstone 1 km north of the type locality, and of a siltstone and sandstone unit 4 km south of Burekup are included in the unit. J.M. Dickens, quoted by Playford & Wilmott (1958), identified *Pterotrigonia* from the type locality.

The Arckaringa Weathering Zone

A distinctive pallid zone is developed in numerous "laterite profiles" along the south-west margin of the Australian Precambrian Shield, particularly where bauxite is present below the ferricrete and above the mottled zone. In these profiles (Figs 8 & 10), according to Smurthwaite (1990), the basal clay underlying the fragmental horizon (bauxite) is commonly mottled by iron staining in its upper parts (the San Marino mottled zone equivalent – later described – in the stratigraphy employed herein), but becomes more pallid with depth. It is commonly composed predominantly of clay particles, remnant quartz and partly weathered mica. This zone varies in thickness from 20–30 m before

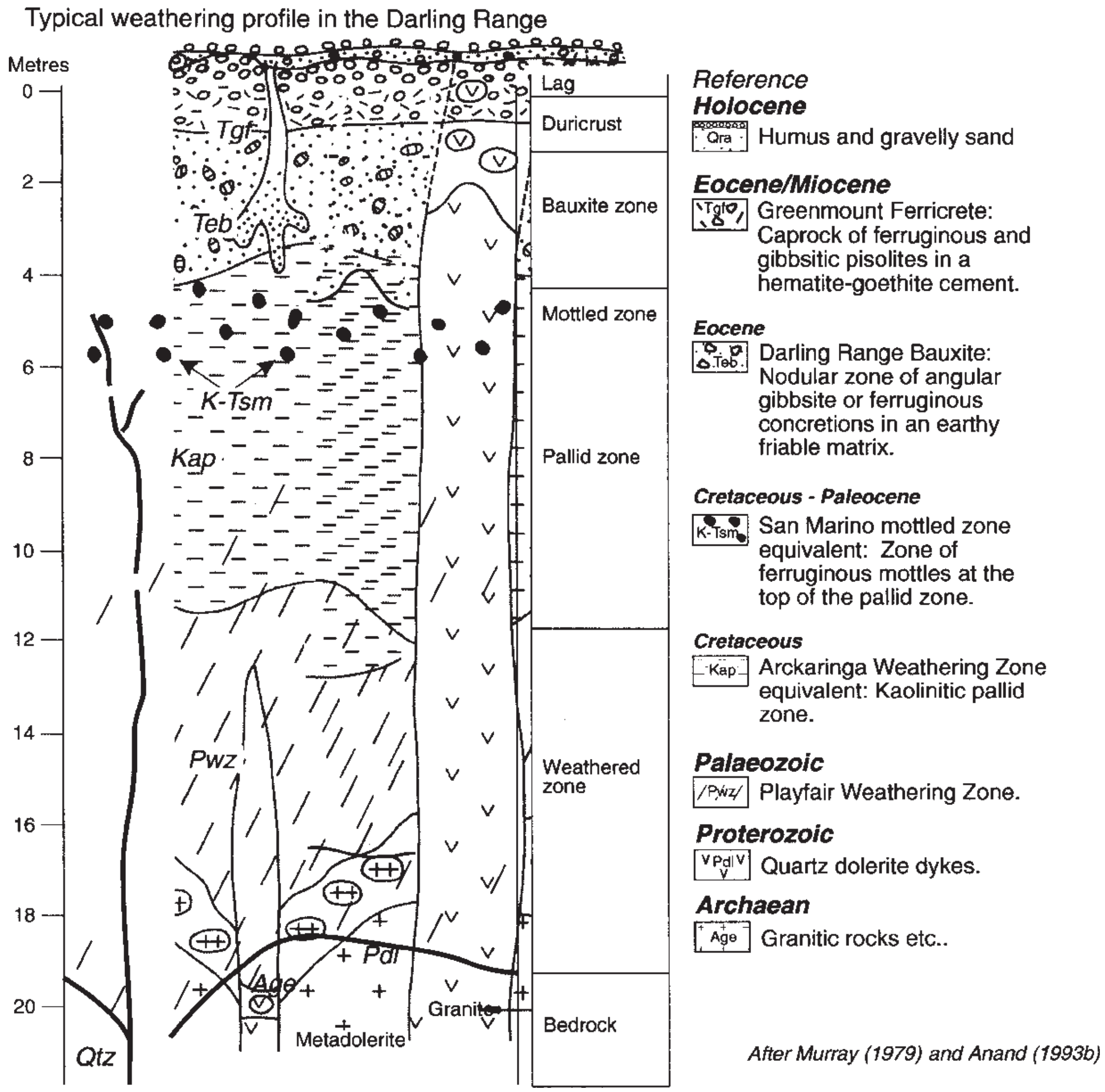

Figure 10. Typical weathering profile on the western margin of the Darling Range. Note the bauxite zone stratigraphically placed between the mottled zone and the overlying Greenmount Ferricrete (pisolitic nodular duricrust). This is a "high-level laterite profile". The weathered upper part of the Precambrian rocks intruded by a Proterozoic dyke has been assigned an age of Mesozoic (Kap, and K-Tsm) because this is the age of the weathered zone, and not the age of the basement rocks.

weathered bedrock, and then fresh is encountered. In some places the basal clay is absent below the bauxitic fragmental zone which rests directly on relatively unweathered bedrock in some places.

Silcrete profiles on the south-east margin of the Australian Precambrian Shield contain a pallid zone developed on previously weathered basement rocks in the uplands and on flat-lying sedimentary rocks of Mesozoic age within the Great Australian Basin (Wopfner 1964; Firman 1994); note that the term “Great Australian Basin” is used in preference to Great Artesian Basin, which has hydrogeological rather than stratigraphic connotations. The name Arckaringa Weathering Zone is derived from Arckaringa Homestead (Fig. 3). the type section is at Russo’s Folly, an opal mine at Coober Pedy, where the pallid zone is developed in Cretaceous Bulldog Shale capped by younger beds (Firman 1980, 1994). The pallid zone has the consistency of stiff to hard clay or claystone.

The pallid zone is up to 30 m thick. North-east of Lake Eyre, where the zone is thinner, it is superimposed on an older, coloured weathering zone which itself is up to 24 m thick. In some places the Jurassic Algebuckina Sandstone separates the bleached sediments above from older weathered rocks below that unit so that the Arckaringa Weathering Zone is younger. Eocene Eyre Formation overlies the unit.

Near Adelaide, remnants of this ancient weathering zone are found overlying the Playfair Weathering Zone. Robertson (1974) has reported on this feature in the Verdun to Littlehampton Section of the South East Freeway where the material forms the pallid zone of a “Tertiary laterite profile”.

The stratigraphic evidence suggests that development of the Arckaringa Weathering Zone, which post-dates some Late Cretaceous sediments and pre-dates early Cainozoic sediments, began in the Late Cretaceous.

The San Marino mottled zone

On the south-west margin of the shield, east of the Darling Fault, “laterite profiles” developed over basement rocks are exposed in many places (Figs 7 & 8). Although iron oxides are present in the mottled zone at the top of the Arckaringa Weathering Zone, they are not derived from the pallid zone, but are a groundwater feature developed below the eroded top. The mottled zone in these profiles is correlated with the San Marino mottled zone (the San Marino Palaeosol in Firman 1994). On the Dandaragan Plateau, in the north of the Study Area, Middle Jurassic limestones of the Cadda Formation and Champion Bay Group are leached and ferruginized in the weathered zone below ferricrete. On the Blackwood Plateau in the south the mottled zone in exposed Cretaceous “Maxicar Beds” near Dardanup resembles the San Marino mottled zone developed in Bulldog Shale and other Cretaceous sediments in the Great Australian Basin on the south-east margin of the shield, but the zone is not so well developed and may be younger.

Mottled zones and ferricretes associated with manganese deposits have been described by de la Hunty (1963) on the southern margin of the Pilbara Craton. The main area of outcrop is in the manganese province near Marble Bar. (Fig. 11). The oldest unit is the mottled zone found at a high-level in the landscape as an erosional remnant. This is capped in some place by a ferricrete and by younger units later described. The mottled zone is correlated herein with the San Marino mottled zone.

The San Marino mottled zone defined by Firman (1980, 1994) is exposed in the Stuart Range on the western margin of the Great Australian Basin. The name is derived from San Marino Homestead west of Oodnadatta on the headwaters of the Neals River, the type area for this unit (Fig. 3). The best exposures are found on higher ground on the margin of the basin. The unit is developed over a very wide area on an erosion surface at the top of early Cretaceous Cadnaowie Formation. Particularly good exposures are seen along Algebuckina Creek and near Coober Pedy.

The unit is characterized by ferruginous red or purple mottles developed in older materials. The individual mottles are up to 30cm across and in some places merge at the top of the zone of mottling to form a more-or-less continuous ferricrete. Similar ferruginous accumulations have been described elsewhere on the south-east margin of the Australian Precambrian shield by Reyner (1955), Coats (1963), and Wopfner (1964). Where ferruginous mottles occur in silcrete profiles the mottles below and close to the silcrete are silicified in many places. There are some sequences – near Coober Pedy for example – where ferruginous mottles are developed in Tertiary sediments overlying the San Marino mottled zone, but this mottling is not affected by silification and marks a younger period of ferruginous accumulation. The oldest sediments unaltered by formation of mottles of this kind and overlying the zone are part of the Miocene Edadunna Formation.

Idnurm & Senior (1978) have carried out palaeomagnetic dating of ferruginous material in profiles that are morphologically similar to those investigated by Firman (1980) in an adjoining area in the Great Australian Basin (Fig. 3). The kaolinitic Morney Profile developed in the Cretaceous Rolling Downs Group is similar to profiles containing the San Marino mottled zone developed in Cretaceous Bulldog Shale. A late Cretaceous (Maastrichtian) to Early Eocene age was determined for the ferruginous material in the Morney profile, which indicates that the San Marino mottled zone post-dates the Arckaringa weathering zone.

Stratigraphic relationships indicate a Late Cretaceous to Paleocene age for the San Marino mottled zone.

Early and Middle Cainozoic – marine sediments, bauxite, ferricrete and silcrete

In this part of the text new names are introduced for ferricrete and silcrete on the western margin of the shield. The geological setting for ferricretes and silcretes on the south-east margin of the shield is outlined in the references quoted.

Early Cretaceous in the Perth Basin is represented by Leederville Formation on the Dandaragan Plateau, by the Donnybrook Sandstone on the Blackwood Plateau, and by the Leederville Formation (underlying the Late Cainozoic sediments) in the central Swan Coastal Plain.

