Australia goes it alone

the emerging island continent 100 Ma to present

by

AE Cockbain

Government of **Western Australia**
Department of **Mines and Petroleum**

Geological Survey of Western Australia

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with contributions from RM Hocking,

and on economic geology from F Pirajno, JN Guilliamse,

TJ Beardsmore, P Duuring*, JF Johnston, and CA Strong

* Centre for Exploration Targeting, The University of Western Australia

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REFERENCE
The recommended reference for this publication is:
Cockbain, AE 2014, Australia goes it alone — the emerging island continent 100 Ma to present: Geological Survey of Western Australia, 63p.

National Library of Australia Cataloguing-in-Publication entry:

Author:	Cockbain, AE (Anthony Edward), 1934–
Title:	Australia goes it alone — the emerging island continent 100 Ma to present / Anthony Edward Cockbain; contributors: Roger M Hocking, Franco Pirajno, Joshua N Guilliamse, Trevor J Beardsmore, Paul Duuring, Jean F Johnston, and Caroline A Strong
ISBN:	9781741685640 (paperback) 9781741685633 (PDF)
Subjects:	Geology, Stratigraphic—Cenozoic Geology—Western Australia
Other contributors:	Hocking, Roger M, Pirajno, Franco, Guilliamse, Joshua N, Beardsmore, Trevor J, Duuring, Paul, Johnston, Jean F, Strong, Caroline A Geological Survey of Western Australia. Western Australia. Department of Mines and Petroleum
Dewey Number:	551.78

Editing and design:	JF Johnston
Design and layout:	MC Jones
Cartography:	M Prause, S Dowsett, J Peng, A Symonds, and T Lenane
Printed by:	Daniels Printing Craftsmen, Osborne Park, Western Australia

Published 2014 by Geological Survey of Western Australia
This book is also published in digital format (PDF) and is available online at <www.dmp.wa.gov.au/GSWApublications>

Further details of geological publications and maps produced by the Geological Survey of Western Australia are available from:
Information Centre
Department of Mines and Petroleum
100 Plain Street
EAST PERTH WESTERN AUSTRALIA 6004
Telephone: +61 8 9222 3459   Facsimile: +61 8 9222 3444
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Photographs:

Front cover: Deep weathering in the Eocene has resulted in mesas (foreground) and the flat peneplain that covers much of the arid interior of Western Australia, Ashburton Embayment, north of Nanutarra Roadhouse

Preface: Lateritized and weathered Archean metasandstone peaks in the Edemurta Range near Bunnawarra Station, some 30 km southwest of Yalgoo

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Acknowledgements

Thanks to the following photographers who have provided photos for this volume:

AE Cockbain, Geoscience Australia, JR Gozzard, RM Hocking, Iluka Resources Limited, JF Johnston, CBE Krapf, Landgate, DC Lowry, P Maddern, S Morin-Ka, AJ Mory, F Pirajno, PE Playford, S Romano, B Striewski, A Thomson, MJ Van Kranendonk, *The West Australian* newspaper, IR Williams, MTD Wingate, and I Zibra

About the author

Anthony (Tony) Cockbain was born in England and obtained BSc (Hons) and PhD degrees from the University of Nottingham. He has worked in universities, geological surveys, and briefly in industry. He was Assistant Director at the Geological Survey of Western Australia when he retired in 1992.

His research interests have included marine geology, paleontology, and basin studies. For 17 years he was the Editor of the Australian Journal of Earth Sciences, and he has had two stints as Editor of the Journal of the Royal Society of Western Australia, one in the days of linotype and galley proofs and another when doc and pdf files prevailed.

Preface

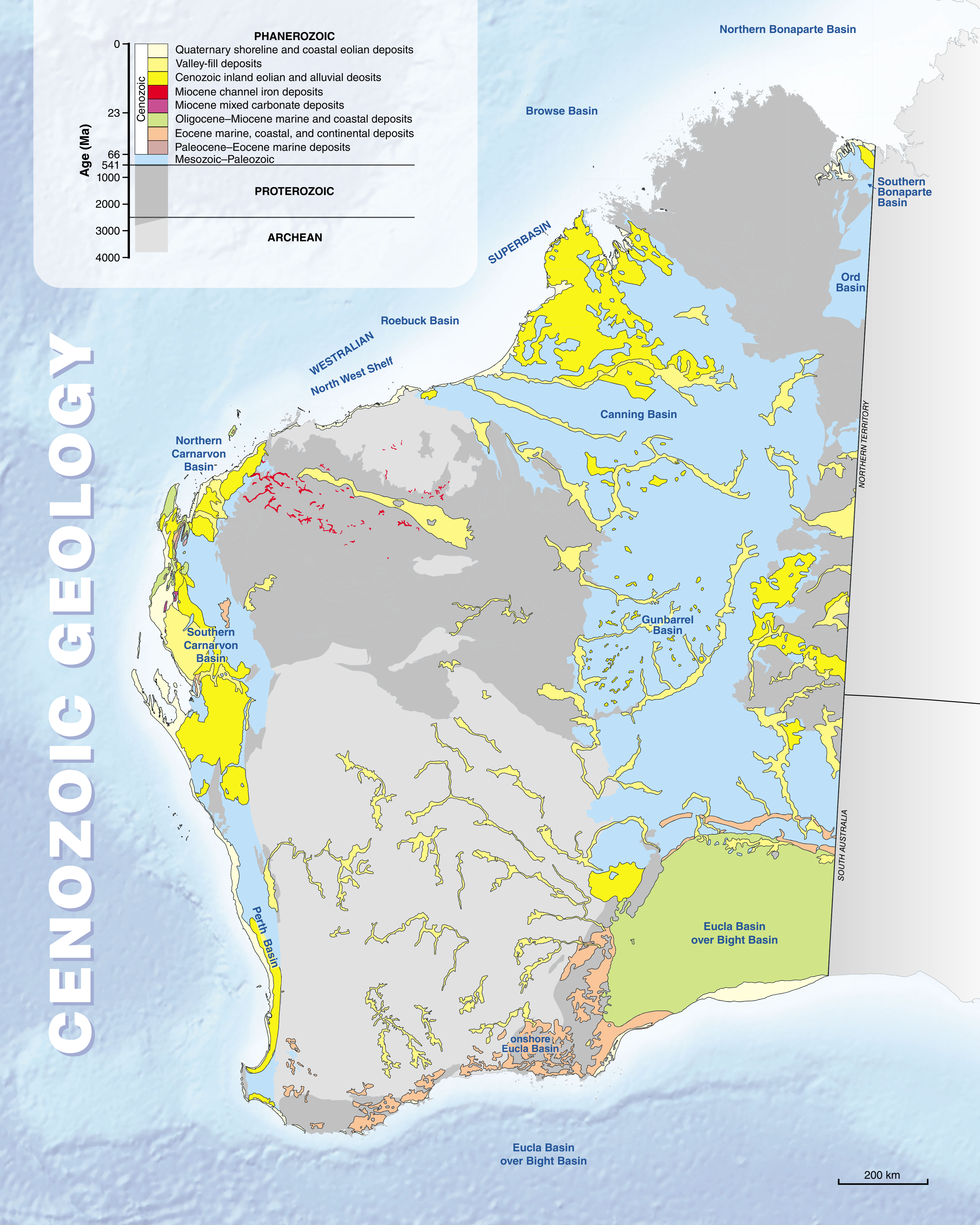
Under the banner of 'Western Australia unearthed', the Geological Survey of Western Australia (GSWA) is progressively publishing a new compilation of Western Australia's geology.

This volume, *Australia goes it alone — the emerging island continent 100 Ma to present,* is the second to be published, following on from *The birth of supercontinents and the Proterozoic assembly of Western Australia*. Two more titles will be published — *Archean: building the core of the continent*; and *Gondwana: from assembly to breakup*. These books are aimed at trainee and professional geologists, and particularly newcomers to Western Australia, to enable them to quickly get a feel for the geology and economic potential of the diverse terrains that make up the State. Each book provides our current ideas on the geological history of Western Australia, and a list of recommended references is provided for follow-up reading. GSWA has amassed knowledge on the geology and resources of Western Australia over more than 120 years. This book is a summary of all that information available through our website — the next step is to access the web: <www.dmp.wa.gov.au/GSWA>.

Rick Rogerson
Executive Director

May 2014

CENOZOIC GEOLOGY



Setting the scene

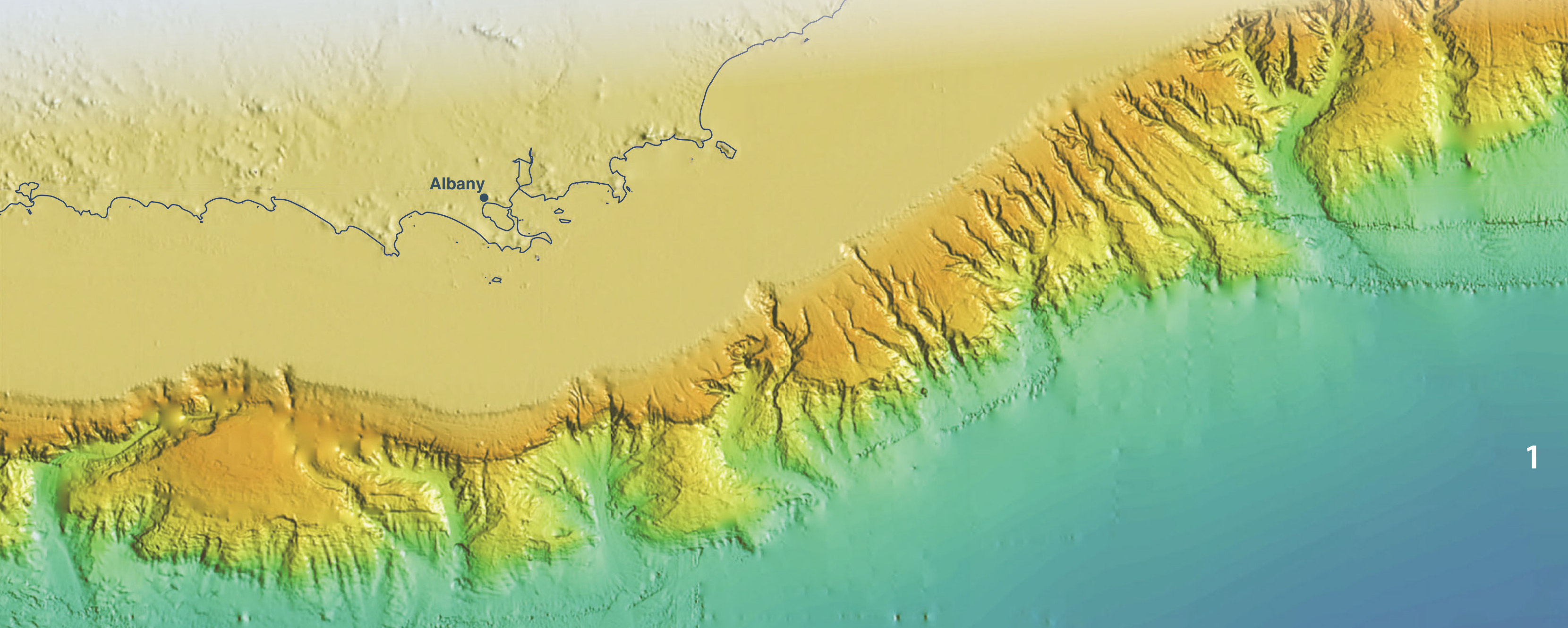
The portion of the Earth's crust that became the island continent of Australia was originally part of a succession of supercontinents — single landmasses that contained most, if not all, the cratons at a given time in Earth history. Supercontinents assembled, broke up, and reassembled, in cycles lasting hundreds of millions of years. The configuration and position of the supercontinental landmasses changed through time with each assembly, and each has been named. Nuna (sometimes called Columbia) may have been the first true supercontinent, in the Paleoproterozoic. It was succeeded in the Mesoproterozoic by Rodinia. This, in turn, was followed by Gondwana, which existed from the latest Neoproterozoic until it broke up in the Mesozoic (Fig. 1). Gondwana was for the most part a southern supercontinent, and had a complex ever-changing relationship with Pangea, an even larger supercontinent comprising Gondwana and a northern element, Laurasia. Pangea existed in various forms from the late Paleozoic, about 300 million years ago, until breakup started about 200 million years ago.