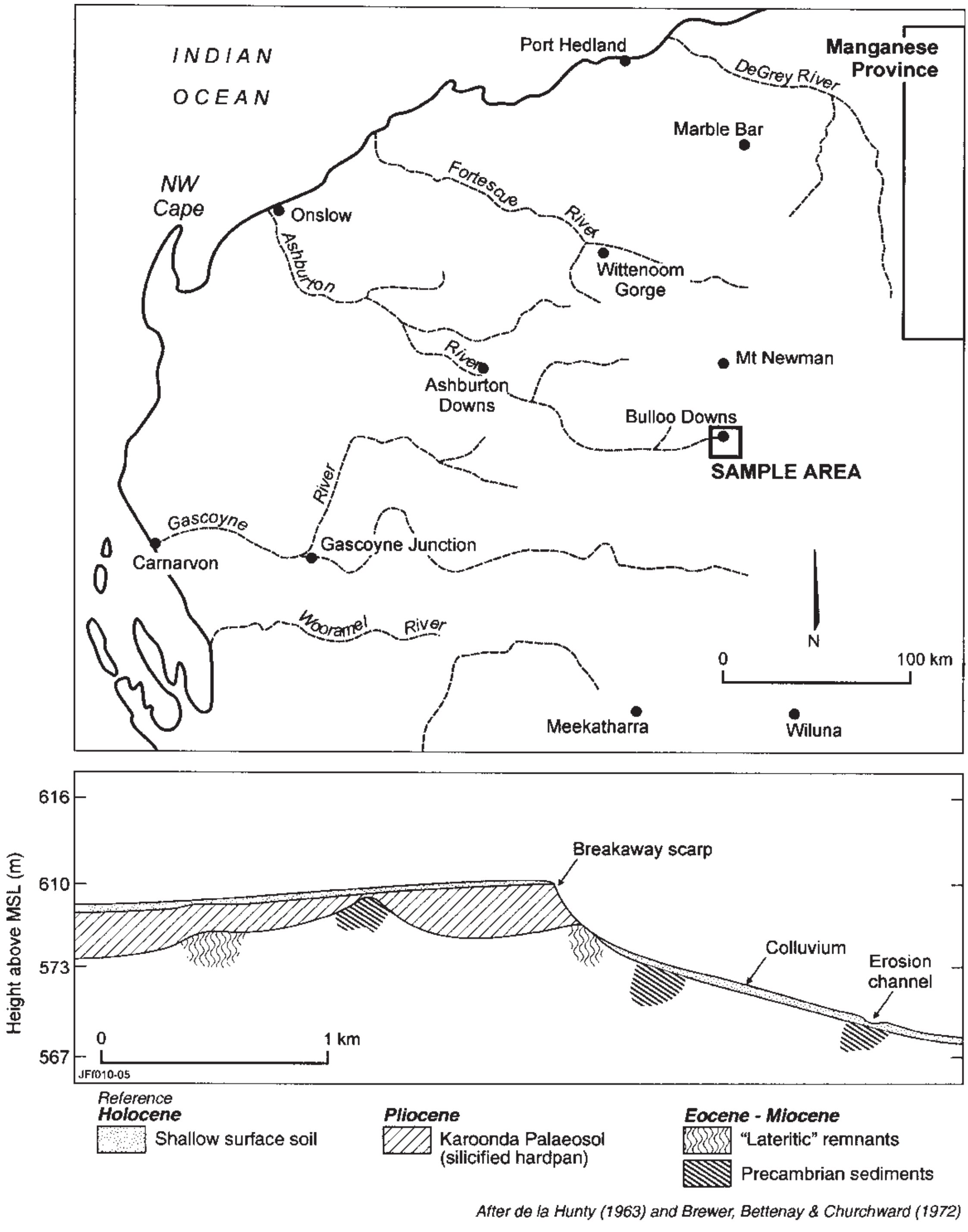

Figure 11. Karoonda Palaeosol near Bulloo Downs and the Pilbara (Goldfield) Manganese Province. The section is diagrammatical and no R.F. is available. The boxed area to the NE is the Manganese Province.

The apparent displacement, which is said by Finkl & Fairbridge (1979) to be due to downwarping, is marked by structural lineaments which, from north to south, control the Gingin Scarp, the Darling Scarp and the Whicher Scarp along the western margin of the Blackwood Plateau.

Paleocene and Eocene sediments

Throughout the Cainozoic, the Perth Basin was on the continental margin bordering the Indian Ocean, with a shoreline which fluctuated between the shelf edge and the Darling Scarp. Foraminifers indicate an Early Cretaceous to Late Paleocene age for these sediments. The ancestral Swan River cut a deep valley into the underlying sediments in the Perth region. This valley may once have connected with the Perth canyon, which now cuts the continental slope west of Rottnest Island. Sea-level rose and fine-grained quartz sands (the Kings Park Formation of Late Paleocene to Eocene age) were laid down in the drowned river valley.

Crustal thinning and downwarping led to separation of the southern margin of Australia from Antarctica and the creation of the Southern Ocean during the Eocene. Emergence took place during the Early Eocene. Following a brief interval of erosion the sea again covered the continental shelf and another cycle of shallow-marine carbonate sedimentation took place.

The Kojonup Sandstone, a quartz sandstone overlying a thin basal conglomerate of Eocene age (Wilde & Backhouse 1977), directly overlies Precambrian granite rocks to the south and south-west of Kojonup. The unit contains the plant fossils *Araucaria, Nothofagus, Ficus* and *Banksia* similar to those found around the Stirling Range. Similar fluviatile sandstone extends for 380 km north to the vicinity of Calingiri, but the sandstone in that area may be younger.

The Darling Range Bauxite

Alumina-rich clay occurs along the south-west margin of the Australian Precambrian Shield in residual deposits associated mainly with Archaean granite and migmatite and doleritic bedrock. The name "the Darling Range Bauxite" is commonly used in the literature for bauxite deposits in the south-west of Western Australia (Darling Range is used herein for the south-west margin of the Australian Precambrian Shield marked by exoreic drainage). These bauxite deposits extend along the Darling Range from the Bindoon-Chittering area in the north through Jarrahdale and Pinjarra to Wagerup south, and east to Mount Saddleback, where metamorphosed basalt is the parent material (Figs 7 & 8). The name Darling Range Bauxite is used herein for the bauxite ore including the lowermost gibbsite horizon in sections described as *in situ* by Hickman *et al.* (1992).

Smurthwaite (1990) states that the bauxite deposits of the Darling Range occur as lenticular ore bodies within a "laterite profile". These profiles consist of four layers: overburden, duricrust (ferricrete or bauxitic ferricrete herein), friable fragmental horizon and basal clay. The lowermost fragmental horizon is the original bauxite, the younger layers consist of material reworked from the lower fragmental unit. The upper part of the friable unit is characterized by nodules of gibbsite, which decrease in concentration below the unit. The basal clay is commonly mottled by iron staining in its upper parts, as in the San Marino mottled zone of the Great Australian Basin discussed earlier, but becomes more pallid with depth in the Arckaringa weathering zone.

Grubb (1971) has described several profiles in the bauxite deposits at Jarrahdale. In the Seldom Seen open-cut only two profiles are of *in situ* eluvial or residual bauxite, four profiles show varying degrees of erosional redistribution. The *in situ* profiles are composed of four horizons. From top to bottom these are: fine uniform pisolitic bauxite often showing significant surface hardening, a coarser unconsolidated pisolitic zone, a very coarse concretionary zone ferruginous in many places, and mottled and pallid clay, a "…distinctive basal horizon which underlines all true laterites". Hematite is characteristic of the hardcap in these profiles. Brimhall & Lewis (1992) have shown that the mineral framework of the hardcap (the Greenmount Ferricrete – later described) contains small rounded grains of zircon. Ore thickness over granitic bedrock ranges from 2 to 7 m. In the Mt Saddleback region, bauxite ore is generally 6–7 m thick and locally attains a thickness of 20 m (Hickman *et al.* 1992).

Grubb (1971) was of the opinion that the bauxite deposits of the Darling Range began with reconstitution of a colluvial mantle to form fluvial sediments during the Cretaceous. Intense leaching of kaolinite and halloysite may have followed an elevated ground-water table during the Middle Eocene high sea and formation of gibbsite in favourable areas during the world-wide drop in sea level that followed..

The friable fragmental unit in the bauxitic deposits of the Darling Range is stratigraphically placed between the Late Cretaceous-Paleocene San Marino mottled zone and the Eocene-Miocene Greenmount Ferricrete next discussed. An Eocene age for the Darling Range Bauxite is suggested.

In Western Australia, the relationship of basement rocks to the geochemistry of typical bauxite profiles has been discussed by Baker (1975), Sadlier & Gilkes (1976), Gilkes & Suddhiprakarn (1981), Ball & Gilkes (1985) and Anand *et al.* (1991).

On the south-east margin of the shield at Pidinga Lake, about 80 km north-west of Chundie Swamps (Fig. 3; and Firman 1985) alunite has been formed in sediments at the top of Paleocene-Eocene Pidinga Formation. King refers to the localization of alunite – now beneath younger "lateritic cappings" – and claims that impeded drainage resulted in the formation of alunite rather than gibbsite. At Chundie Swamps Pidinga Formation is overlain by silcrete and the younger Miocene Nullarbor Limestone.

The Greenmount Ferricrete

There are two classes of laterite (ferricrete) according to Simpson (1912), the primary or "high-level laterite" and the secondary or "low-level laterite" composed largely of mechanically transported fragments derived from the "high-level laterite". Near Perth the "high-level laterite" is about 215 m above sea level and the "low-level laterite" about 80 m above sea level (Figs 7 & 9).

"High-level laterite" was used by Simpson (1912) to describe ferricrete – "pisolitic" in many places – as in the giant laterite profile shown on Figure 10. This material was called ironstone by early explorers in Western Australia. The ferricrete associated with other sediments in many places around the southern coastal margin is an iron cemented sedimentary sandstone.

Prider (1948) has described laterite (ferricrete) in the Ridge Hill Shelf area near Perth and his work forms the basis for the description and formal definition of the older high-level Greenmount Ferricrete, now described, which is named after Mount Helena, and the younger Jumperdine Ferricrete described later. Prider (1948) states that the "high-level laterite" varies in character according to the nature of the underlying Precambrian rocks. All the "high-level laterites" are underlain by a highly weathered (kaolinized) zone which passes down into the unweathered country rock, as described by Simpson (1912).

In the Perth area, Wilde & Low (1978) state that laterite (ferricrete) is generally massive and well-cemented, and may be pisolitic. It is about 4 m thick and overlies a pallid zone of variable thickness and weathered bedrock. Although there are many sections through these profiles where the ferricrete is only about 1 m thick, it has an average thickness in the Pinjarra area of 4–5 m and a 14 m thickness at Del Park near Pinjarra (Fig. 7). A supplementary section is proposed for the Greenmount Ferricrete at Coates Siding about 50 km north-east of Perth near the Great Eastern Highway.

Vesicular and pisolitic laterite (ferricrete) as a caprock is recorded in the Moora area on the Dandaragan Plateau by Carter & Lipple (1982). Wilde & Low (1978) have recorded "strongly lateritized" glauconitic greensand (Poison Hill Greensand) of Cretaceous age cropping out at Poison Hill (31° 18′ S 115° 53 E, 7.5 km north-west of Gingin). In the Gingin – Mooliabeenie area (Firman 1952), the eroded top of the Late Cretaceous Poison Hill Greensand slopes down to the west between the Darling Fault to the east and the Gingin Scarp to the west. The greensand – and other quartz sand of uncertain age on the eastern margin of this area – is heavily ferruginized in the high-level laterite (ferricrete) which extends to the west from the Australian Precambrian Shield.

On the Blackwood Plateau a massive high-level laterite (ferricrete) is correlated with that on basement rocks to the east of the Darling Fault described by Finkl (1971). The ferricrete is generally quartz-rich, reflecting the composition of the bedrock. Near the western margin, it is bounded by distinct breakaways.

On the Pilbara Craton north of the study area, de la Hunty (1963) refers to scattered outcrops of a ferricrete which forms a caprock on the mottled zone. Manganese oxides overlie the ferricrete in some places. The caprock is correlated herein within the Greenmount Ferricrete of the Darling Range to the south and the Yallunda Ferricrete on the south-east margin of the shield.

Finkl & Fairbridge (1979) assumed that the laterite (ferricrete) in Western Australia was due to desiccation in the Oligocene after marine regression in the Eocene. Woolnough (1918) suggested a Miocene age.

On the south-east margin of the Precambrian Shield, mottled zones and ferricrete – the Yallunda Ferricrete (Firman 1967b) – were formed on old land surfaces in the upland areas marginal to the southern sedimentary basins where they occur at the top of assemblages of materials in "laterite profiles". Ferruginous accumulations described by other investigators and attributed to the Yallunda Ferricrete by the writer have been recorded by Firman (1994). The Yallunda Ferricrete is developed over sediments of Paleocene to Eocene age – Pidinga Formation and equivalents on the coastal margin and Eyre Formation inland – and is overlain by sediments of Oligocene to Miocene age – Nullarbor Limestone on the coastal margin and Etadunna Formation inland.

In the Mount Lofty Ranges near Adelaide, The Yallunda Ferricrete occurs as remnants of an extensive sheet of ferricrete overlying the Playfair Weathering Zone. The zone was developed below a surface formed over Proterozoic, Cambrian and Ordovician rocks moderately folded in the Delamerian Orogeny. Hard pisolitic ferricrete closely resembles that of the Mount Helena Ferricrete on the western margin of the shield in the Darling Ranges near Perth.

The pisolitic ferricrete near Adelaide is correlated with the stratigraphically bracketed ferricrete within the Middle Eocene sequence exposed on the coastal margin at Witton Bluff near Christies Beach in the St. Vincent Basin as described by Glaessner & Wade (1951).

The ferruginous sandstones overlying alunite of Eocene age at Pidinga Lake and Chundie Swamps on Eyre Peninsula – previously described in relation to the Darling Range Bauxite – are probably of the same age as the ferruginous non-marine sandstones in the Mt. Lofty Ranges near Adelaide.

Oligocene and Miocene sediments

During the Oligocene and Miocene, the geometry of the Perth Basin was similar to that of the present day. The Oligocene and Miocene sequence rests disconformably on the Paleocene and Eocene sequence in the offshore basin, and unconformably overlies the Permian sequence onshore. The Stark Bay Formation and Victoria Plateau Sandstone are the only named formations. The sequence is 230 m thick. West of Perth, the sequence is less than 20 m thick. Fossils include foraminifers, bryozoans and echinoderms and the former suggest an Early to Middle Miocene age. Where carbonates have been sampled they are a friable white, bryozoan and echinodermal calcarenite, with brown dolomite and chert.

In South Australia – in the Murray Basin – pisolitic "ironstone gravel" is found in the Oligocene Compton Conglomerate (Firman 1973).

Palaeomagnetic dating of ferruginization in the kaolinitic Canaway profile in the Cretaceous Rolling Downs Group of southwest Queensland (Idnurm & Senior 1979; Senior & Mabbutt 1979), indicates an Oligocene to Miocene age.

The Calingiri Silcrete

Silicified rocks are widespread on the Australian Precambrian Shield and in adjoining basins. Stephens (1971) shows that silcrete profiles dominate in the Canning, Officer and Great Australian basins (Figs 2 & 3). In those regions, older ferricrete profiles have been partially eroded prior to development of the silcrete. Uplift produced topographic features showing inversion of relief and an abundance of silcrete at high levels in the landscape. Pliocene sediments occupy a lower position in the landscape.

The Calingiri Silcrete has been described by Wilde & Low (1978) as a unique deposit, which occurs 6 km south of Calingiri (Fig. 12). This is the type area for the silcrete. The silcrete is a subhorizontal flaggy unit that contains large quartz and kaolinized feldspar fragments in a cemented sandy matrix, and is associated with sand rich in quartz cobbles. The deposit has been ferruginized in part. It occurs on the drainage divide between the Moore, Avon and Mortlock river systems and may represent a pre-Pleistocene drainage system. The silcrete caps a fluvial sequence of fine-grained quartz sand overlying well-rounded conglomerate at the base. The original cap may have been no more than a metre thick. The sand below the silcrete has been strongly cemented by silica. The deposit, which occurs in many places at elevations above modern drainage patterns, records an inversion of

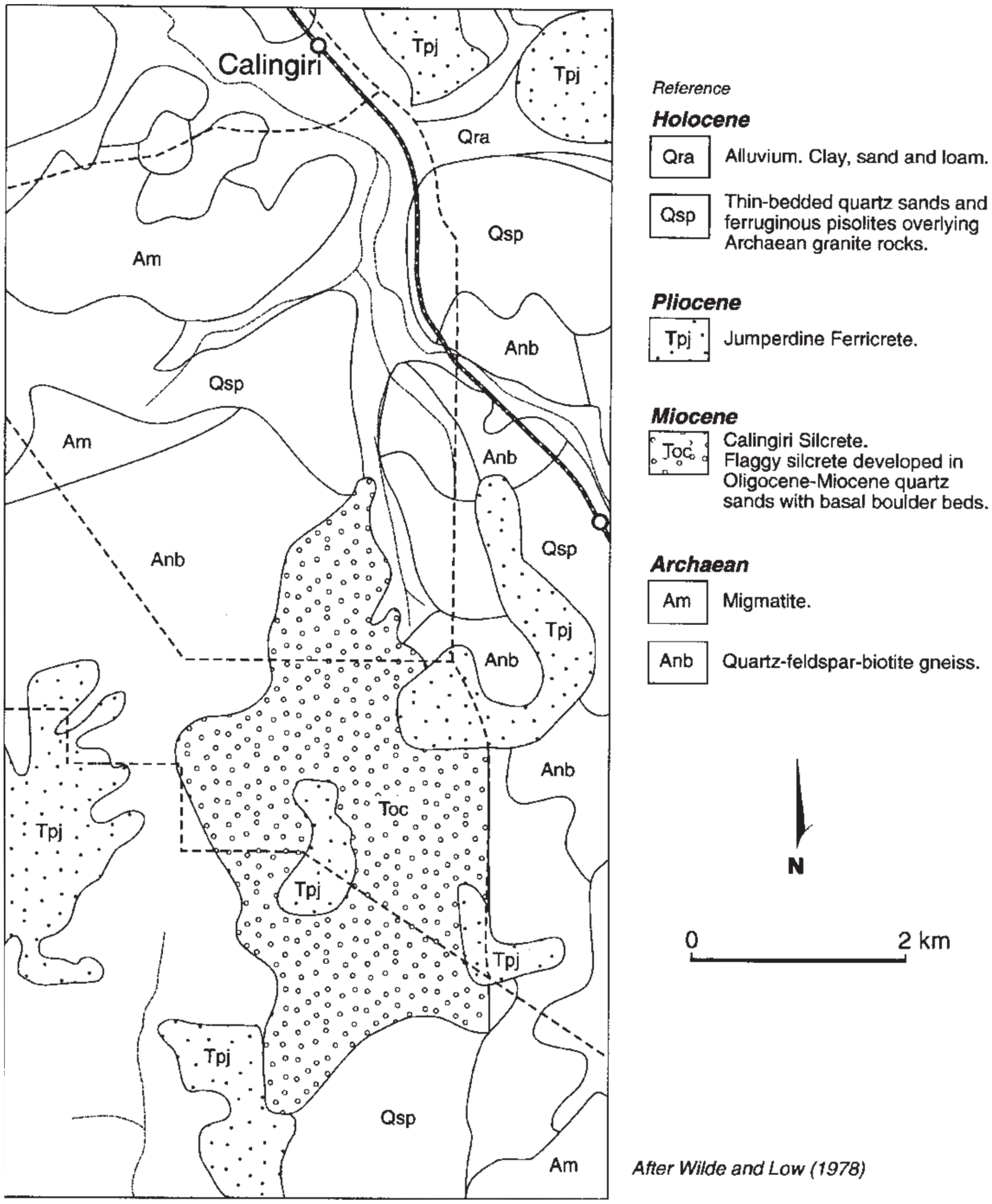

Figure 12. Occurrence of the Calingiri Silcrete 6 km south of Calingiri, the type area for the silcrete.

relief. This unit crops out discontinuously as far south as Muradup near Kojonup (Fig. 7) and may be as old as the Kojonup Sandstone which has sediments of Eocene age at the base (Wilde & Walker 1982), but may itself be younger. The silcrete cap is a hard dense silcrete found at the top of the sequence as large tabular boulders.

Silcrete of uncertain age has been reported from the other areas in the southern part of Western Australia: Silcrete described as small patches of pale grey, porcellanitic conglomerate up to 5 m thick is recorded in the Moora area (Carter & Lipple 1982). Wilde & Walker (1982) refer to the Greenbushes Formation which is also cemented by silica. Palaeodrainage deposits extending in a discontinuous arc from Salmon Gums to Cundeelee are outlined by undulating duricrust surfaces at high level and chains of playa lakes (Hocking & Cockbain 1990). Hill cappings of silcrete with laterite (ferricrete) on lower slopes and valley floors are recorded elsewhere on the Yilgarn Craton by Hocking & Cockbain (1990). This suggests a topographic sequence with older materials at high level, a common feature of terrain in this area. The ferricrete at lower level could be the younger Pliocene Jumperdine Ferricrete later described.

On the Pilbara Craton, silcrete is widespread on the plateau near the junction of the Oakover and Davis rivers, which are tributaries of the De Grey River (de la Hunty 1963). The silcrete was developed on an erosion surface from which other surficial materials have been removed to expose dolomites and other rocks of the Proterozoic succession.

The Calingiri Silcrete is probably of Miocene age, which is in agreement with the suggestion of Butt (1985), that silcrete on the Yilgarn Craton is of Oligocene to Middle Miocene age.

The Clayton River Silcrete on the south-east margin of the shield (Firman 1980, 1994) occupies a similar stratigraphic position to the Calingiri Silcrete. On the south coast margin, silcretes of Miocene age have been recorded at Wallaroo (Lindsay 1970) and Chundie Swamps (Firman 1983), where silcrete overlies Eocene Pidinga Formation and is overlain by Miocene Nullarbor Limestone. Inland the Clayton River Silcrete is developed on Eocene Eyre Formation and is overlain by Oligocene-Miocene Etadunna Formation. In the inland the Arckaringa Weathering Zone is found below the silcrete. Silcrete of Miocene age has been recorded by Barnes & Pitt (1976) which contains reworked silcrete clasts, and by Ambrose & Flint (1981) who have also described syndepositional silcrete south-west of Lake Eyre (Fig. 3).