Rocks and deformations related to the assembly and breakup of Nuna, Rodinia, and Gondwana are found in Western Australia. Evidence for the progressive breakup of Gondwana can be seen in the Westralian Superbasin along the North West Shelf, in the Perth Basin on the western margin, and in the Bight and Eucla Basins along the southern margin.

Further details on the Gondwana and Proterozoic supercontinents are in the accompanying volumes in this series.

This book has two main parts. The first, *100 million years of history*, discusses the advance and retreat of the sea across the Australian continent-to-be as it separated from Gondwana. After breakup (see *The end of Gondwana*), the newly formed oceans encroached onto the continent depositing clastic and carbonate sediments in a series of cycles (see *Cycling through the Cenozoic*). The dynamic forces responsible for these cycles also resulted in gentle tilting of the continent as it moved north to collide with southeast Asia (see *Tilting of Australia*); such forces also cause earthquakes (see *Quakes and shakes*).

Surveying the history of sedimentation and slow earth movements, the first section sets the scene for the second — *Evolution of a landscape* — that covers the development, over millions of years, of plains, hills, and rivers formed by weathering and erosion. An important part of Western Australia's ancient landscape is the regolith. This weathered veneer blankets bedrock and contains large and valuable mineral resources, the extraction of which forms a fundamental part of the State's economy.



100 million years of history

The end of Gondwana

Gondwana comprised what is now South America, Africa, Arabia, India, Antarctica, and Australia. Gondwana's breakup was prolonged — from the mid-Jurassic until the mid-Cenozoic. Along the North West Shelf, initial rifting in the mid-Jurassic (c. 165 Ma) was followed by the Argo or breakup unconformity (evidenced by seismic horizon Ca) at c. 156 Ma (Fig. 2; see Table 1 for Time Scale in Stages). Even then, early rifting was preceded by pre-rift sag along pre-existing crustal sutures along Western Australia's northwest margin, in the Late Permian, Triassic, and Early Jurassic. This phase formed the thick sandy successions that host the giant oil and gas accumulations along the North West Shelf today.

Table 1. Time scale in millions of years for the Cenozoic and part of the Mesozoic

Era	S/P	Epoch	Stage	Age (Ma)
Cenozoic	Quaternary	Holocene		Present
		Pleistocene		2.588
	Neogene	Pliocene		
		Miocene		23.03
	Paleogene	Oligocene		
		Eocene		
		Paleocene		66
Mesozoic	Cretaceous	Upper	Maastrichtian	
			Campanian	
			Santonian	
			Coniacian	
			Turonian	
			Cenomanian	100.5
		Lower	Albian	
			Aptian	
			Barremian	
			Hauterivian	
			Valanginian	
			Berriasian	145
	Jurassic	Upper	Tithonian	
			Kimmeridgian	
			Oxfordian	164
		Middle	Callovian	
			Bathonian	
			Bajocian	
			Aalenian	174
		Lower	Toarcian	
			Pliensbachian	
			Sinemurian	
			Hettangian	201

Note: S/P, System or Period

Development of the southern margin of the continent was a much slower process. Rifting and crustal extension in the Bight Basin (*see grey thumbnail maps showing all the basin locations) formed an east-trending string of half grabens in the Middle Jurassic – Early Cretaceous (c. 165 to 125 Ma), above older Paleozoic and ?Neoproterozoic lines of weakness, but final separation did not happen until c. 84 Ma, in the Late Cretaceous.

In the initial breakup phase the sea flooded across much of Western Australia from an ever-widening ocean in the northwest (Fig. 3). A basal transgressive sandstone and overlying marine siltstone (Lower Cretaceous Winning Group and its equivalents) spread across the Perth, and Northern and Southern Carnarvon Basins. Fluvial and nearshore sandstone was deposited in the southern Canning Basin. Post-rift thermal subsidence was followed by accelerated subsidence in the Albian, possibly a consequence of a change in spreading direction between the Australian and Indian Plates at c. 99 Ma, from northwest–southeast to north–south. This change, in turn, may have been caused by a change in absolute motion of the Pacific Plate.

Radiolarian siltstones (the Albian Windalia Radiolarite in the North West Shelf, the Darwin Formation around Darwin, and the Bulldog Shale in South Australia) extend over much of western and central Australia and mark the height of the Cretaceous transgression. The siltstones are absent in the onshore Canning Basin, which may have been emergent or paralic at the time, but to the south a radiolarian-rich unit, the Bejah Claystone, extends through the Gunbarrel Basin. This suggests flooding from the south via the Bight Basin, rather than from the northwest via the Canning Basin. The presence of radiolarians in a shallow epeiric sea is not easy to account for, although shallow-water radiolarian faunas have been described elsewhere (Jurassic of Queen Charlotte Islands, Canada).

Thumbnail maps outline the tectonic units under discussion dark blue = onshore; light blue = offshore

The island continent

Continental shelves built outwards around Western Australia, after breakup led to the development of passive margins on the northwestern, western, and southern margins. These shelves faced increasingly larger oceans with oceanic water masses and oceanic current patterns. Figure 2 shows a typical continental shelf, with prograding post-breakup strata overlying the rifted sequence beneath the breakup unconformity. Frontispiece map (page vi) shows the Cenozoic rocks of Western Australia.

As the ocean widened and a truly oceanic circulation became established, sedimentation around post-Gondwana Western Australia changed to mainly carbonate-dominated on the newly formed shelf on the west coast, and clastic and cool-temperate carbonate-dominated on the southern shelf. However, the seas never again spread across Western Australia to the extent they had in the earliest phase of the Gondwana breakup.

Deposition briefly ceased in the Westralian Superbasin at the end of the Maastrichtian (c. 66 Ma), and some erosion of Maastrichtian strata took place in the Northern Carnarvon Basin. The climate was probably warm temperate rather than hot, with moderate to low seasonality. Along the North West Shelf area the climate was relatively wet to the south, but drier in the north.

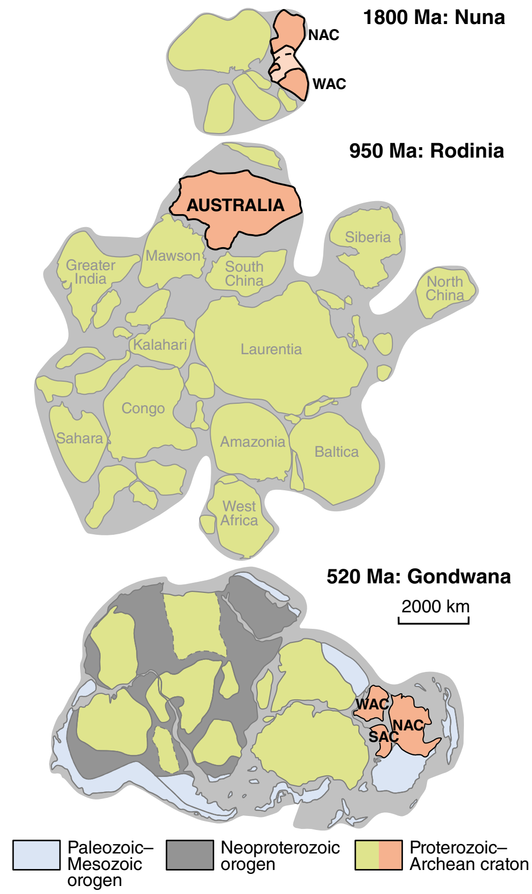


Figure 1. Reconstructions of three supercontinents (Nuna modified from Söderlund et al., 2010; Rodinia after Li et al., 2008; and Gondwana modified from Meert and Lieberman, 2008). Abbreviations: NAC, SAC, WAC, are North, South, and West Australian Cratons respectively

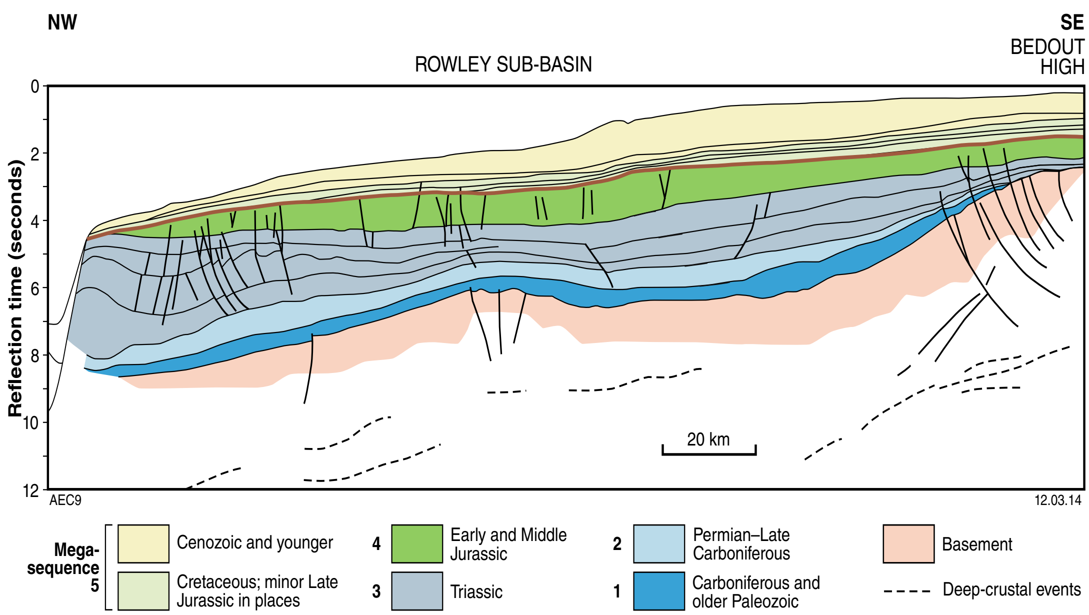


Figure 2. Cross section from the Bedout High across the Rowley Sub-basin on the North West Shelf showing prograding post-breakup strata overlying the rifted sequence beneath the breakup unconformity marked in red (after Colwell and Stagg, 1994, fig. 7)

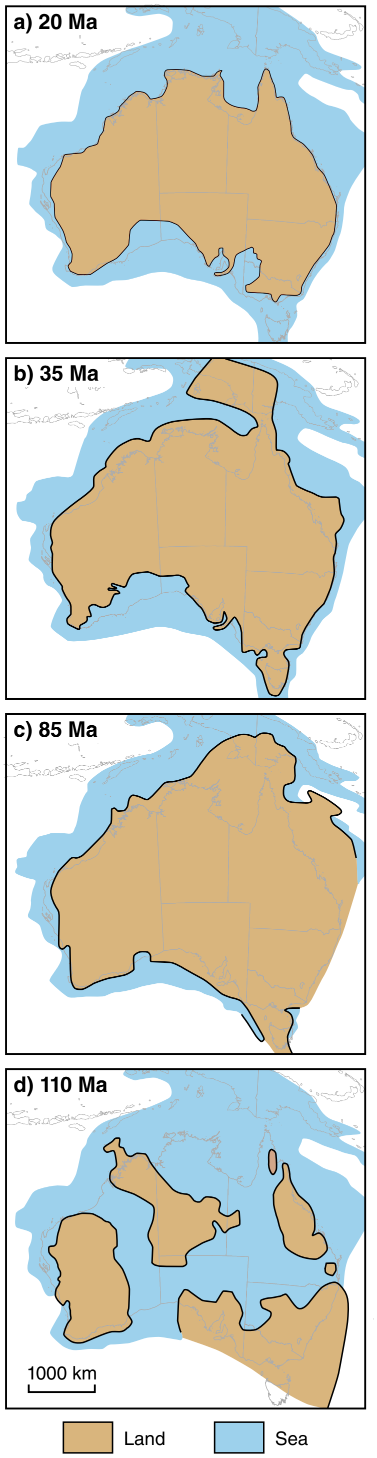


Figure 3. Distribution of sea over the Australian continental platform at 20 Ma (early Miocene), 35 Ma (latest Eocene), 85 Ma (Santonian), and 110 Ma (Albian); after Veevers (2001, fig. 75)

Chalk everywhere

Chalk is made up of minute calcite plates (coccoliths) shed from single-celled algae called coccolithophores. A world-wide phenomenon of chalk deposition characterized the Late Cretaceous, so much so that the word Cretaceous is from the Latin 'creta' for chalk. Two famous areas are the chalk cliffs of Dover in the UK, and the Gulf Coast of USA. On Western Australia's margins extensive chalk sedimentation took place in the Perth Basin (Gingin Chalk) and the Northern and Southern Carnarvon Basins (Toolonga Calcilutite, with *Inoceramus* prisms). In the Southern Carnarvon Basin, flat-lying chalk is found relatively close to and at the same height as Precambrian and Paleozoic hinterland, indicating it accumulated under open-ocean but nearshore conditions where there was very little clastic influx, rather than in a deep-sea environment. Greensands (Molecap and Poison Hill Greensands) and calcareous mudstones or marls (Miria Formation, Haycock Marl) were also laid down on the prograding shelf in the Late Cretaceous. None are found in the onshore Canning Basin.