A sequence of separate events can be interpreted from the silcrete profile: this includes – from oldest to youngest – bleaching of pre-existing fine-grained rocks, development of a clastic mantle, formation of ferruginous mottles, erosion of ferruginous duricrust and impregnation of the clastic mantle and underlying mottled zone with silica to form a silcreted clastic mantle overlying a "porcellanized" siltstone (Fig. 13).

Important references dealing with silcrete profiles in South Australia are those of Milnes *et al.* (1985), Wells & Callen (1986), and Drexel & Preiss (1995), the latter prepared subsequently to Firman (1994).

Late Cainzoic – sediments, pisolitic deposits, siliceous pans and mottled zones

Tectonic activity beginning in the Miocene led to the break-up of Tertiary basins in southern Australia and to the elevation of the ranges on the basin margins. The western margin of the Dandaragan Plateau, the Precambrian Shield in the Perth area and the Blackwood Plateau have been eroded during a high stand of the Early Pliocene sea to form the Ridge Hill Shelf which extends from Eneabba in the north to Tutunup in the south. The oldest of a sequence of strandline deposits, some with heavy-mineral sands, occurs along the scarp up to 130 m above present sea-level.

Pliocene sediments

The Pliocene sequence probably occurs throughout the offshore Perth Basin. It is widespread onshore where it occurs across the basin as far as the Darling Scarp. The sequence rests disconformably on Oligocene to Miocene sediments offshore, and unconformably overlies the earlier, mainly Mesozoic, sequences onshore. The Pliocene sequence includes all of the late Cainozoic stratigraphic units assigned to the Wadjemup, Yoganup and Ascot formations in the Perth Basin. The sequence consists predominantly of medium to coarse-grained sand with lenticular beds of clay and conglomerate. Shells, especially molluscs, are abundant in some units and are the basis for dating the sequence as late Cainozoic (Cockbain 1990).

Near Perth, at Walyunga (Fig. 9), conglomeratic sediments are unconformably overlain by the Jumperdine Ferricrete. The conglomerates may be coeval with similar deposits described by Churchward & Bettenay (1973) and named the Harvey Formation in Hocking & Cockbain (1990), and also the Kirup Conglomerate near Mullalyup, although this may be older (Finkl & Fairbridge 1969). These deposits mark prior streams at a high level along the scarp which post-date the Eocene – Miocene Greenmount Ferricrete and pre-date the Guildford Formation equivalents at lower levels in adjoining valleys.

In the Pinjarra area isolated patches of sand at elevations of 75–90 m above sea-level have been recorded by Wilde & Low (1980). They describe the sediments as bleached shoreline sand with a thin basal conglomerate. The sand deposits in the Pinjarra area are possibly equivalent to the beach and dune sand, with local concentrations of heavy minerals, found along the Happy Valley Shoreline of Welch (1964) and Wilde & Walker (1982). In the Collie area, conglomerate, sand and clay occupy the highest position in the landscape. The sediments overly strongly silicified Kojonup Sandstone and have a "lateritic hardcap" (Wilde & Walker 1982).

The Jumperdine Ferricrete

The Jumperdine Ferricrete has its clearest geomorphological expression along the Ridge Hill Shelf on the western margin of the Australian Precambrian Shield. The Jumperdine Ferricrete is named after Jumperdine Creek south-west of Calingiri (Figs 7 & 13). The type area is at Ridge Hill south of the Helena River valley in the Perth area. The description follows Prider (1948): the low-level laterite (ferricrete) occurs as a thin discontinuous layer above ferruginous sandstone (The Ridge Hill Sandstone of Mesozoic age; pers comm. Professor Simon Wilde 2005). It has, on the exposed surface, a somewhat fragmental appearance, but on breaking the rock these fragments are seen to be of ferruginous sandstone. These fragments in a typical specimen average 5 mm diameter and are coated with a dense layer of light brown, fine-grained and compact bauxitic material and the spaces between the fragments are largely filled with this bauxitic material, but some cavities remain giving the rock a slightly cellular structure. The surface "lateritic" crust passes down into ferruginous sandstone at about one metre below the ground surface.

Along the Ridge Hill Shelf the Jumperdine Ferricrete overlies weathered bedrock, unweathered bedrock or younger sedimentary rocks. The development of the unit over sedimentary rock interposed between weathered bedrock below and the ferricrete demonstrates that the ferricrete is not genetically related to the underlying weathered bedrock. The ferricrete has been interpreted as a deposit which contains reworked ferruginous and bauxitic material derived from the older high-level laterite profile adjoining to the east.

In the present interpretation, the low-level ferricrete post-dates the high-level Eocene-Miocene Greenmount Ferricrete and pre-dates the Pliocene Yoganup Formation

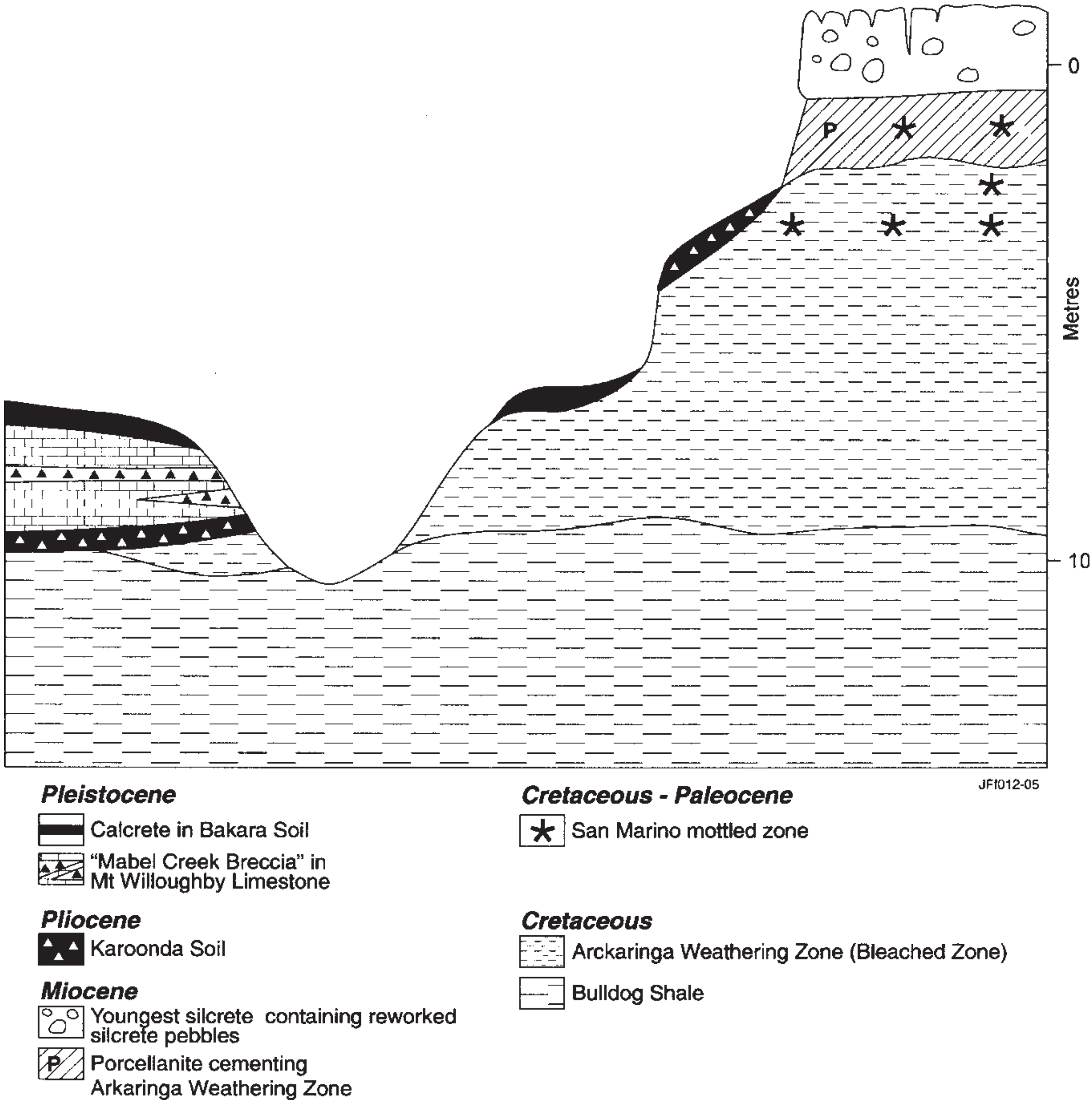

Figure 13. Silcrete near Wurdlata west of Coober Pedy in South Australia. The right hand sequence is a typical silcrete profile in the Great Australian Basin. It contains pebbles of older silcrete and is typical of silcretes in palaeochannels in the region. The left hand sequence of younger pedocretes and sediments is unusual in that a number of surfaces converge at the one site.

found at a lower level at the base of the Gingin, Darling and Whicher scarps on the eastern margin of the Swan Coastal Plain. A Pliocene age is suggested for the Jumperdine Ferricrete.

There are other localities along the Darling Scarp north of Perth where the ferricrete occurs: approximately 280 km north of Perth in the High Hill – Mt Lesueur area overlooking the Hill River; from about 130 km north of Perth near Two Brooks Park along the Brand Highway to the high ground east of Cervantes; and at Gingin 76 km north of Perth in the valley of an antecedent stream deeply incised into the Cretaceous marine sequence and now occupied by Gingin Brook (Fig. 7). Wilde & Low (1978) describe a "partially lateritized" gritty sandstone at the head of present drainage channels in the Calingiri area east of the Ridge Hill Shelf. This is the Jumperdine Ferricrete described earlier and overlying the Calingiri Silcrete south of Calingiri.

Near Perth the Jumperdine Ferricrete occurs at Walyunga (Fig. 9) where it overlies conglomeratic sediments unconformably. The Jumperdine Ferricrete also caps sandy valley fill along Good's Road South of The Lakes on the Great Eastern Highway. At the last-named site the ferricrete is below the level of the

Greenmount Ferricrete, and the sediments underlying the ferricrete cap have been derived by erosion of the Playfair Weathering Zone from the adjoining uplands.

Crudely bedded pisolitic ferricrete re-worked from the Mount Helena Ferricrete and now weakly cemented occurs near 'Yalanbee" Experiment Station (Anon 1993). This also may be Jumperdine Ferricrete.

Along the Whicher Scarp a distinct bench at about 80 m above sea-level is in the same topographic position as the Ridge Hill Shelf. The bench is "lateritized" and there is a local concentration of heavy minerals. Elsewhere on the Blackwood Plateau a dissected "lateritized bench" at the heads of the valleys rising upstream from 80 m to 130 m above sea level has been recorded (Wilde & Walker 1982).

On the south-east margin of the Australian Precambrian Shield, ferruginous sediments were deposited and now form caprocks over weathered Proterozoic rocks at the "Gun Emplacement" near Adelaide, and over the Hallett Cove Sandstone (Firman 1994). In the Murray Basin ferruginous caprocks were formed on late Pliocene sediments including the Loxton Sand and the Diapur Sandstone. In the Murray Basin the fossiliferous Norwest Bend Formation, which is coeval with the uppermost Parilla Sand, marks a high stand of the late Pliocene Sea in the same way as the Yoganup Formation in the Perth Basin on the south-west margin.

Ferruginous and siliceous deposits formed below the level of older deposits stranded in the uplands and overlying the older deposits within the basins have been discussed by Coates 1963, Freytag *et al.* 1967, and Forbes 1975.

Pliocene sediments and the Robe Pisolite

Deposits of pisolitic limonite (the Robe Pisolite) have been described by de la Hunty (1965) in the Mt Bruce area north-west of Newman in the Pilbara region. The unit, which consists of close-packed iron oxide cemented pisolites with bands of more massive goethite is up to about 50 m thick in places, can be traced along palaeovalleys for up to 80 km in the Hamersley Basin. Black shales underlying the unit contain spores and pollens of Eocene age (Blockley 1990). In many places older laterite and silcrete profiles are found at a high level in the landscape, and the younger pisolitic deposits in the lowlands are overlain by calcrete.

A more appropriate name for the Robe Pisolite is 'Robe Formation' because the unit is lithologically diverse. Basal parts of the unit are chiefly massive goethite and upper parts typically range from oolitic goethite to mixed oolitic – pisolitic goethite to pisolitic goethite (D.K. Glassford per comm 2005).

Deposits similar to the Robe Pisolite form part of the Doonbara Formation in northern South Australia. Doonbara Formation was defined near Cordillo Downs Homestead in the north-east of South Australia in the Great Australian Basin by Wopfner (1974). A red ferruginous sandstone overlain by the Karoonda Soil – later described – was recorded by Forbes (1969) and Firman (1994) on the south-west margin of the basin near Kingoonya and was assigned to this unit. Forbes (1977) also describes the sandstone in the Tallaringa area, west of Coober Pedy (Fig. 3), where it overlies the Avondale Clay. On the south-east margin of the shield the Avondale Clay is an important Pliocene sequence. It is described briefly because it helps to define the stratigraphic position of Doonbara Formation, which includes pisolitic ironstone resembling the Robe Pisolite in Western Australia.

The Avondale Clay (Firman 1967a) is a grey clayey sand. It contains vertically oriented ferruginous patches and mottles which in some places are lithified. Outcrops – base not exposed – are up to 10 m thick. The type section is on the plateau margin north of Leigh Creek (Fig. 3) near Mt Playfair and 2 km south of Lyndhurst. The unit crops out near Lake Frome at Mulligans Hill. At Lake Eyre North, a possible equivalent of Avondale Clay is underlain by a sequence of dolomite and mudstone (King 1956). Similar sequences in Lake Palankarinna and Lake Kanunka named the Etadunna Formation (Stirton & Tedford 1961) contain the Ngapakaldi Fauna of pelicans, flamingoes, ducks, crocodiles, lungfish and an ancestral koala of Oligocene to Miocene age. P.A. Rogers (pers.comm 2002) correlates the Namba Formation of Callen & Tedford (1976) at Lake Palankarinna with Avondale Clay.

At least 140 m of sediment was recorded near Port Augusta at the head of Spencer Gulf by Hullett, 1882 (Firman 1965). The uppermost is assigned to the Hindmarsh Clay, a stratigraphic equivalent of Guildford Formation in south western Australia described later. The lower part of the sequence contains Avondale Clay and is underlain by lignitic clays and carbonaceous sands that may be of Eocene age. The position of the boundary between Avondale Clay and the underlying lignitic clays and carbonaceous sands is not known. Avondale Clay also occurs on Yorke Peninsula at Wallaroo where it underlies Hindmarsh Clay.

The Doonbara Formation in northern South Australia and the Robe Pisolite in the Pilbara area. are both overlain by limestones with opaline silica at the top: The Mt Willoughby Limestone (Nichol 1971) and some other limestones in northern South Australia described by Wopfner (1974) are assumed to be the stratigraphic equivalent of the Oakover Formation in the Pilbara area.

Palaeomagnetic dating of ferruginous material in Doonbara Formation suggests a Miocene to Pliocene age for the unit (Indurm & Senior 1978).

Sediments of Pliocene – Pleistocene age

Non-marine sediments of Late Pliocene-Pleistocene age are host rocks for palaeosols in sequences on the south-west and south-east margins of the Australian Precambrian Shield. The sediments are sandy clays and clayey sands with ferruginous mottles and gravels which together form alluvial fans and piedmont slope deposits. Most of the clay deposits of this age have well-developed soil structures.

In the Perth Basin (Fig. 2) west of the Ridge Hill Shelf, the material of fans, channels and flood plains was named the Guildford Formation (Baker 1954; Low 1971). The sediments of the Guildford Formation are interbedded alluvial clays and sands with thin lenses of basal conglomerate according to Wilde & Low (1978).

The type section of the Guildford Formation is in the west Guildford artesian bore (lat.31° 54' 30" S, long. 115°

57' 20" E) from the surface down to 32.99 m (Low 1971). The unit includes a thin bed containing marine fossils (*Anadara, Dosinia,* etc), at a height of about 4.5 m above low-tide level in the brick clay pits at Caversham (lat. lat.31° 53' 5" S, long. 115° - 58' E). The fossiliferous bed and the overlying units including gypsiferous material are possibly much younger than the clays of the underlying formation (Teichert 1967; Gill 1974).

The thickness of the sequence rarely exceeds 100 m. It unconformably overlies the Early to Late Cretaceous Osborne Formation, the Late Cretaceous Leederville Formation, the Late Paleocene to Eocene Kings Park Formation and the Late Pliocene Yoganup Formation elsewhere below the coastal plain. The unit is overlain by late Cainozoic alluvium and marine and aeolian sediments of the Kwinana Group within the Perth Basin.

The younger beds of Guildford Formation are exposed in irrigation channels near Mundijong (Fig. 7) where the lowest unit is a stiff to hard, light grey, clayey sand or sandy clay with coarse dark red and yellow mottles. Older mottled clays and sands are exposed in deep pits in the piedmont zone and on the walls of the Murray River valley near Avondale Homestead where they are overlain by yellow clay of the soil system known as Boyanup Loam. Similar deposits occur inland near Boorabbin on the Great Eastern Highway (Stop 2 in the Excursion Guidebook prepared for the International Conference on Desert Landscapes and IGCP252 by Glassford & Semeniuk 1991). The Guildford Formation is the oldest known part of the sequence of fans, channel and flood plain deposits developed west of the Darling Scarp following the retreat of the shallow sea marked by Yoganup Formation. The exposed part of the sequence is separated into upper and lower beds by "siliceous and silicified rock" (McArthur & Bettenay 1960).

On the south-east margin of the Australian Precambrian Shield, Late Pliocene-Pleistocene non-marine sediments crop out which are stratigraphic equivalents of the Guildford Formation. These include clays and sands on the shield itself, clays and sands in alluvial fans flanking the central ranges, and lacustrine and fluvial sediments within Tertiary basins.

Palaentological investigations summarized in Firman (1976) show that the youngest clays and sands exposed at ground surface along the southern coastal margin are of Pleistocene age. These deposits rest upon clays and sands within Tertiary basins which palaeomagnetic studies of the Blanchetown Clay and associated sediments in the Murray Basin show extend back into the Late Pliocene (An *et al.* 1986).

The Karoonda Soil

The Karoonda Soil (the Karoonda Palaeosol of Firman 1988) is a prominent feature in alluvial fans on range margins and in sedimentary basins where it is associated with coastal and non-marine clays and sands of late Pliocene age (Firman 1994). It marks the Karoonda Surface of Firman (1966, 1969a). Inland, it is developed on older rocks and commonly occurs as ferruginous clasts cemented by silica to form a caprock, which in some places, rests upon older laterite (ferricrete) and silcrete profiles.

On the south-west margin of the shield, beneath the Swan Coastal Plain, there is a widespread occurrence of siliceous and silicified rock which underlies meadow podzolic and "lateritic podsolic" soils (Pym 1955; McArthur & Bettenay 1960). The unit crops out in drainage channels near Mundijong (Fig. 7) where it is a syndepositional unit between upper and lower beds of the Guildford Formation. This silicified zone is correlated with the Karoonda Soil.

North of the Study Area in WA, the bronze coloured Wiluna Hardpan of Bettenay & Churchward (1974) occurs south of Mt Newman in the Pilbara area (Figs 2 & 11). The distinctive colour is due to the inclusion of "bronze" ferruginous nodules. There are two episodes of illuviation of clay separated by deposition of secondary silica. Upper horizons are not silicified and are probably younger. The hardpan consists of silica-cemented colluvium derived from profiles of "older laterite" and is part of a sequence of sediments and pedocretes – which from oldest to youngest – includes the Robe Pisolite, Wiluna Hardpan and calcrete.

Near Yeelirrie in the Eastern Goldfields, Glassford (1987) has described the Westonia Formation. The upper beds in the Westonia Formation contain fossilized wasp or beetle puparia that resemble beds unconformably overlying Parilla Sand in the Murray Basin later ferruginized and silicified in the Karoonda Soil.

On the south-east margin of the Australian Precambrian Shield the Karoonda Soil in the type section near Chowilla Homestead, in the Murray Basin, is a paleosol unconformably overlying the late Pliocene Parilla Sand. Here it occurs as thin layers of sand less than 0.5 m thick, including an horizon of fossilized wasp or beetle puparia, which has been ferruginized and silicified (Firman 1973). The soil takes its name from Karoonda, an important town in the Murray Basin (Fig. 3). Upstream from the type section it is represented by a silicified zone up to 2 m thick at the base of the Chowilla Sand where it separates the upper and lowermost beds of Blanchetown Clay (Gill 1973).

From the correlation of the magnetic polarity sequence with the absolute time scale (An *et al.* 1986), the age of the Karoonda Soil in the type section near Chowilla Homestead in the Murray Basin is Late Pliocene (in excess of 2.5 million years) and is older than the Olduvai event.

The Karoonda Soil has been identified at sea-level on the east coast of Eyre Peninsula, near Pidinga Lake north-west of Chundie Swamps on Eyre Peninsula, and at Wurdlata in the Great Australian Basin (Fig. 3).

Pleistocene – Recent sediments and soils

On the south-west margin of the shield, the sequence in the Perth Basin spans the time of recent changes in sea level, and records a series of Pleistocene-Holocene regressions and transgressions of the sea which have not yet been fully documented. Recent deposits cover all of the Perth Basin. They are usually less than 60 m thick and consist principally of shoreline and associated dune deposits with older fluvial beds underlying the Swan Coastal Plain, and colluvium in the piedmont zone.

The upper bed of Guildford Formation above the Karoonda Palaeosol contains a lateritic podzolic soil – which is virtually a laterite – with characteristic ferruginous, mottled and pallid zones according to McArthur & Bettenay (1960). The writer believes that this part of the profile is equivalent to Menzies Formation in the Yeelirrie area. On the Swan Coastal Plain a late Cainozoic unit, the Bassendean Sand (Playford & Low 1972), overlies the upper bed of Guildford Formation and contains iron oxides called "coffee rock" (Mulcahy 1973).