And in the south ...

The sequence offshore along the southern margin has been penetrated in only one well in Western Australia, Jerboa 1 in the Great Australian Bight. Our knowledge of the geology is based on a few seismic surveys, dredging of the continental shelf and slope, and submarine canyons cutting back into the slope and shelf. Mesozoic rocks are allocated to the Bight Basin, and overlying Cenozoic rocks to the Eucla Basin. Initial northwest–southeast to north–south crustal extension during the Middle Jurassic to Early Cretaceous formed a string of half grabens — the 'Southern Rift System' — extending from south of Cape Leeuwin to south of Kangaroo Island in South Australia (Fig. 4). These may have been 'anchored' by a pre-existing crustal suture along which poorly known

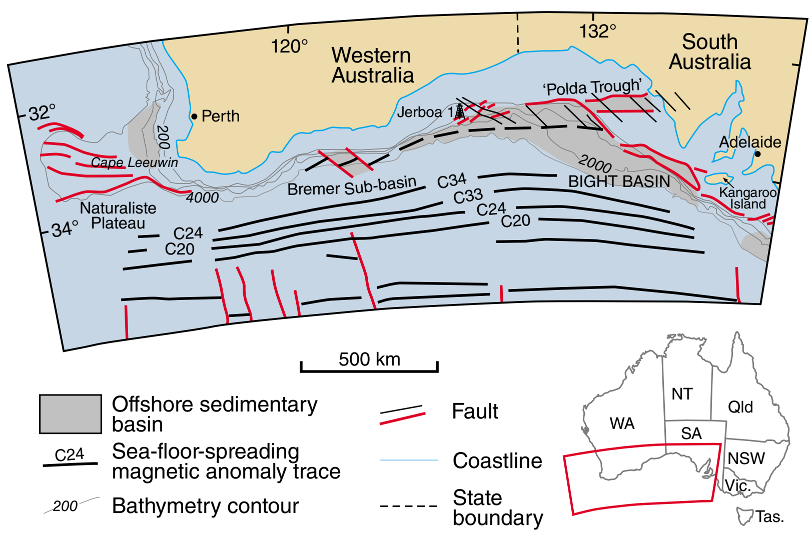


Figure 4. 'Southern Rift System' (after Totterdell et al., 2003, fig. 4.8)

Neoproterozoic basins had developed locally. Seismic profiles and dredging suggest the Bremer Sub-basin overlies one of these basins. In South Australia the 'Polda Trough' is a similar feature (Fig. 4).

The Jurassic and Cretaceous rocks infilling the half grabens are mainly sandstone, siltstone, and claystone, equivalent to various Jurassic units found further east in the Bight Basin and the Cretaceous rocks (Loongana, Madura, and Toondi Formations) underlying the Eucla Basin succession onshore (Fig. 5). The oldest rocks are non-marine, with marine deposition starting in the Albian. The glauconitic sandstone found onshore (Nurina Formation) under the northern Eucla Basin is absent from Jerboa 1, where the mid-Cretaceous shales (Toondi Formation) are unconformably overlain by Eocene Hampton Sandstone of Cenozoic Cycle 2 (see *Cycling through the Cenozoic*).

Interpretations from seismic sections along the southern margin of the Bremer Sub-Basin (part of the Bight Basin) suggest the succession grades up from fluviolacustrine sediments of Middle Jurassic to Early Cretaceous age to marine sediments in the Aptian and later rocks.

Breakup and emplacement of oceanic crust along Australia's southern margin first occurred in the Turonian then, some 5 million years later, in the Santonian in the Bight Basin. The oldest magnetic anomaly along the southern margin is C34 (83.5 Ma, Santonian). After initial extrusion of oceanic crust, there was further thermal subsidence and a passive margin developed. Spreading was fairly slow, only 0.8 cm/yr, until c. 43 Ma. Then the Australian and Indian Plates fused, the spreading rate accelerated to 3.0 cm/yr, and Australia moved steadily north away from Antarctica (Fig. 6). Today, Australia is moving rapidly towards the Asian continent, at 5.6 cm/yr, almost 2 cm/yr faster than the western part of the plate (which is colliding against the Himalayas), and the Indo-Australian Plate may be shearing into separate plates.

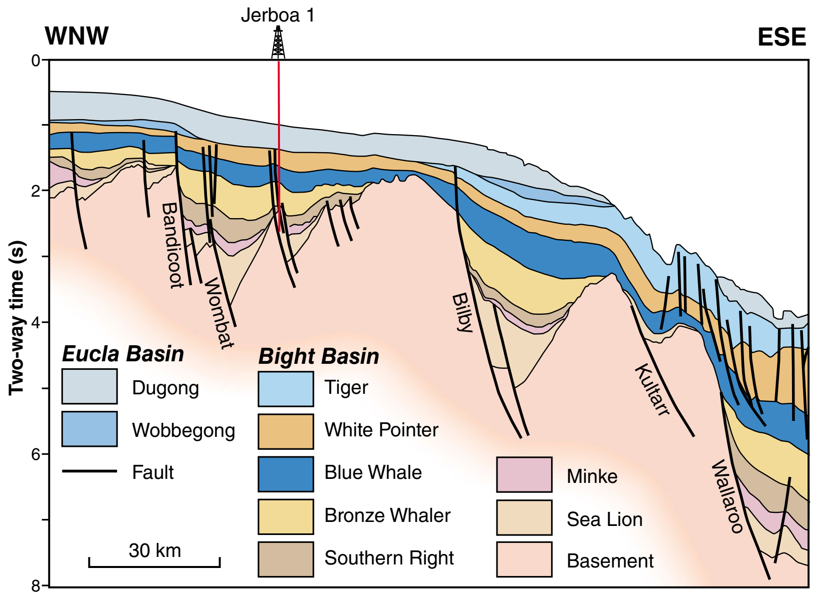


Figure 5. ***Cross section through Jerboa 1 on the offshore Eucla and Bight Basins. The legend shows the supersequences recognized in the seismic data by Geoscience Australia (after Bradshaw et al., 2003, fig. 14). Dugong equates to the Nullarbor and Wilson Bluff Limestones and Hampton Sandstone; White Pointer and Blue Whale to the Toondi Formation; Bronze Whaler to the Madura Formation; and Southern Right to the Loongana Formation***

Spreading was fairly slow, only 0.8 cm/yr, until c. 43 Ma, then the spreading rate accelerated to 3.0 cm/yr, and Australia moved steadily north away from Antarctica.

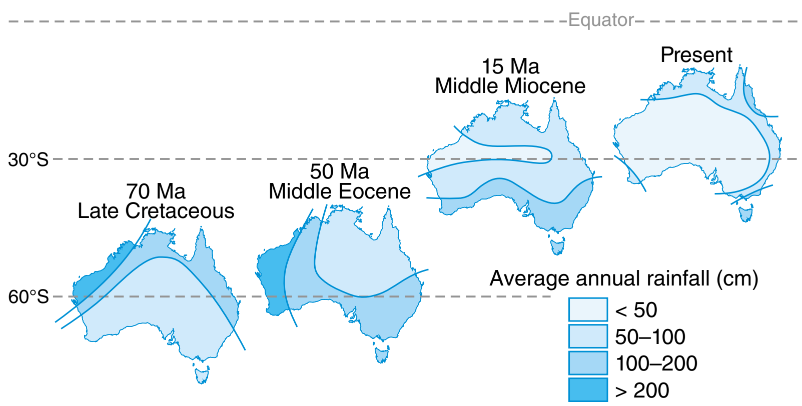


Figure 6. ***Australia's migration north since the Late Cretaceous (after Anand, 2005, fig. 5)***

Tertiary no more

Based on field observations in Italy, Giovanni Arduino classified the geological time scale into primitive (or Primary), Secondary, and Tertiary periods in 1759. The names Primary and Secondary have long been abandoned; and the Tertiary has more recently been superseded. Charles Lyell used the term Neozoic for all post-Permian systems and John Phillips placed these systems in his Mesozoic and Cainozoic (now Cenozoic). The latter includes the Tertiary and Quaternary. Other subdivisions were recognized until eventually the Tertiary comprised the Paleocene, Eocene, Oligocene, Miocene, and Pliocene. Subsequently the Tertiary was subdivided into the Paleogene (Paleocene to Oligocene) and Neogene (Miocene and Pliocene). Although the International Commission on Stratigraphy discourages the use of the term, many geologists still find 'Tertiary' useful for Paleogene plus Neogene strata.

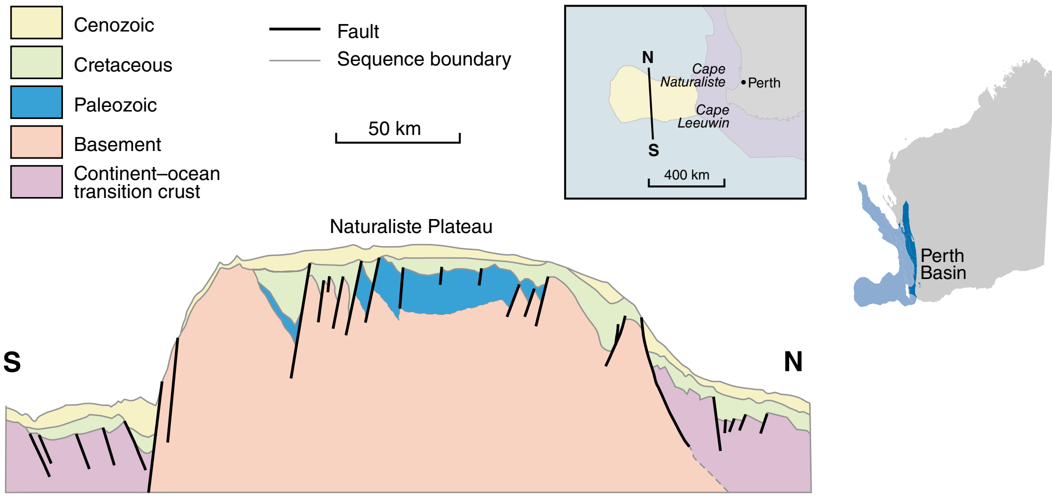


Figure 7. North–south section across the offshore Naturaliste Plateau (simplified from Geoscience Australia, 2011)

Naturaliste Plateau

One consequence of breakup along the southern margin was the development of the Naturaliste Plateau (Fig. 7). This covers an area of 90 000 km^2 in water depths of between 2000 and 5000 m, and is one of several large submarine plateaus off Western Australia, such as the Exmouth and Wallaby Plateaus in the north. Although the origin of the plateau is controversial, seismic surveys, drilling, and dredging suggest the Naturaliste Plateau is a structurally complex fragment of continental crust that may have affinities with Mesoproterozoic crust in the Pinjarra Orogen. Granite and orthogneiss dredged from the southern margin of the plateau have a magmatic age of c. 1230 to c. 1190 Ma and were metamorphosed during the Cambrian Leeuwin Orogeny at c. 515 Ma. Cretaceous (135 Ma) volcanic rocks, of a similar age to those exposed near Bunbury, have also been dredged from the Naturaliste Plateau.

Seismic surveys reveal several small rift basins on the Naturaliste Plateau filled with up to 2.5 km of sediment. Deep Sea Drilling Program (DSDP) drilling has intersected Cretaceous and Cenozoic sedimentary rocks but the age of the older sedimentary rocks overlying basement is unknown (Fig. 7). The oldest sedimentary sequence is Albian clay and sandstone with volcaniclastic conglomerate, overlain by clay-rich chalk and siliceous limestone of Cenomanian to Santonian age. The unconformably overlying Cenozoic sediments are Paleocene, Eocene, and Pliocene–Holocene chalk and ooze of Cycles 1, 2, and 4; rocks of Cycle 3 are missing (see *Cycling through the Cenozoic*).

Seismic surveys reveal several small rift basins on the Naturaliste Plateau filled with up to 2.5 km of sediment.

Ashburton Embayment — an exhumed Cretaceous landscape

Cycling through the Cenozoic

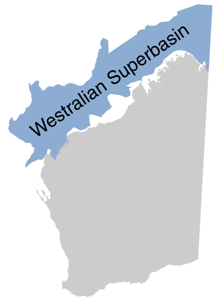
The Cenozoic history of Australia has long been interpreted in terms of four cycles (second-order sequences generated by mantle thermal processes and plate movements):

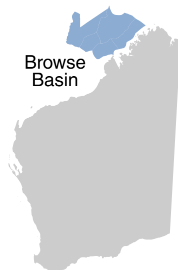
Cycle 1: Paleocene – early Eocene
Cycle 2: middle Eocene – early Oligocene
Cycle 3: late Oligocene – middle Miocene
Cycle 4: late Miocene – Holocene.

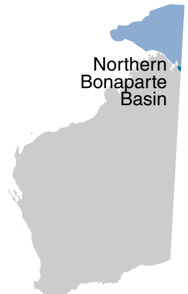
These cycles were initially identified in onshore deposits and were separated by lengthy hiatuses. Nevertheless, even offshore in the Westralian Superbasin (Figs 8 and 9), where sedimentation was more continuous, there are hardgrounds spanning time breaks of 2 to 4 million years between the cycles. Detailed work along the southern margin of Australia has enabled the recognition of a number of third-order sequences within these cycles. The second-order cycles are of ~10^7 years duration, whereas the third order sequences are in the order of 10^5–10^6 years, each characterized by an unconformity and marine transgression (Fig. 10).

Where is the K/T boundary?

The actual Cretaceous/Tertiary (K/T) boundary (see box, *K/T boundary*) is nowhere to be seen in Western Australia. Throughout the Western Australian record there seems to be a hiatus between the Cretaceous and the Cenozoic, with the earliest Paleocene missing (Fig. 9). There are no indications of emergence or erosion in outcrop sections across the boundary, only a condensed section perhaps, so it is probable that this is the result of a submarine hiatus rather than uplift and subaerial erosion. No doubt in far-offshore areas on the North West Shelf, sedimentation may have been continuous across the boundary.







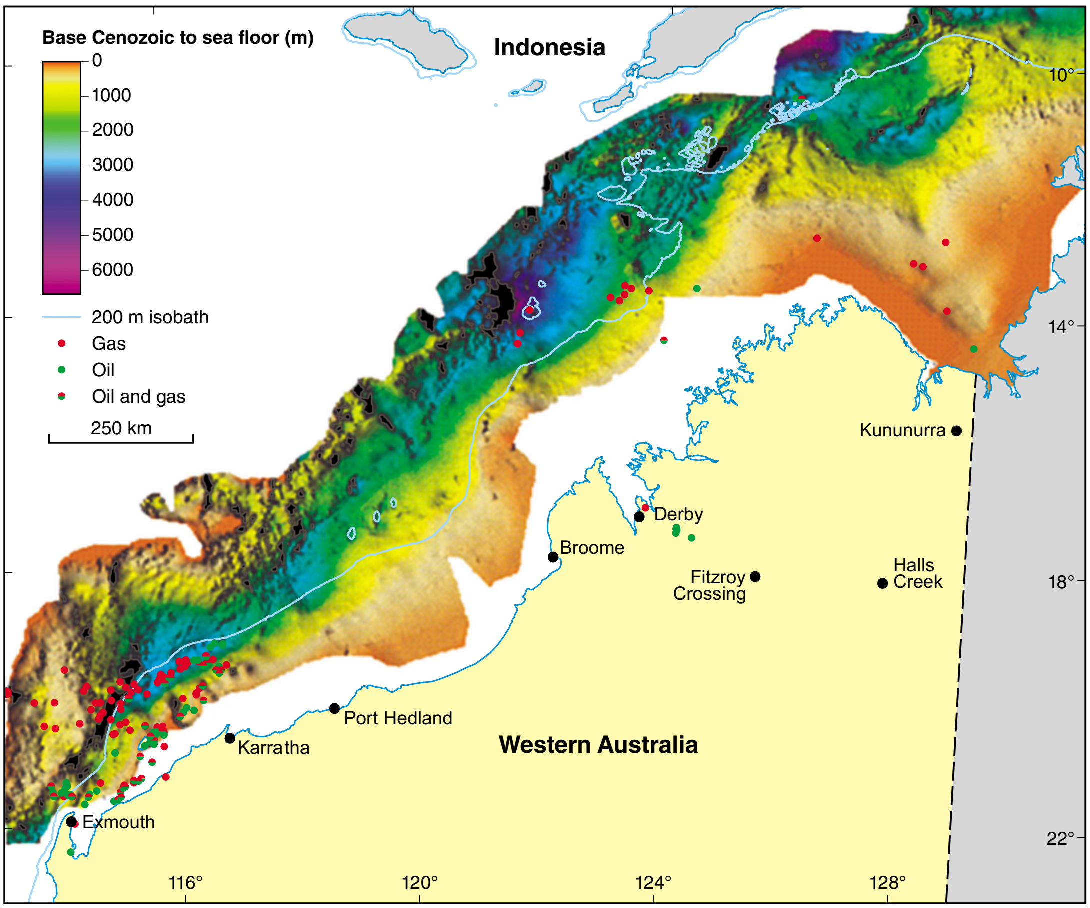


Figure 8. Thickness of the Cenozoic succession on the North West Shelf (image courtesy Woodside Petroleum Limited)

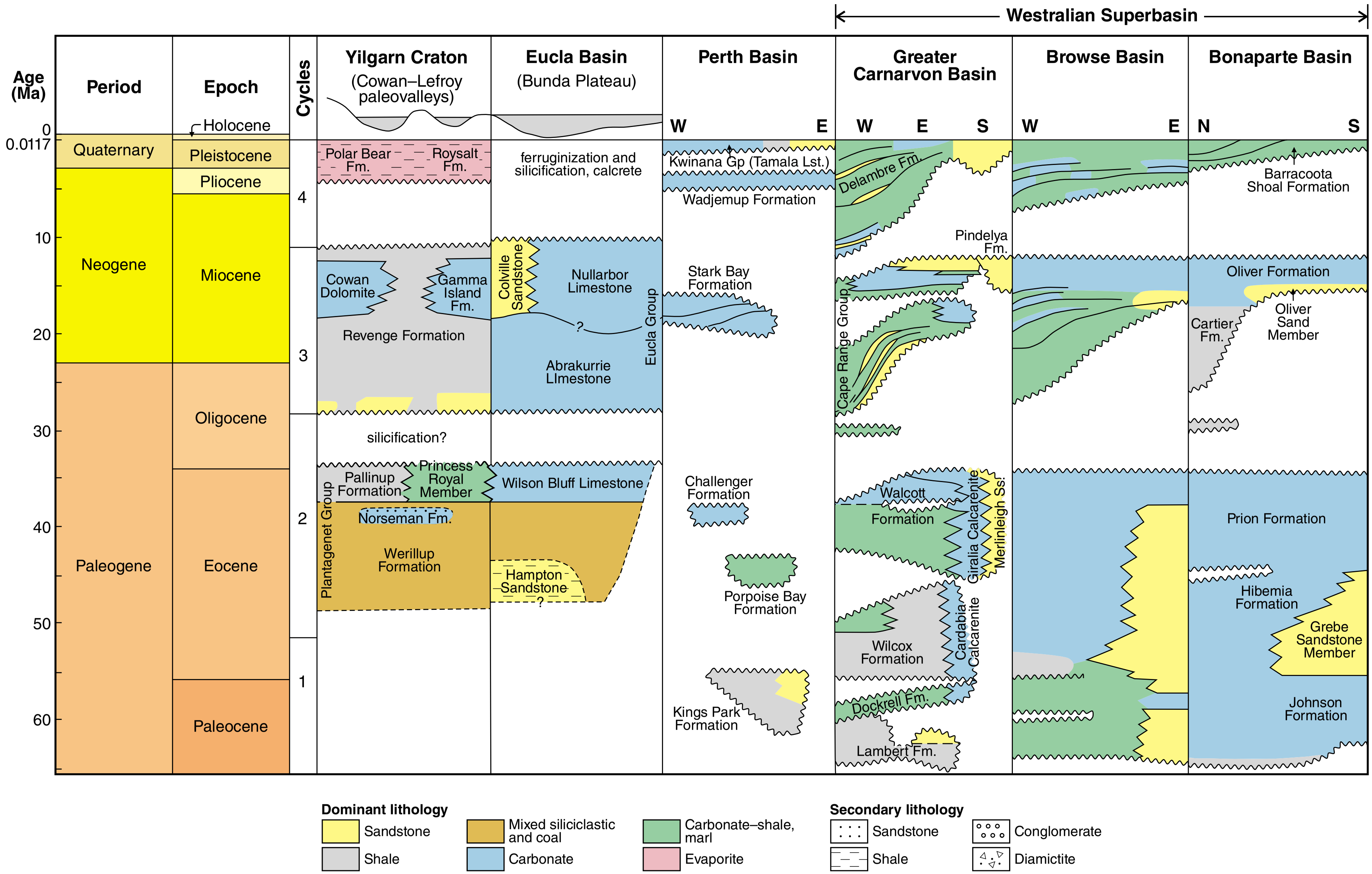
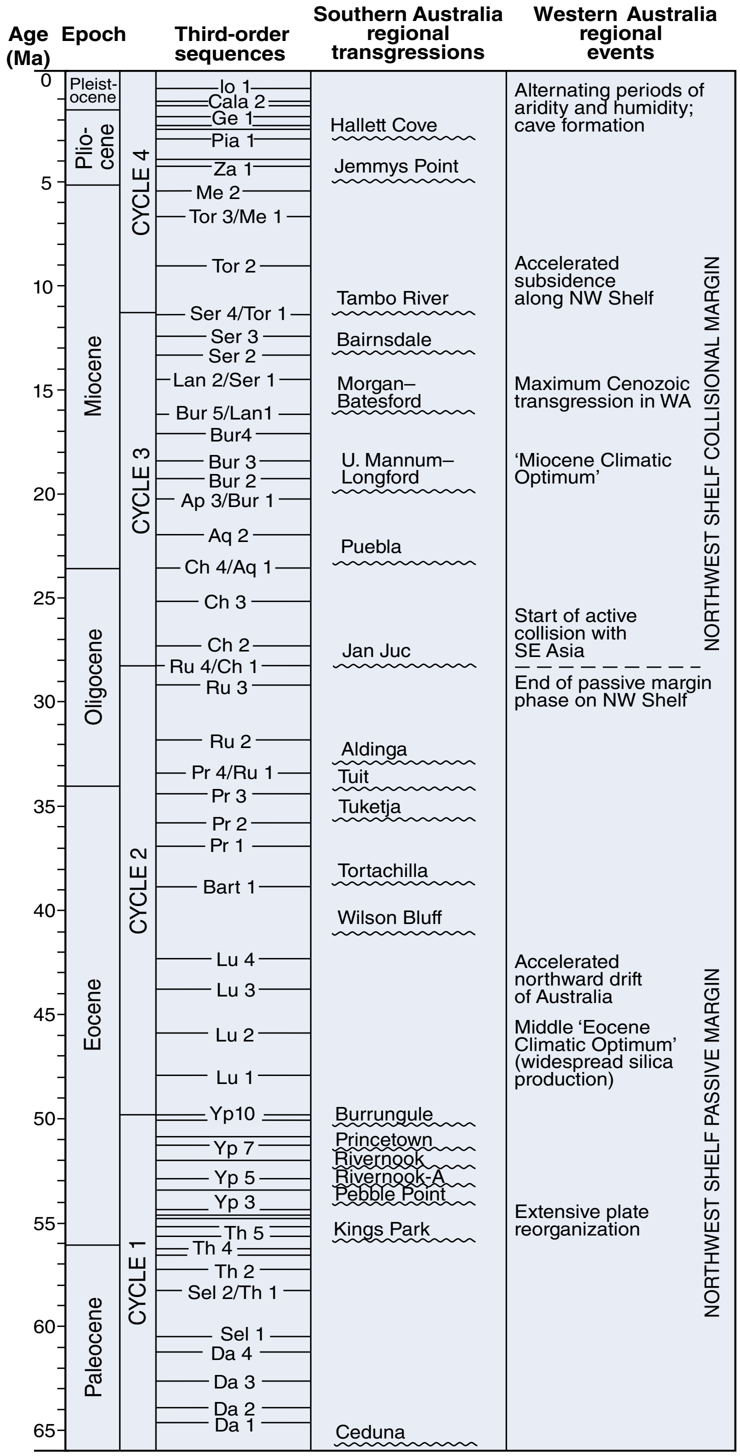


Figure 9. Cenozoic stratigraphy and depositional cycles across Western Australia. There are no formal lithostratigraphic units in the Browse Basin



Cycle 1: Paleocene – early Eocene

Cycle 1 is recognized along the western margin of Western Australia as well as in the Westralian Superbasin along the northwest margin. As in the Late Cretaceous, deposition was carbonate-dominated, except for canyon fills in the Perth Basin.