In the Eastern Goldfields, the Menzies Formation (Glassford 1987) occurs along the axis of the Yeelirrie valley and along the floors and sides of tributary incisions. Red sandy clay and sandy claystone form the bulk of the formation. Lithologically, the basal beds resemble Hindmarsh Clay on the south-east margin of the Australian Precambrian Shield. Younger members of the unit contain calcrete which may indicate a stratigraphic position similar to that of the medial Pleistocene calcretes which overlie the Hindmarsh Clay on the south-east margin of the shield. The unit and its equivalents in other valleys on the shield have been drilled extensively in the search for uranium (Mann & Horwitz 1979).

Glassford & Semeniuk (1995) have presented evidence to suggest that the valley fill of major valleys in arid and semi-arid areas of the Yilgarn Craton is of aeolian origin. At Flinders Red Cliff at the head of Spencer Gulf in South Australia units showing aeolian cross-bedding overlies Hindmarsh Clay. Williams (1982) has suggested that they may be a few hundred thousand years old, and they may well be older.

On the south-east margin of the shield near Adelaide, Hindmarsh Clay occurs in the St Vincent Basin. Lindsay (1969) has correlated the basal beds of Hindmarsh Clay, which contains a fauna with a definite marine influence (possibly uppermost Pliocene transitional to Pleistocene) with Carisbrooke Sand. At Hallett Cove in the same area, Hindmarsh Clay equivalent with a well-developed zone of ferruginous mottling about 2 m above the base of the lowermost unit contains the Brunhes/Matuyama boundary (0.70 Ma) according to Pillans & Bourman (1996),

A mottled zone resembling the Ardrossan Palaeosol overlies the lowermost unit.

A younger silcrete of Pleistocene age has been developed in the Pliocene-Pleistocene Hindmarsh Clay and equivalents of the Mt Lofty Ranges at Baldoon Homestead near Sedan, in piedmont clays near Port Lincoln (where the local name is Boston Bay Silcrete Firman 1967a), at Ceduna (Thevenard) on Eyre Peninsula and interbedded with Pleistocene Mount Willoughby Limestone inland near Coober Pedy. These silcretes resemble siliceous lenses exposed on the eroded top of silty sand in the Murray River near Mundijong in Western Australia.

In the Murray Basin of South Australia, bedded gypsum deposits occur in the upper beds of Blanchetown Clay. Calcareous loess appears below the uppermost lacustrine limestone (Bungunnia Limestone) and underlies the Ripon Calcrete and Bakara Calcrete, which in this area represent the Medial Pleistocene Bridgewater Formation of the coastal margin (Wetherby 1975; Firman 1982; Pillans & Bourman 2001).

Summary and conclusions

Geological events controlling the development of weathering zones, pedocretes and palaeosols along the south-west margin of the Australian Precambrian Shield were as follows:

1. Darling Fault zone reactivated. Marine sediments of the Proterozoic Cardup Group displaced, possibly during the early Palaeozoic, so that they now lie over 15 km below younger sediments west of the Darling Fault.
2. Rifting and development of the graben continued. Palaeozoic sedimentation began during the opening of the Dandaragan Trough. Deep valleys were incised along the basement margin.
3. Deep weathering of post-Ordovician/pre-Permian time created the Playfair Weathering Zone. Strong ferruginous mottling.
4. Carboniferous-Permian continental sedimentation extended onto the Yilgarn Craton. Glaciation preceded deposition of coal beds. Permian palaeochannels were incised into the Playfair Weathering Zone.
5. Sedimentation continued into the Triassic. No major movements of faults occurred on the eastern margins of the areas now identified as the Dandaragan and Blackwood plateaux after the Jurassic.
6. An early Cretaceous high-sea eroded the Darling Scarp and the Ridge Hill Sandstone was deposited.
7. Separation of Greater India at the end of the early Cretaceous. Renewed faulting. There was a wide marine gulf in the Cretaceous. Cretaceous sediments are now found at the same level on either side of the Darling Fault.
8. A pallid zone (Arckaringa Weathering Zone) developed at the top of the Playfair Weathering Zone on the shield and in Cretaceous sediments to the west. A ferruginous mottled zone (San Marino mottled zone) was emplaced below an ancient erosion surface cut across the bleached zone.
9. Mesozoic – early Cainozoic separation of Gondwana. Revival of downwarping around the south-west margins of the Australian Precambrian Shield. Palaeocene-Eocene dissection. Eocene sedimentation.
10. Middle Eocene high sea. Groundwater table rises. Retreat of the high sea and formation of the Darling Range Bauxite above the Playfair Weathering Zone and Arckaringa Weathering Zone from reconstituted colluvium.
11. Eocene-Miocene Greenmount Ferricrete (Yallunda Ferricrete equivalent) formed above older weathered zones. Ferricrete includes pisolites accumulated during repeated local reworking of granular material.
12. Gravels and sands deposited east of the Darling Fault were silicified to form the Miocene Calingiri Silcrete. Retreat of the Miocene sea.
13. Uplift of Tertiary basin sediments. Erosion of older ferricrete.

14. Jumperdine Ferricrete developed as a cap over conglomeratic sediments and older sediments forming part of the "laterite bench".
15. The "laterite bench" was displaced down to the west of the Gingin, Darling and Whicher Scarps. Erosion of the Arrowsmith and Gingin areas and incision of streams through the high-level laterite and the Ridge Hill Shelf continued.
16. A rise of the Late Pliocene sea led to deposition of Yoganup Formation against the scarps. Retreat of the Late Pliocene sea was followed by erosion of the Dandaragan and Whicher Scarps.
17. Deposition of Late Pliocene-Pleistocene clays and sands on the Swan Coastal Plain.
18. Formation of the Karoonda Soil.
19. Deposition of clays and sands continued.
20. Development of "lateritic podsolic" soil in upper beds of Guildford Formation.
21. Calcrete pans formed in older brown soils.

The stratigraphic relationships of the weathering zones, pedocretes and palaeosols are shown on Figures 5 & 6.

In previous discussions of palaeosols in ancient soil profiles (Firman 1968; Firman & Lindsay 1976; Firman 1988; Firman 1994), palaeosols were described in the context of the geological evolution of materials on the south-east margin of the Australian Precambrian Shield: The conclusions from those studies were that pedogenic events were episodic; that is, weathering zones, pedocretes and horizons in palaeosols were formed in different ways at different times, due mainly to changes in climate and groundwater composition. "Laterite" and silcrete profiles were shown to be assemblages of weathered rock, sediments and palaeosols, the assemblages being characteristic of different morpholithological provinces.

The study of weathering zones, pedocretes and palaeosols on the south-west margin of the Australian Precambrian Shield has confirmed the earlier conclusions derived from South Australia (Fig. 6): sedimentary sequences (some of which are greater than a group or supergroup) are intercalated in the profiles between the Playfair Weathering Zone and the Arckaringa Weathering Zone, between the San Marino mottled zone equivalent and the Greenmount Ferricrete, which is itself a mixed sediment cemented by iron oxides, and (after erosion of the ferricrete and formation of the Calingiri Silcrete) between the Playfair Weathering Zone and the younger Jumperdine Ferricrete. Sediments also are intercalated between the Jumperdine Ferricrete and the Karoonda Palaeosol.

The oldest weathering zones mark bounding surfaces that extended to other continents prior to the break up of Gondwana. The ferricretes and silcretes mark surfaces developed in southern basins during the separation of Australia and Antarctica. Older structured clays mark soil development along the piedmont zones marginal to mountain chains in the Pliocene, and calcretes identify older brown soils developed during sea-level changes in the medial Pleistocene.

Younger surfaces are recorded by palaeosols formed within the great soil groups which themselves are soil assemblages with a world-wide distribution (Firman 1986, 1988, 1994).

Acknowledgements: Appreciation for critical discussions and readings of early drafts is expressed to Max Churchward, Dr Donald K Glassford, J.M. Lindsay, Bill McArthur, Dr Wolfgang Preiss and Paul A Rogers (Minerals and Energy Resources, SA). Professor R T Prider of the University of Western Australia, Dr Ray Smith (CSIRO CRC LEME), Western Australia, and Simon Wilde, Professor of Applied Geology, Curtin University. Don Glassford, Bernie Masters and Bill McArthur demonstrated important sequences on the western margin of the shield, and A.M. Firman and J.T. Firman provided assistance in the field. Joice Wardjiman and Minuteman Press Fremantle typed the present text and Angelo Vartesi (CRC LEME) prepared the maps and sections.
The writer acknowledges the assistance of the Science and Industry Endowment Fund administered by the Commonwealth Scientific and Industrial Research Organisation, the Australian UNESCO Committee (for IGCP 252), and of CSIRO Exploration and Mining (CRC LEME), Western Australia.

References

Ambrose G J & Flint R B 1981 Explanatory Notes Billa Kalina, South Australia. 1: 250,000 Geological Map Series SH/53-7. Geological Survey of South Australia, Adelaide, South Australia.

An, Zhisheng, Bowler J M, Opdyke N D, Macumber P G. & Firman J 1986 Palaeomagnetic stratigraphy of Lake Bungunnia: Plio-Pleistocene precursor of aridity in the Murray Basin, South Eastern Australia. *In:* Palaeoenvironments of salt lakes. (eds A R Chivas, T. Thorgensen and J M Bowler) Palaeogeography, Palaeoclimatology, Palaeoecology, 54: 219–239.

Anand R R 1993a The regolith and its economic significance. *In:* An International conference on crustal evolution, metallogeny and exploration of the Eastern Goldfields. (P R Williams and J A Haldane, Compilers). Excursion Guidebook. Australian Geological Survey Organisation Record 1993/53: 75–100.

Anand R R 1993b Lateritic weathering and regolith evolution in the Yilgarn Craton, Western Australia. *In:* R.E. Smith, R.R. Anand, H.M. Churchward, I.D.M. Robertson, E.C. Grunsky, D.J. Grey, J.E. Wildman, & J.L. Perdrix. Laterite geochemistry for detecting concealed mineral deposits, Yilgarn Craton, Western Australia. CSIRO Division of Exploration and Mining. Geoscience Open File Report 50 p.170, Cooperative Research Centre for Landscape Evolution and Mineral Exploration, Perth, Western Australia.

Anand R R, Gilkes R J & Roach G I D 1991 Geochemical and mineralogical characteristics of bauxites, Darling Range, Western Australia. Applied Geochemistry, 6: 233–248.

Anonymous 1993 Notes to accompany the F7 Field Tour, South West Australia. Tenth International Clay Conference, Adelaide South Australia, July 1993, 2.

Aurousseau M & Budge E A 1921 The Terraces of Swan and Helena Rivers and their bearing on recent displacement of the strand line. Journal of the Royal Society of Western Australia, 7: 24–44.

Baker G F U 1954 Some aspects of Quaternary sedimentation in the Perth Basin, Western Australia Part 2 Perth area. Thesis. University of Western Australia.

Baker G F U 1975 Darling Range bauxite deposits. Western Australia. Economic Geology of Australia and Papua New Guinea. Metals, Volume 1: 980–986. *In:* Monograph 5 (ed C L Knight) Australian Institute of Mining and Metallurgy.