In the Perth Basin the main record of early Cenozoic deposition is around Perth. A drowned river valley — an ancestral 'Swan River' — or submarine canyon that once connected with the present-day Perth Canyon west of Perth (see *Submarine canyons*) was filled by a shallow-marine to estuarine siltstone and sandstone (Kings Park Formation). This unit was deposited during the oldest of the 20 marine transgressions recognized in the Cenozoic along the southern margin of the continent (Fig. 10).

In the Northern and Southern Carnarvon Basins there was an extensive shelf covered with carbonate rocks (calcareous siltstone and claystone) with shoals nearer shore (bioclastic calcarenite and calcisiltite). Further north in the central to northern North West Shelf (Browse and Northern Bonaparte Basins) fine-grained carbonate rocks (Hibernia Formation) were deposited in quiet offshore conditions. Disconformities between the Lambert, Dockrell, and Wilcox Formations in the Westralian Superbasin separate Cycle 1 into 1a and 1b, and are attributed to widespread submarine erosional events or prolonged depositional hiatuses, rather than uplift and subaerial erosion.

Cycle 1 strata may be present along the State's southern margin where there is an unconformity

Figure 10. Cenozoic depositional cycles on the southern margin showing third-order sequences and their mnemonics, southern Australian regional transgressions (after McGowran et al., 2004, fig. 5), and Western Australian regional events

K/T boundary

The K/T (Cretaceous–Tertiary) — now more usually referred to as the K/Pg (Cretaceous–Paleogene) — boundary dated at 66 Ma marks the most recent of the five great mass extinction events in Phanerozoic Earth history. At this boundary about 75% of all species became extinct, including the dinosaurs and ammonites. The K/T extinction has attained prominence because of the concentration of iridium in the K/T boundary, a very thin layer of sedimentation found in various parts of the world. Iridium is extremely rare on Earth, but is abundant in asteroids and comets. Did a massive asteroid impact cause the mass extinction through wildfires, acid rain, and a temporary nuclear winter? The subsequent discovery of the Chicxulub Crater on the Yucatan Peninsula lends credence to this. The eruption of the Deccan Traps flood basalts in India was also posed as the cause, by similarly producing dust clouds and a greenhouse effect. Still others argue for multiple causes. The jury is still out on the cause of the mass extinctions.

above the Cretaceous: the earliest Cenozoic rocks are of late Paleocene age (see box, *Tertiary is no more*). In Jerboa 1 (Fig. 5) the hiatus is more marked, with middle Eocene Hampton Sandstone resting on Cenomanian sandstone and siltstone (Madura Formation).

The climate was warm temperate in the early part of this cycle and later became hot in the north. Within this broad trend, a cool phase has been recognized in the Northern Carnarvon Basin in the early Eocene, which may equate to a global cooling episode. The distribution of planktonic foraminifers on the North West Shelf suggests that a warm south-flowing counter-current (analogous to the present-day Leeuwin Current) was established at this time (Fig. 11).

Cycle 2: middle Eocene – early Oligocene

The hiatus between Cycles 1 and 2 coincides with extensive plate reorganization and an acceleration in the northward drift of the continent at 43 Ma.

Cycle 2 is more widespread and is the first cycle to be recorded on the southern margin of Western Australia (although Cycle 1 strata do occur further east in the Otway Basin in Victoria, and on the Naturaliste Plateau). Onshore it can be recognized in the Southern Carnarvon, Canning, Gunbarrel, and Eucla Basins, and offshore in the Perth Basin and Westralian Superbasin. Cycle 2 saw the resumption of carbonate deposition, with calcarenites in more proximal (presently nearshore to onshore) parts of Western Australia, and calcareous siltstones to mudstones in more distal (presently nearshore to further offshore) regions of Western Australia and adjoining offshore areas.

Shallow-shelf carbonate sedimentation commenced in the offshore Perth Basin with the deposition of calcareous siltstone (Porpoise Bay Formation) and then calcarenite (Challenger Formation). The latter also contains chert (see below), but the source of the Eocene chert Aboriginal artefacts that are widespread in the Perth Basin is more likely to be from the southern coast (Plantagenet Group, Norseman Formation, Wilson Bluff Limestone).

In the Northern and Southern Carnarvon Basins, Cycle 2 consists in onshore areas of a coarse-grained calcarenite (Giralia Calcarenite) notable for large, ferruginized discoid foraminifers. The ferruginization suggests contemporaneous ferricrete development in basin hinterlands. The calcarenite grades offshore into calcareous siltstone (Walcott Formation), and eastward into a nearshore to fluvial sandstone (Merlinleigh Sandstone) that contains sparse marine fossils and some fossilized plant material, notably *Banksia* cones. Fluvial sediments in the Canning and Gunbarrel Basins (Lampe Formation), preserved mostly as isolated hill-cappings, may also belong to Cycle 2.

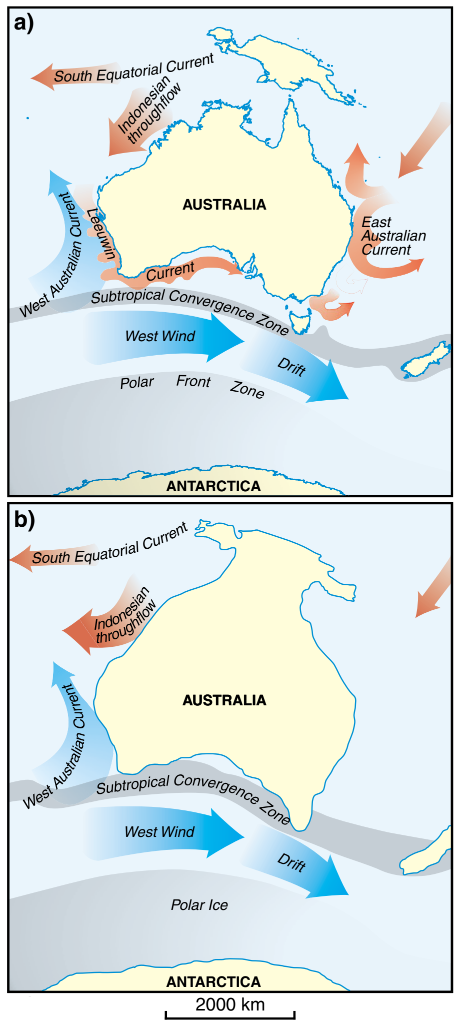
Further north in the Westralian Superbasin (Browse and Northern Bonaparte Basins) carbonate deposition continued, and sedimentation may have been continuous between Cycles 1 and 2.

A widely recognized middle to late Eocene warming ('Middle Eocene Climatic Optimum') is attested by a widespread larger foraminifer fauna along the North West Shelf, although whether the climate was 'tropical' or 'warm temperate' is debatable.

The Wilson Bluff transgression at c. 42 Ma has been taken to mark the beginning of the geologically modern southern Australia. This transgression is the Australian equivalent of the widespread Indo-Pacific Khirthar transgression and was accompanied by a warming of the oceans as shown by the appearance of larger foraminifers.

Cycle 2 is present in the Eucla Basin — Plantagenet Group (Werillup and Pallinup Formations) and lower Eucla Group (Hampton Sandstone and Wilson Bluff Limestone) — and in paleovalleys in the Norseman–Kalgoorlie area (Eundynie Group, Werillup Formation, Perkolilli Shale, Wollubar Formation). Broadly speaking, the western part of the basin was a clastic-dominated shelf (Plantagenet Group), and the east was a carbonate-dominated shelf above a basal sand (Eucla Group), with the Norseman–

Figure 11. Development of the Leeuwin Current in (a) warm (e.g. present-day) and (b) cool (e.g. last ice age) times. The Leeuwin Current comes from the warm South Equatorial Current via the Indonesian throughflow. During cooler periods the West Wind Drift and Subtropical Convergence move north and the Leeuwin Current is shut down (after McGowran et al., 2004, fig. 6)



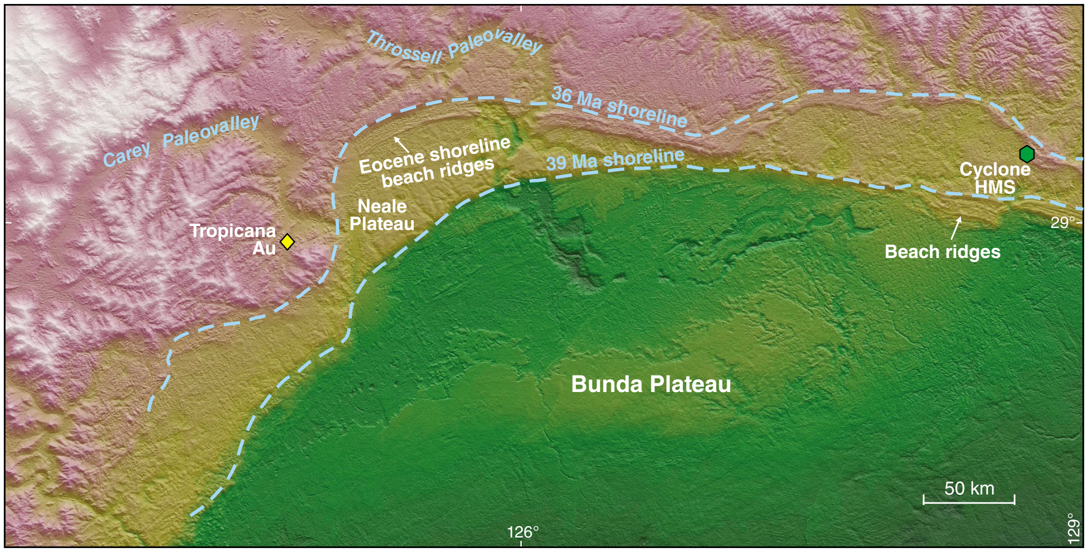


Figure 12. The marine Tortachilla and Tuketja transgressions with associated heavy mineral sand deposits. Shuttle Radar Topography Mission (SRTM) image of the western Eucla Basin

The hiatus between Cycles 1 and 2 coincides with extensive plate reorganization.

Kalgoorlie area an intermediate marine embayment (Eundynie Group) grading north to fluvial deposits in a series of paleovalleys, such as the Lefroy and Cowan Paleovalleys (Fig. 9). The basin was a simple epeiric ramp with an open arcuate coast in the east, but a more complex, partly barred and embayed archipelago in the west.

In the west, sandstone, siltstone, and lignite (Werillup Formation) with local limestone (Nanarup Limestone Member) are overlain by sandstone and siltstone (Pallinup Formation) with widespread spongolite (Fitzgerald Member). The limestone contains a rich fauna of foraminifers and bryozoans, of which larger foraminifers (*Asterocyclina*) suggest that the proto-Leeuwin Current may have reached this far south. The southern extension of this current is confirmed by estimated water temperatures of about 20° C from Miocene limestones — warmer than expected for a mid-latitudinal position even during the 'Miocene Climatic Optimum'. Spongolite is widespread in the upper Eocene succession, and is used as a building and facing stone. Lignite is present in the lower part of the succession along the south coast (at Coal Seam Beach near Denmark, in the Fitzgerald River National Park, and around Esperance) but is nowhere as extensively developed as the lignite and brown coal deposits of the same age in Victoria that produce 85% of that State's electricity.