Ball P J & Gilkes R J 1985 The Mount Saddleback bauxite deposit, South Western Australia. Japanese National Commission of IGCP and Mining and Metallurgy Institute of Japan. International Conference on Lateritization Processes, 3rd, Tokyo, 1985. Proceedings, p.14.

Barnes L C & Pitt G M 1976 The Mirrackina Conglomerate. Quarterly Geological Notes 52: 2–6. Geological Survey of South Australia. Adelaide, South Australia.

Bettenay E & Churchward H M 1974 Morphology and stratigraphic relationships of the Wiluna Hardpan in arid Western Australia. Journal of the Geological Society of Australia. 21(1): 73–80.

Blockley J G 1990 Iron ore. *In:* Geology and Mineral Resources of Western Australia. Geological Survey of Western Australia Memoir 3: 679–692. Perth, Western Australia.

Brewer R., Bettenay E & Churchward H M 1972 Some aspects of the origin and development of the red and brown hardpan soils of Bulloo Downs, Western Australia. Commonwealth Scientific and Industrial Research Organisation Technical Paper 13.

Brimhall George H and Lewis Christopher J 1992 Encyclopaedia of. Earth Systems Science 1: 321–336.

Brown D A. 1975 Australia. *In:* The Encyclopaedia of World Regional Geology Part 1, Western Hemisphere, (ed. R.W. Fairbridge) 28–34. Dowden Hutchinson and Ross, Stroudsburg.

Bunting J A & Williams S J 1979 Explanatory Notes Sir Samuel, Western Australia. 1: 250,000 Geological Map Series. Geological Survey of Western. Australia, Perth, Western Australia.

Butt C R M 1985 Granite weathering and silcrete formation on the Yilgarn Block, Western Australia. Australian Journal of Earth Sci.ence 32: 415–432.

Callen R A & Tedford R H 1976 New late Cainozoic rock units and depositional environments, Lake Frome area, South Australia. Transactions of the Royal Society of South Australia 100 (3): 125 – 167.

Carter J D & Lipple S J 1982 Explanatory Notes Moora, Western Australia. 1: 250,000 Geological Map Series SH/50–10. Geological Survey of Western Australia, Perth, Western Australia.

Churchward and Bettenay 1973 The physiographic significance of conglomeratic sediments and associated laterite in valleys of the Darling Plateau, near Harvey, Western Australia. Journal of the Geological Society of Australia, 20: 309–317.

Coates R P 1963 The Geology of the Alberga 4-mile military sheet. Report of Investigation 22. Geological Survey of South Australia, Adelaide, South Australia.

Cockbain A E. 1990 Perth Basin. *In:* Geology and Mineral Resources of Western Australia, Memoir 3: 495–524. Geological Survey of Western Australia., Perth, Western Australia.

Cowley W M & Freeman 1993 Geological Map of South Australia. Adapted from the 1982 edition with contributions by the Regional Geology Branch. Geological Survey of South Australia, Adelaide, South Australia.

de Broekert 2003 Stratigraphy and origin of regolith in the East Yornaning Catchment, south-western Yilgarn Craton, Western Australia. Journal of the Royal Society of Western Australia 86: 61–82

de la Hunty L E 1963 The Geology of the Manganese Deposits of Western Australia. Geological Survey of Western Australia. Bulletin 116.

de la Hunty L E 1965 Explanatory Notes Mount Bruce, Western Australia. 1: 250: 000 Geological Map Series SF 50–11. Geological Survey of Western Australia, Perth, Western Australia.

Drexel J F, Preiss W V & Parker A J (eds.) 1993 The Geology of South Australia. The Precambrian. Bulletin 54, Volume 1. Mines and Energy. Adelaide, South Australia.

Drexel J F & Preiss W V (eds.) 1995 The Geology of South Australia. The Phanerozoic. Bulletin 54, Volume 2: 1–347. Mines and Energy. Adelaide, South Australia.

Embry, Aston 2003 Coming to grips with sequence stratigraphy. Newsletter No.2 (Circular 103) of the International Classification (1SSC). *In:* Albert Brakel (National Convener, Stratigraphic Names Committee). The Stratigraphic Column, The Australian Geologist, Newsletter No: 128, September 30, 2003.

Fairbridge, Rhodes W & Finkl C W 1978 Geomorphic analysis of the rifted cratonic margins of Western Australia. Zeitschrift fur Geomorphologie N.F. Berlin-Stuttgart, 22 (4): 369–389.

Finkl C W Jr 1971 Soils and geomorphology of the middle Blackwood River, Western Australia. Thesis. University of Western Australia.

Finkl C W & Fairbridge R W 1979 Palaeogeographic evolution of a rifted cratonic margin, South West Australia. Palaeogeography, Palaeoclimatology, Palaeoecology, 26: 221–252.

Firman J B 1952 The description and correlation of physiographic factors: A sample transect across portion of the Darling Peneplain and the Swan Coastal Plain. Thesis. University of Western Australia.

Firman J B 1965 Late Cainozoic sedimentation in Northern Spencer Gulf, South Australia. Transactions of the Royal Society of South Australia 89: 125–131.

Firman J B 1966 Stratigraphy of the Chowilla area in the Murray Basin. Quarterly Geological Notes, 20: 3–7. Geological Survey of South Australia, Adelaide, South Australia.

Firman J B 1967a. Late Cainozoic stratigraphic units in South Australia. Quarterly. Geological Notes, 22: 4–8. Geological Survey of South Australia, Adelaide, South Australia.

Firman J B 1967b Stratigraphy of late Cainozoic deposits in South Australia. Transactions of the Royal Society of South Australia, 91: 165–178.

Firman J B 1968 Soil distribution – a stratigraphic approach. 9th International Congress of Soil Science, 1968. Transactions, 4: 569–576. Adelaide, South Australia.

Firman J B 1969a Quaternary period. *In:* Handbook of South Australian Geology. (ed L W Parkin) pp.204–223. Geological Survey. Geological Survey of South Australia, Adelaide, South Australia.

Firman J B 1969b Stratigraphy and landscape relations of soil materials near Adelaide, South Australia. Transactions of the Royal Society of South Australia, 93: 39–54.

Firman J B 1975 Australia – South Australia. *In:* The Encyclopaedia of World Regional Geology. Western Hemisphere Part 1 (ed R W Fairbridge) 61–81. Dowden, Hutchinson and Ross. Stroudsburg.

Firman J B 1976 Limestone at the base of the Pleistocene sequence in South Australia. Quarterly. Geological Notes, 58: 2–5. Geolological Survey of South Australia, Adelaide, South Australia.

Firman J B 1978 Explanatory Notes Fowler 1: 250,000 Geological Map, South Australia. Sheet SH/53/13 Geological Survey of South Australia, Adelaide, South Australia.

Firman J B 1979 Palaeopedology applied to land use studies in Southern Australia.

Geoderma 22: 105–1M.

Firman J B 1980 Regional stratigraphy of the regolith on the south-west margin of the Great Australian Basin Province, South Australia. Thesis. Flinders University of South Australia.

Firman J B 1982 Regional Stratigraphy of Australian dune fields. *In:* Quaternary Dust Mantles of China, New Zealand and Australia (ed. R.J. Wasson) pp.201–210 International Quaternary Association Loess Commission. Australian National University, 1980, Canberra, Australia.

Firman J B 1983 Silcrete near Chundie Swamps: The stratigraphic setting. Quarterly. Geological Notes 85: 1–5. Geological Survey of South Australia, Adelaide, South Australia.

Firman J B 1986 Adelaide Region Palaeosols. 1: 250,000

Geological Atlas Special Series, Geological Survey of South Australia, Adelaide, South Australia.

Firman J B 1988 Soil Evolution: Evidence from Southern Australia. *In:* Landscapes of the Southern Hemisphere (ed Jon Firman) Earth – Science Revue, 25(5,6): 373–386. Elsevier Science Publishers B B Amsterdam.

Firman, J B, 1991 Palaeosols in laterite and silcrete profiles. International Conference on Desert Landscapes and International Correlation Programme 252: Past and Future Evolution of Deserts. Final Meeting October, 1991. University of Western Australia, Perth, W.A.

Firman J B 1994 Palaeosols in laterite and silcrete profiles. Evidence from the south-east margin of the Australian Precambrian Shield. Earth-Science Revue, 36: 149–179.

Firman J B and Lindsay J M 1976 Geology – Cainozoic. *In:* Natural History of the Adelaide Region. (eds C R Twidale, M J Tyler and B P Webb) Transactions of the Royal Society of South Australia, 99: 197–209.

Firman J B, Bowler J M, Conea A, Fink J, Fotakieva E, Gerasimov I D, Gile L H and Ruhe R V, 1971 Criteria for the recognition of and classification of palaeosols. *In:* Palaeopedology. Origin, Nature and Dating of Palaeosols (ed Dan H. Yaalon pp.153–161. INQUA Commission on Palaeopedology. International Society of Soil Science and Israel Universities Press, Jerusalem.

Forbes B G 1969 Helicopter survey of the Officer and Eucla Basins. Preliminary Report 68/107 Geological Survey of South Australia, Adelaide, South Australia.

Forbes B G 1975 Kopperamanna, South Australia. Explanatory Notes, 1 : 250,000 Geological series. Sheet SH 54-1. Geological Survey of South Australia, Adelaide, South Australia.

Forbes B G 1977 Notes on the Kingoonya 1: 250,000 preliminary geological map. Rep. 77/71: 6 Geological Survey of South Australia, Adelaide, South Australia.

Freytag J B, Heath G R & Wopfner H. 1967 Oodnadatta map sheet, Geological Atlas of South Australia 1 : 250,000 series. Geological Survey of South Australia, Adelaide, South Australia.

Giddings J W 1976 Precambrian palaeomagnetism in Australia I: Basic dykes and volcanics from the Yilgarn Block. Tectonophysics, 30: 91–108.

Gilkes R J & Suddhiprakarn A 1981 Mineralogical and chemical aspects of laterization in southwestern Australia, *In:* Laterization processes. International Seminar on Laterization Processes, Trivandrum, India, 1979. Proceedings, pp.34–44.

Gill Edmund D 1973 Geology and Geomorphology of the Murray River Region between Mildura and Renmark, Australia. *In:* Memoirs of the National Museum of Victoria 34 (ed Edmund D Gill) Melbourne, Australia, 281pp.

Gill Edmund D 1974 *Anadara* (Bivalvia) in the Indian and Pacific waters of Australia Journal of the Marine Biology Association of India,14 (2): pp. 726 – 731.

Glaessner M F & Wade M 1958 The St Vincent Basin. *In:* The Geology of South Australia (ed M F Glaessner and L W Parkin),. Geological Society of South Australia. Journal, 5: 117.

Glassford D K 1987 Cainozoic stratigraphy of the Yeelirrie area, north-eastern Yilgarn Block, Western Australia. Journal of the Royal Society of Western Australia, 70: 1–24.