A similar mix of sediments was laid down in marine embayments along the margin of the Eucla Basin in the Norseman to Kalgoorlie area and south of Zanthus (Norseman Formation, Princess Royal Spongolite Member). These

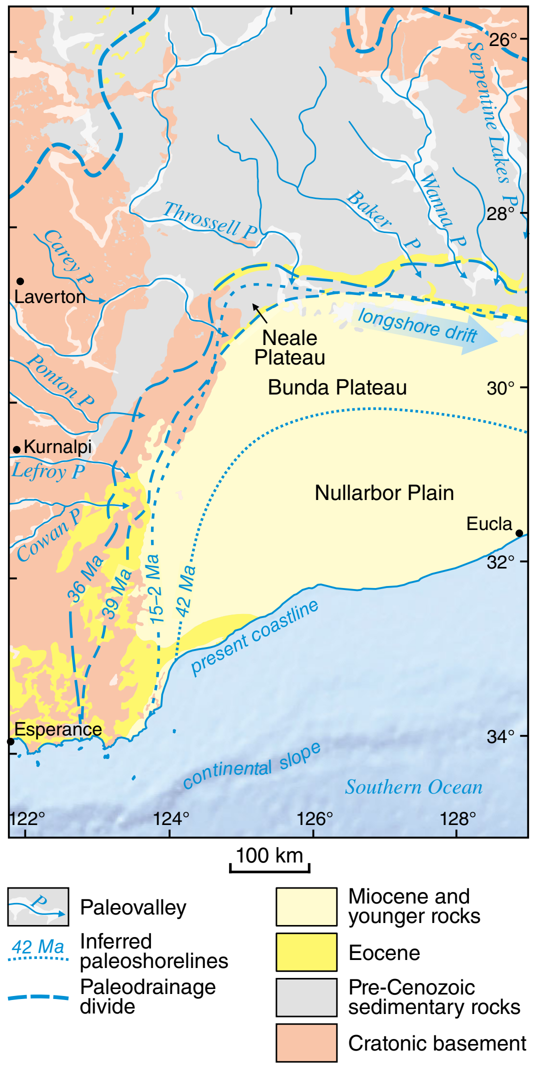


Figure 13. Early Cenozoic shorelines in the Eucla Basin (modified from Hou et al., 2011, fig. 1)

embayments reverted to paleochannels after transgressions peaked, and remained as channels in the Miocene.

A basal sandstone (Hampton Sandstone) was deposited in the central Eucla Basin in the wake of the transgression, followed by chalk and bryozoan calcarenite with chert in places (Wilson Bluff Limestone). This pair of units occurs throughout the western and central Eucla Basin and is present offshore in Jerboa 1. Fine-grained glauconitic calcarenites were deposited in the Bremer Sub-basin of the Bight Basin at this time.

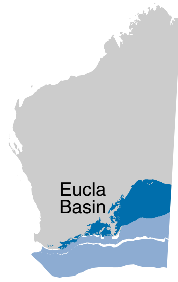
Four third-order marine transgressions — Wilson Bluff, Tortachilla, Tuketja, and Tuit — have been recognized in the Eocene, with sequence-bounding unconformities at around 42, 39, 36, and 34 Ma, respectively (Fig. 10). At their peaks, the transgressions formed extensive coastal barrier deposits along the basin margins (Fig. 12). Along the northern and eastern margins, particularly in South Australia, these are largely preserved in the subsurface and locally are highly prospective for heavy mineral sands. Mineralized shoreline deposits developed primarily during the Tortachilla to Tuit transgressions (Fig. 13). Longshore drift was eastward, and there was differential uplift of the western side of the Eucla Basin compared to the eastern side of the basin in South Australia (see *Tilting of Australia*), so comparatively fewer shoreline deposits appear to be preserved along the western margin.

The Eocene Princess Royal Spongolite Member rests on benches eroded into bedrock at 270–280 m ASL in the Lefroy and Cowan Paleovalleys. A long-recognized bench on Mount Ragged has a similar elevation at 260–280 m (Fig. 14). All were probably cut in the Tuketja transgression. They may equate to the scarp at 140 m ASL recognized in the northeastern Eucla Basin in South Australia, suggesting tilting of the basin (see *Tilting of Australia*).

Chert horizons and spongolite are local examples of widespread silica production in all the oceans at this time. Chert of this age is also in the Westralian Superbasin. Abundant siliceous sponge spicules are recorded in Brecknock 1 in the Browse Basin. The abundance of chert may have been due to the warm humid climate of the 'Middle Eocene Climatic Optimum' resulting in enhanced weathering and runoff bringing more silica into the ocean.

A period of transition: early middle Oligocene

The break between Cycles 2 and 3 spans the early and middle Oligocene, and marks one of the more important series of events in the evolution of modern Australia: the end of the passive margin phase on the North West Shelf and the start of an active collisional margin, as the Australian Plate collided with the plates of southeast Asia. On the western margin there



The break between Cycle 2 and Cycle 3 marks the end of the passive margin phase on the North West Shelf.

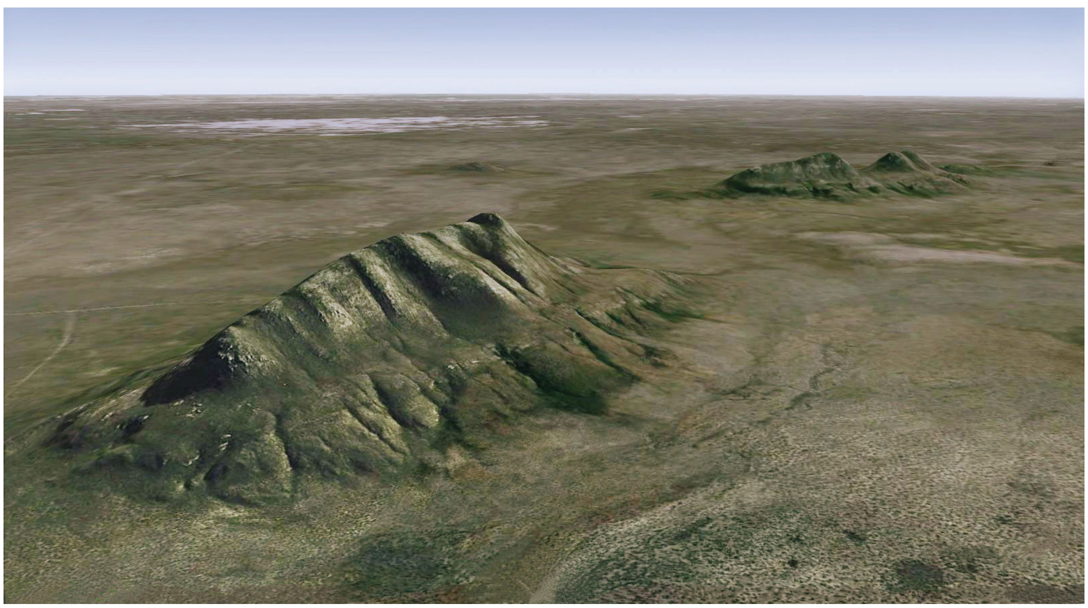


Figure 14. Mount Ragged, a Precambrian inlier at the eastern end of the Bremer Sub-basin, Bight Basin. Peak is at 593 m ASL, the bench surrounding the central ridge is at 260–280 m ASL, and the plateau surface at ~150 m ASL. Attribution: Google Earth, 2014 Cnes/Spot Image, Image 2014 Digital Globe, date of imagery 2003

was a major phase of duricrust formation in the onshore Southern Carnarvon Basin, and deposition did not resume until the late Oligocene. In the Westralian Superbasin there was a hiatus in sedimentation over the entire North West Shelf that extended through the early and middle Oligocene, and until the beginning of the Miocene in the Browse and Northern Bonaparte Basins.

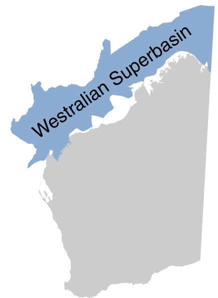
Along the southern margin of Western Australia uplift and emergence took place during the early and middle Oligocene. Emergence must have been remarkably uniform as the same brachiopod-rich bed is found at the top of the Eocene Wilson Bluff Limestone in caves 60 km apart.

Cycle 3: late Oligocene – middle Miocene

Cycle 3 is widespread in Western Australia, being well developed along the southern and western margins of the continent. Much of the prograding of the carbonate shelf in the Eucla and Northern and Southern Carnarvon Basins took place during Cycle 3, whereas the bulk of carbonate buildup in the Northern Bonaparte Basin had been in Cycles 1 and 2.

In the Cape Range region (Fig. 15) of the onshore Northern Carnarvon Basin, deposition was carbonate-dominated, with the upper Oligocene to middle Miocene Bullara, Mandu, Tulki, and Trealla Limestones laid down as a shallowing-upward succession from calcilutite and marl to calcarenite, calcirudite, and coralgal limestones. The units can be traced offshore where they are locally more than 1 km thick. Further north, in the Browse and Northern Bonaparte Basins (of the Westralian Superbasin), marls and claystone (Cartier Formation) and an overlying (unnamed) limestone were deposited. At this time calcarenite (Stark Bay Formation) was deposited offshore in the Perth Basin.

Quartzose calcarenites and calcareous sand-stones deposited as coastal barrier sands



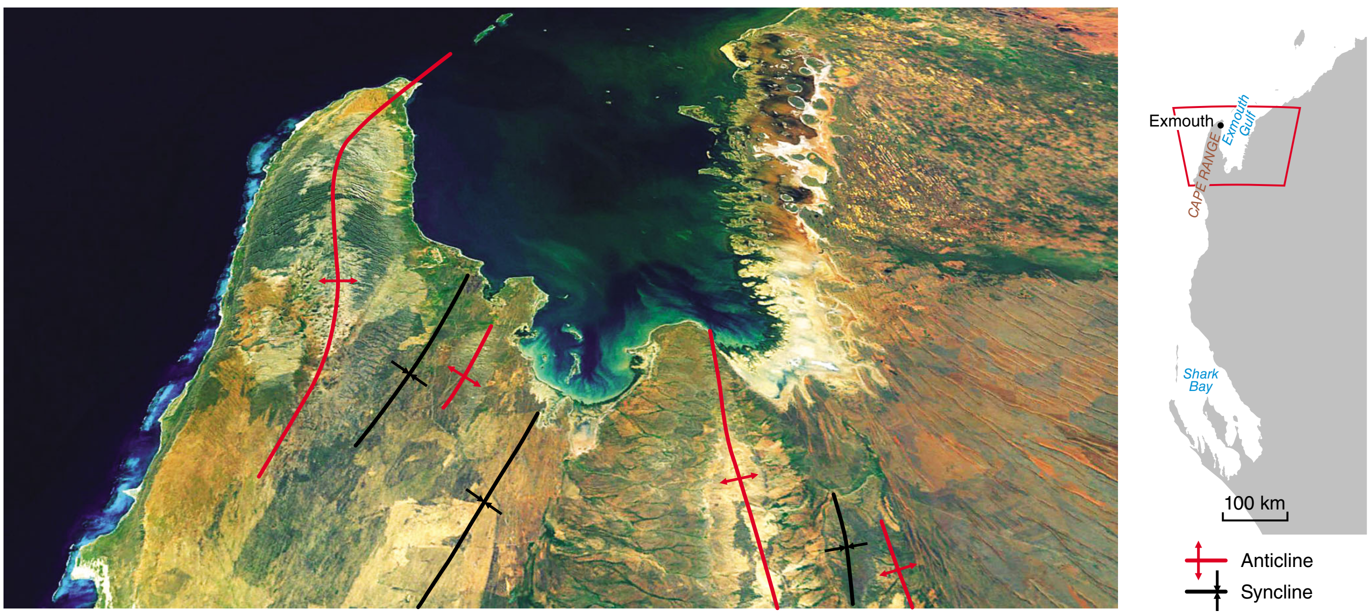


Figure 15. Oblique satellite view north over (from west) Cape Range, Rough Range, Giralia, and Marrilla Anticlines. Wide supratidal flats fringe the east side of Exmouth Gulf, and encroach on older dunes formed 15 000–20 000 years ago. National Aeronautics and Space Administration (NASA) World Wind Image

Shothole Canyon, Cape Range

(Pilgramunna Formation) and then dunes (Vlaming Sandstone) formed along the crest of the Cape Range Anticline above locally reefal limestone in the middle and late Miocene. They extend northward (as the Bare Formation) along linked emergent structural highs to the north of Barrow Island, and owe their presence to tectonic inversion along the Cape Range Fault and linked structures as northwest Australia collided with Indonesia. When this happened, a series of anticlines — the 'coastal anticlines' (of which Cape Range Anticline [Fig. 15], Giralia Anticline, and offshore Barrow Island are the largest) — developed as drapes over upthrust fault blocks. This was due to reverse movement on underlying normal faults as extension

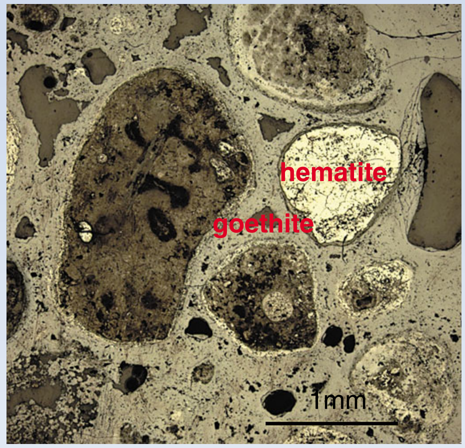
Giant iron resources in old river systems

Goethite–hematite channel iron deposits (CID) are one of the most important sources of iron ore in Western Australia, second only to the deposits hosted in Neoarchean–Paleoproterozoic banded iron-formations (BIFs). Channel iron deposits contain about seven billion tonnes of iron ore, representing about 40% of the total iron resources in the Hamersley region. CID generally have lower iron grades compared with enriched BIF deposits (56 to 58 wt% Fe), with more aluminium (1.5–2.7 wt% Al_2O_3) and silica (3.2–4.6 wt% SiO_2). Despite the lower iron grades the CID represent an attractive target for exploration as the ores are located close to the present surface and the phosphorus content is generally lower than in BIF-hosted ores (~0.03 wt% P compared with >0.07 wt% P). The two best-known examples of CID in Western Australia are deposits along the Robe River in the west of the Hamersley region, and Yandi, a series of deposits located along Marillana Creek in the east (Fig. 16). Elsewhere, CID are rare, with some large deposits known in Kazakhstan.