Glassford D K & Semeniuk V 1991 Arid zone landforms and Cainozoic regolith of the Yilgarn Block of Western Australia. Guidebook for the post-conference excursion. International Conference on Desert Landscapes and International Geological Correlation Programme 252: Past and Future Evolution of Deserts. Final Meeting, October, 1991 Perth, Western Australia, 1991. (Available from the authors: 33 Rockett Way, Bull Creek, W.A., 6149), 35pp.

Glassford D K & Semeniuk V 1995 Desert-aeolian origin of late Cainozoic regolith in arid and semi-arid Southwestern Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 114: 131 – 166.

Gravestock D I, Benbow M C, Gatehouse C G & Krieg G W 1995 Early Palaeozoic of the Western region. *In:* 1995. The Geology of South Australia. The Phanerozoic (eds J F Drexel and W V Preiss). Bulletin 54, Vol. 2: 35–45. Adelaide, South Australia.

Grubb P L C 1971 Mineralogical anomalies in the Darling Range Bauxite at Jarrahdale, Western Australia. Economic Geology 66: 1005–1016.

Harrison P H 1990 Mineral sands. *In:* Geology and Mineral Resources of Western Australia, 1990. Geological Survey of Western Australia Memoir 3: 694–701. Perth, Western Australia.

Hickman, A.H, Smurthwaite, A.J., Brown, J.M., & Davey, R., 1992. Bauxite mineralization in the Darling Range, Western Australia. Report 33: 82. Geol. Surv. West. Aust. Perth, W.A.

Hocking R M & Cockbain A E 1990 Regolith: *In:* Geology and Mineral Resources of Western Australia Memoir 3. pp. 592–603 Geological Survey of Western Australia, Perth, Western Australia.

Idnurm M. & Senior B R. 1978 Palaeomagnetic ages of Late Cretaceous and Tertiary weathering profiles in the Eromanga Basin, Queensland. Palaeogeography, Palaeoclimatology, Palaeoecology, 24: 263–77.

Jutson J T 1934 The Physiography (Geomorphology) of Western Australia. Geological Survey of Western Australia Bulletin 95: 366 pp. Perth, Western Australia.

King D 1953 Origin of alunite deposits at Pidinga, South Australia. Economic Geology 48 No.8: 689–703.

King D 1956 The Quaternary record at Lake Eyre North and the evolution of existing topographic forms. Transactions of the Royal Society of South Australia 79: 93–103.

Lindsay J M 1969 Cainozoic Foraminifera and stratigraphy of the Adelaide Plains sub-Basin, South Australia. Geological Survey of South Australia Bulletin 42: 60p. Adelaide, South Australia.

Lindsay J M 1970 Pt. Willunga Beds in the Port Noarlunga – Seaford area. Quarterly. Geological Notes, 36: 4–10. Geological Survey of South Australia, Adelaide, South Australia.

Low G H 1971 Definition of two Quaternary formations in the Perth Basin, Western Australia. Geologicial Survey of Western Australia Ann. Rep. 1970 p.33–34.

Lowry D C 1965 Geology of southern Perth Basin. Geological Survey of Western Australia Record, 1965/17.

Mann A W & Horwitz R D 1979 Groundwater calcrete deposits in Australia: some observations from Western Australia, Journal of the Geological Society of Australia, 26: 293–303.

McArthur W M & Bettenay E 1960 The development and distribution of the soils of the Swan Coastal Plain, Western Australia. Commonwealth Scientific and Industrial Research Organisation. Soil Publication No.16: 1–55.

Milnes A R, Bourman R P & Northcote 1985 Field relationships of ferricrete and weathered zones in Southern South Australia: a contribution to laterite studies in Australia. Australian Journal of Soil Research. 23: 441–465.

Mory A J & Iasky R P 1996 Stratigraphy and structure of the onshore northern Perth Basin, Western Australia. Geological Survey of Western Australia, Perth, Western Australia.

Mulcahy M J 1973 Landforms and soils of south-western Australia. Journal of the Royal Society of Western Australia 56: 16–22.

Murray A M 1979 Bauxite: *In:* Mining in Western Australia (ed Rex T Prider), pp.101–110. University of Western Australia.

Myers J S 1990 Pinjarra Orogen. *In:* Geology and Mineral Resources of Western Australia. Geological Survey of Western Australia Memoir 3, p.265. Perth, Western Australia.

Myers J S & Hocking R M 1988 1: 2 500 000 Geological Map of

Western Australia (Twelfth Edition). Geological Survey of Western Australia. Perth, Western Australia.

Netterberg F 1985 Engineering Geology of Southern Africa Vol 4: Post-Gondwana Deposits (ed ABA Brink) Building Publications, Silverton, South Africa, 1985 pp 286–307.

Nichol D 1971 The Mt. Willoughby Limestone. Quarterly Geological Notes, 39: 1–2. Geological Survey of South Australia, Adelaide, South Australia.

Pillans Brad & Bourman Robert 1996 The Brunhes/Matuyama Polarity Transition (0.78 Ma) as a chronostratigraphic marker in Australian regolith studies. Journal of Australian Geology and Geophysics 16(3), 289–294. Australian Geological Survey Organisation.

Pillans Brad & Bourman Robert 2001 Mid-Pleistocene arid shift in southern Australia, dated by magnetostratigraphy. Australian Journal of Soil Research 2001, 39: 89–98.

Playford P E & Wilmott S P 1958 Stratigraphy and structure of the Perth Basin, Western Australia. Western Australian Petroleum Pty. Ltd.

Playford P E & Low G H 1972 Definitions of some new and revised rock units in the Perth Basin. Geological Survey of Western Australia. Annual Report 1971, pp. 44–46. Perth, Western Australia.

Playford P E, Cope R N, Cockbain A E, Low, G H & Lowry D C 1975 Perth Basin; Collie and Wilga Basins; Superficial Phanerozoic Deposits on the West Australian Shield. Memoir 2: 227–259; 420–431; 432–433. Geological Survey of Western Australia, Perth, Western Australia.

Prider R T 1943 The contact between the granitic rocks and the Cardup Series at Armadale. Journal of the Royal Society of Western Australia 27: 27–56.

Prider R T 1948 The geology of the Darling Scarp at Ridge Hill. Journal of the Royal Society of Western Australia 32: 105–129.

Pym L W 1955 Soils of the Swan Valley vineyards area, W.A. Commonwealth Scientific and Industrial Research Organisation. Australian Division of Soils and Land Use Series No.15.

Reyner M L 1955 The Geology of the Peake and Denison Region. Report of Investigations, 6: 23pp. Geol. Surv. S. Aust. Adelaide, S.A.

Robertson, R.S., 1974. Extremely weathered cut material on the South East Freeway. Quarterly Geol. Notes, 52: 9–12, Geological Survey of South Australia. Adelaide, South Australia.

Robertson R S 1974 Extremely weathered cut material on the South East Freeway. Quarterly Geological Notes 52: 9–12. Geological Survey of South Australia. Adelaide, South Australia.

Sadlier S B & Gilkes R J 1976 Development of bauxite in relation to parent material near Jarrahdale, Western Australia. Journal of the Geological Society of Australia 23 (4): 333–334.

Salvador Amos (ed) 1994 International Stratigraphic Guide. A Guide to Stratigraphic Classification, Terminology, and Procedure (Second Edition). The International Union of Geological Sciences and the Geological Society of America, Inc.

Senior B R & Mabbutt J A 1979 A proposed method of defining deeply weathered rock units based on regional geological mapping in south-west Queensland. Journal of the Geological Society of Australia 26: 237–254.

Simpson E S 1912 Notes on laterite in Western Australia. Geological Magazine 9: 399–406.

Smurthwaite A J 1990 Alumina: *In:* Geology and Mineral resources of Western Australia. Geological Survey of Western Australia Memoir 3: 615–624. Perth, Western Australia.

Stirton R A, Tedford R H & Miller A H 1961 Cenozoic stratigraphy and vertebrates of the Tirari Desert, South Australia. South Australian Museum Records 14: 19–61.

Stephens C G 1971 Laterite and silcrete in Australia: A study of the genetic relationships of laterite and silcrete and their companion materials, and their collective significance in the formation of the weathered mantle, soils, relief and drainage of the Australian continent. Geoderma, 51: 5–52.

Teichert C 1967 Age of the Coastal Limestone, Western Australia.. Australian Journal of Science 30: 71.

Trendall A F & Cockbain A E 1990 Basins, *In:* Geology and Mineral Resources of Western Australia. Memoir 3: 730–755. Geological Survey of Western Australia. Perth, Western Australia.

Veevers J J, Powell C, McA and Roots S R (1991). Review of seafloor spreading

around Australia. I: Synthesis of the patterns of spreading. Australian Journal of Earth Science, V. 38 pp.373–389.

Welch B K 1964 The Ilmenite deposits of Geographe Bay. Australasian Institute of Mining and Metallurgy Proceedings, 211: 25–48.

Wells R T & Callen R A (eds) 1986 The Lake Eyre Basin – Cainozoic sediments, fossil vertebrates and plants, landforms, silcretes and climatic implications. Australasian Sedimentologists Group Field Guide Series, No. 4, 176 pp.

Wetherby K G (1975) Classification of carbonate layers in highland soils of the northern Murray Mallee, S.A. and their significance in stratigraphic and land – use studies. Australian Journal of Soil Research 13: 119–32.

Wilde S A 1994 Crustal evolution of the south-western Yilgarn Craton. Curtin University of Technology. Excursion Guide, 12th AGC Conference, 18pp.

Wilde S A 1999 Evolution of the western margin of Australia during the Rodinian and Gondwanan supercontinent cycles. Gondwana Research V 2 (3): pp.481–499.

Wilde S A & Backhouse J 1977 Fossiliferous Tertiary deposits on the Darling Plateau, Western Australia. Geological Survey of Western Australia. Annual Report 1976. pp. 49–52.

Wilde S A & Low G H 1978 Explanatory Notes Perth, Western Australia. 1: 250,000 Geological Map Series SH/50-14. Geological Survey of Western Australia. Perth, Western Australia.

Wilde S A & Low G H 1980 Explanatory Notes Pinjarra, Western Australia. 1: 250,000 Geological Map Series SI/50-2. Geological Survey of Western Australia. Perth, W.A.

Wilde S A & Walker I W 1982 Explanatory Notes Collie, Western Australia. 1: 250,000 Geological Map Series SI/50-6. Geological Survey of Western Australia. Perth, Western Australia.

Williams D L G 1982 Multiple episodes of Pleistocene dune-building at the head of Spencer Gulf, South Australia. Search 13: 3–4

Woolnough W G 1918 The physiographic significance of laterite in Western Australia. Geological Magazine 5: 385–393.

Wopfner H. 1964 Tertiary duricrust profile on Upper Proterozoic sediments, Granite Downs area. Quarterly. Geol. Notes, 12: 1–3. Geological Survey of South Australia, Adelaide, South Australia.

Wopfner H. 1974 Post-Eocene history and stratigraphy of north - eastern South Australia. Transactions of the Royal Society of South Australia 98: 1–12.

Yaalon Dan H (ed) 1971 Palaeopedology. Origin, Nature and Dating of Palaeosols. pp.153–161. INQUA Commission on Palaeopedology. International Society of Soil Science and Israel Universities Press, Jerusalem.