The origins of CID are unusual; these giant deposits formed from supergene processes that involved repeated cycles of weathering and erosion during the Miocene. At this time, the climate of the Hamersley region was wetter, being warm to tropical. The land surface was well vegetated with swamp-type plant communities covering a tectonically stable elevated plain locally dissected by meandering river systems. The wet climate meant that outcropping BIFs were deeply weathered, with thick overlying goethite–hematite laterites. Soil creep released goethite fragments from the laterites downhill. In more gently sloping terrains these fragments were consolidated and coated by a rind of new goethite growth. In some instances, the goethite cores and outer coatings were exposed to bush fires and the goethite dehydrated to hematite. Subsequent transport and deposition of these materials led to further coating of hematite cores by goethite. Large river systems transported the iron-rich pelletoids and ferruginized wood fragments and deposited them within channels. Iron-rich groundwaters passed through the channels and precipitated goethite cement and replaced wood and matrix material, thereby enriching the iron content of the CID. Absolute dating of the goethite cements at Yandi suggests that the final cementation process took place between 20 and 5 m.y. ago at progressively deeper horizons in the CID, in reaction to the gradual lowering of the groundwater–atmosphere interface associated with the aridification of Western Australia during the Neogene.

In hand specimen, horizons of CID display iron-rich spherical ooids that have a goethite or hematite nucleus and a vitreous goethite cortex. Ooids are commonly 0.5 to 2 mm in diameter, but can be larger (2–10 mm), when they are termed pisolites or pisoids. In contrast, peloids are fragments of fine-grained goethite that typically display no internal structure. The ooids, peloids, and goethite-replaced wood fragments are cemented by goethite, clay, and carbonate minerals. Fragments of BIF are rarely preserved. CID are horizontally bedded and massive. Many deposits are underlain by lignite or lignitic clays, and metre-thick clay pods are locally abundant within CID horizons.

Paleochannels can be up to 100 m thick and several km wide. The longest example, extending for about 150 km, is the Robe paleochannel (highlighted in Fig. 16).



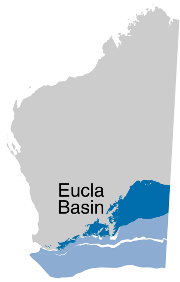
Hematite ooids cemented by goethite (reflected light photomicrograph)

Locally, these river systems may incise their way into exposures of Archean granite, metasedimentary rocks, and metavolcanic basement rocks and the overlying CID then typically reflect the composition of the basement rocks that the channel system traverses.

The present geomorphic forms of CID vary. Some deposits, such as Caliwingina, are concealed beneath layers of unconsolidated Quaternary sediment. Elsewhere, CID are exposed level with the surrounding land surface (e.g. the Yandicoogina deposit). In the Robe River area the CID displays an impressive 'inverted' topography, where the paleochannel stands above the surrounding land surface. This inverted position is the result of the rapid erosion of softer or more friable surrounding rocks, compared with the more-resistant cemented CID.

Paleochannels and mesas, Robe River region

Billions of tons of CID are found in paleodrainages in the Hamersley region.



changed to compression, and crestal areas emerged from the shallow marginal waters of Western Australia. The reverse movement has generally been considered to be Miocene and later ('Neogene inversion'), although there are indications (thinning or absence of Cretaceous rocks over anticline crests) that some anticlines were formed as early as the Cretaceous and reverse movements began much earlier.

The extensive carbonate deposition in the Cape Range area probably reflects a time of maximum transgression during the Miocene, coinciding with the warm peak of the 'Miocene Climatic Optimum'. The warming is attested by the presence of larger foraminifers in some units. This was probably also a time of intense weathering, as shown by the billions of tonnes of channel iron deposits (CID) of the Robe Pisolite and the Poondano and Marillana Formations found further inland in paleodrainages in the Hamersley region (Fig. 16; see box, *Giant iron resources in old river systems*). CID are rare except in the Pilbara, and their origin remains poorly understood even after 50 years of mining. They are sparsely fossiliferous except for charcoal and ferruginized wood fragments, which form cores to goethite peloids, contain little terrigenous contamination, and probably formed in swamp-like, but poorly vegetated, very low pH conditions. Residual and fluvial to sheet-flood sandstone formed a widespread blanket over much of the onshore Southern Carnarvon (Pindilya Formation) and Perth (Victoria Plateau Formation) Basins.

In the Eucla Basin carbonate rocks characterize Cycle 3 (the Abrakurrie and Nullarbor Limestones of the upper Eucla Group) although marginal-marine (Colville Sandstone) to fluvial (Plumridge Formation) sandstone and mudstone accumulated along the northern margin of the basin. Strandline sands are locally significant, and are of economic interest in South Australia. In the basin hinterland, dolomitic (Cowan and Gamma Island Dolomites) and fine-grained clastic (Revenge Formation) rocks accumulated in the Cowan and Lefroy Paleovalleys.

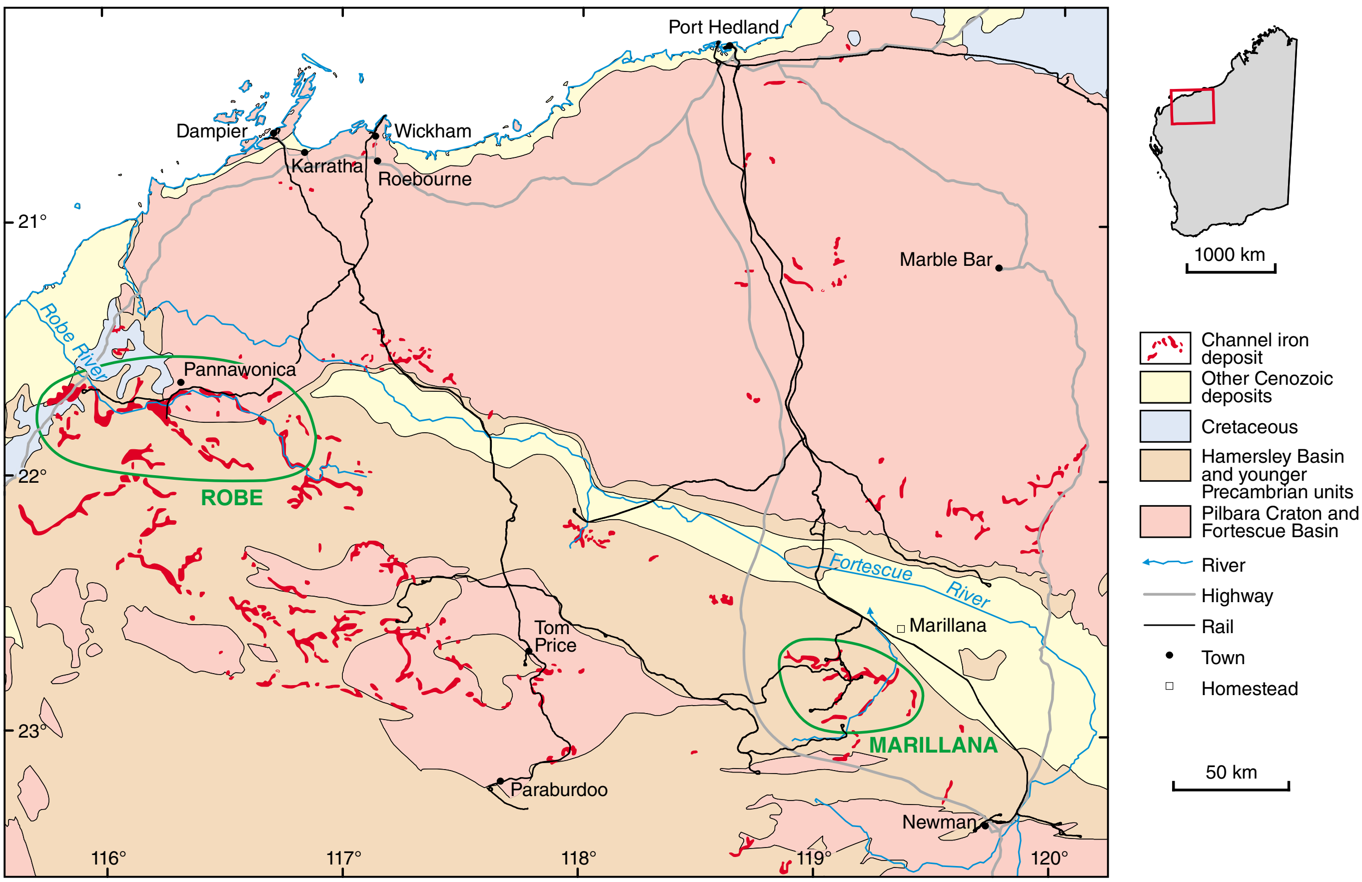


Figure 16. Distribution of channel iron deposits in the paleodrainages in the Pilbara. The positions of the major Robe and Marillana CID are indicated (after Morris and Ramanaidou, 2007, fig. 1)

The succession over the main part of the Eucla Basin was initially of bryozoal calcarenite (Abrakurrie Limestone) formed at depths of about 100 m, with a marked transition from initially cool to later warmer conditions (Fig. 17). This was followed after a slight disconformity by an algal limestone member, then a hard, abundantly fossiliferous calcarenite (Nullarbor Limestone) that forms the main surface of the Eucla Basin (and thus the Nullarbor Plain) and the upper part of the coastal cliffs along the Great Australian Bight. Fossils include the larger foraminifers *Flosculinella bontangensis* and *Marginopora vertebralis*. Deposition was on a broad epeiric ramp in a shallow warm sea that extended the width of the basin and some 450 km north to south, marking the maximum Cenozoic transgression in Western Australia and corresponding to the Bairnsdalian transgression in southeastern Australia at c. 13 Ma. The warm conditions, about 20° C, are attributed to the warm proto-Leeuwin Current, as there is an eastward-cooling gradient apparent from fauna and micritic envelopes, and the basin was located at middle latitudes rather than in a tropical position in the Miocene.

Offshore, along the southern margin, marine carbonate rocks were deposited in the Eucla Basin during Cycles 3 and 4. Neogene volcanic rocks have been identified from seismic sections and dredging in the Bight Basin, and volcanic cones have been identified from sea-floor mapping along the continental slope near the South Australian border, as well as along the western margin, west from Carnarvon and Kalbarri.

Cycle 4: late Miocene – Holocene

Most of Western Australia was emergent, subject to increasingly, but not consistently, arid conditions, and with some sedimentation along the coastal regions. Carbonate sedimentation continued in the offshore Westralian Superbasin during Cycle 4, and there was accelerated subsidence along the North West Shelf after 10 Ma, and more than 1000 m of carbonate sediment was deposited on the outer shelf. Substantial thicknesses of Quaternary eolian and coastal deposits also built up adjacent to the Cape Range Anticline — 300 m beneath the Muiron Islands for example. During the Neogene and Quaternary, discontinuous reef buildups developed along the western margin from the Houtman Abrolhos Islands northward to Ningaloo, Rowley Shoals, Scott, and Ashmore Reefs on the North West Shelf itself, with late Quaternary subsidence being an important control on reef growth (Fig. 18).

In the Westralian Superbasin the late Miocene to Holocene sequence has been little sampled and is poorly known. There are no major breaks in Cycle 4, but here, and elsewhere, there are minor breaks in the Quaternary succession, reflecting the interplay between glacials and interglacials. In the offshore Northern Carnarvon Basin calcilutite and calcisiltite (Delambre Formation) developed on the outer shelf and slope. Equivalent strata in the Browse and Northern Bonaparte Basins are mainly marl and calcilutite (unnamed units). More than 1000 m of carbonate sediment built up on the outer shelf including reef buildups, for instance, at Scott and Ashmore Reefs. The base of Cycle 4 is strongly diachronous, from late Miocene in the south to early Pleistocene in the north. This is a consequence of the continuing collision between the Australian Plate and the southeast Asian plates, causing large-scale downwarping of the western margin and uplift in the Sunrise area of the offshore Northern Bonaparte Basin.

In the Cape Range area of the Northern Carnarvon Basin eolian sandstones (Exmouth Sandstone) and bioclastic calcarenite and coralgal limestone (Bundera Calcarenite) onlap the range.

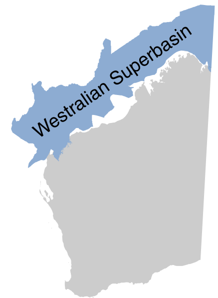


Figure 17. Baxter cliffs, Nullarbor Plain, looking east into South Australia

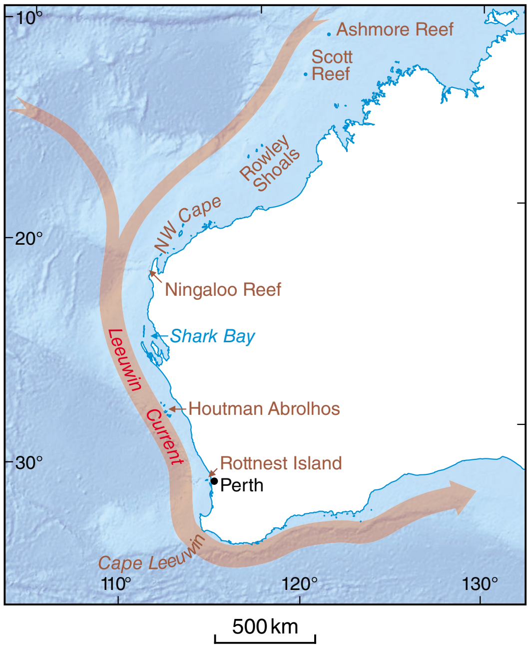


Figure 18. Location of Ashmore and Scott Reefs, Rowley Shoals, Ningaloo and Houtman Abrolhos reefs, and the present-day Leeuwin Current (after Collins, 2002, fig. 2)

On the west side of the anticlinal range, four wave-cut terraces were cut in a series of eustatic transgression and regression cycles during the Quaternary, each terrace warped and elevated progressively with age (Fig. 19). Shoreline and eolian deposits cap each terrace; the youngest, lowest (Tantabiddy) terrace has been dated at 123 ka. The progressive warping and uplift of the terraces demonstrates the ongoing growth of the Cape Range Anticline in the Quaternary.

Further south, around Shark Bay, there is a complex mosaic of Quaternary carbonate-dominated marine to supratidal deposits above older Quaternary quartzose sandstone. Units include quartzose, eolian, and residual sandstone (Peron Sandstone), nearshore to coastal bioclastic limestone to calcarenite (Dampier and Bibra Limestones), eolian calcarenite (Tamala Limestone, see below), and a coquina composed almost solely of stunted *Fragum erugatum* shells (Hamelin Coquina). When lithified, this coquina has been quarried and used as a striking building stone. The world-famous Hamelin Pool stromatolites grow on these shallow-marine deposits around the shoreline of Hamelin Pool in the southeast corner of Shark Bay (Fig. 20).

Further south again, in the Perth Basin, the rocks of Cycle 4 range from marine-shelf calcarenites — the oldest being marine-shelf calcarenites of late Miocene and Pliocene age encountered offshore from Perth (Wadjemup Formation) — below Pliocene shoreline deposits (Ascot Formation), Pleistocene clays (Guildford Formation), and Quaternary eolian and residual sands, shoreline deposits, and swamp and lacustrine deposits. The Quaternary sands and calcarenites (Kwinana Group) form a series of shallow-marine, shoreline, and dune deposits. One of the most widespread

Pleistocene Tamala Limestone fringes the coast from Shark Bay round to Esperance on the south coast.

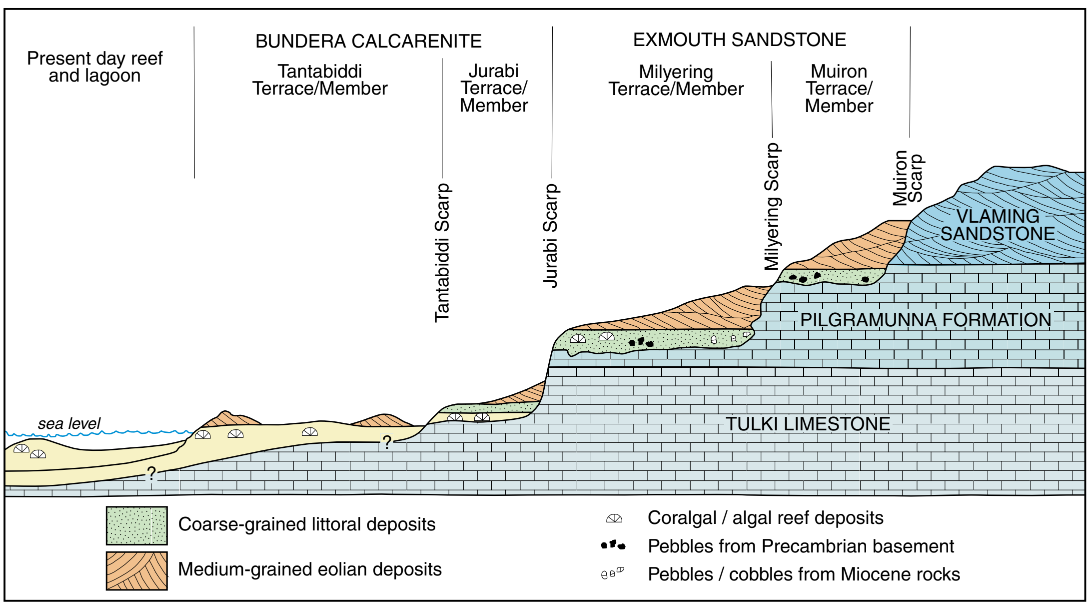


Figure 19. Relationships of four wave-cut terraces on the west side of Cape Range (from Hocking et al., 1987, fig. 115)

Figure 20. Stromatolites exposed at low tide in Hamelin Pool, Shark Bay. Tops range from 20 to 40 cm across

Figure 21. Tamala Limestone at Womerangee Hill on the Zuytdorp Cliffs. The cliffs, about 270 m high here, mark a recent fault-line scarp. Figure for scale

units is the middle and late Pleistocene Tamala Limestone ('Coastal Limestone') of shoreline and dune sands that extends from Shark Bay and the Zuytdorp Cliffs (where they are >300 m thick at Womerangee Hill; Fig. 21) to the Esperance area on the south coast. Lithified columns of Tamala Limestone, possibly around tree roots, form the famous Pinnacles tourist attraction in Nambung National Park (see box, *The Pinnacles — silent sentinels*). Correlative units are present in the Pilbara (Bossut Formation) and in southeastern Australia.

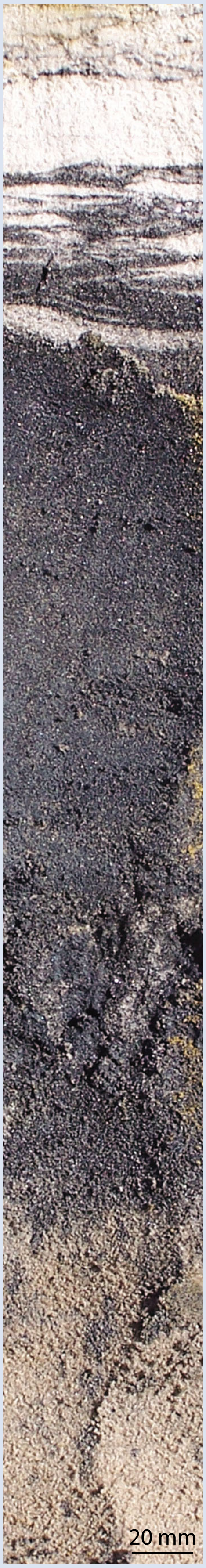
In terms of resources, the Swan Coastal Plain is host to several major heavy mineral sand deposits of Pliocene to Quaternary age (see box, *Strandlines and heavy mineral sands* and Fig. 22). Pliocene sands (Yoganup shoreline) in the Bunbury area are the oldest, the others (Waroona, Munbinea, and Eneabba shorelines) being Quaternary. Between Geraldton and Kalbarri, west of the garnet-rich Northampton Province, shoreline facies of the Tamala Limestone host world-class garnet sand deposits.

Along the southern margin, major headward erosion of the Miocene limestones of the Eucla Basin formed a prominent sea cliff extending continuously across the Great Australian Bight (Fig. 17) from near Israelite Bay east to Head of the Bight in South Australia. At more than 900 km in length this is Australia's longest single cliff scarp. On the Roe Plains in front of the sea cliff between Cocklebiddy and Madura, richly fossiliferous calcarenites (Roe Calcarenite) were laid down during a Pliocene transgression, with the abundant tropical fauna indicating deposition during a warm Pliocene highstand. A similar plain is present in front of the westernmost portion of the cliff, the Wylie Scarp, around Israelite Bay.

Paleovalley deposits of Cenozoic age are important for groundwater supplies for industrial

The Swan Coastal Plain is host to major heavy mineral sand deposits of Pliocene to Quaternary age.

use (see *Groundwater — a vital resource*) and include evaporite deposits (Polar Bear and Roysalt Formations). Permian sedimentary rocks indicate that some paleovalleys formed as long ago as the earliest Permian Gondwana glaciations, whereas others developed in the Mesozoic or maybe as late as the Eocene, based on the ages of infill material. The valleys show complex patterns of infill, locally with multiple inset valleys (now infilled) cut into older infill or basement, occurring in broad valleys up to 50 km across. Those with external drainage, such as in the Murchison region, are less saline than the stagnant valleys in the Eastern Goldfields and central Yilgarn regions, which are not flushed because of relative uplift of their lower reaches. Such uplift is related to the uplift of Australia's southern margin as the continent collides with the Indian Plate to the north.



Strandlines and heavy mineral sands

The Swan and Scott Coastal Plains in southwestern Western Australia are dominated by late Cenozoic marine–estuarine, beach, and dune deposits that together outline a series of near-parallel strandlines extending from the present shoreline to 70 km inland and 115 m height, each a response to changing sea levels. These strandlines host economic concentrations (1.5 to 20% total heavy mineral) of ilmenite, rutile, zircon, monazite, and xenotime, with less significant garnet, kyanite, and staurolite, and form the nucleus of the State's heavy mineral sands (HMS) industry.

In the far south on the Scott Coastal Plain, four strandlines are recognized: the Donnelly line, running along the inboard edge of the plain, and the successively ?younger, parallel Warren (or Scott), Milyeaanup, and Quindalup (or Ledge Point) lines. The last is in modern beaches and dunes, and so is correlated with the Quindalup line on the Swan Coastal Plain. On the southern Swan Coastal Plain, the oldest important strandline is the Yoganup–Waroona line at the base of the Darling and Whicher Scarps, followed by the younger Capel line, within the Spearwood Dune System, and finally the Quindalup line, within modern beaches and dunes. The Eneabba and Munbinea–Gingin strandlines dominate the northern Swan Coastal Plain, immediately adjacent to the Gingin Scarp.

Zircons from HMS deposits in the Swan Coastal Plain are dominated by grains with U–Pb ages of 1100–1300 Ma and 500–600 Ma, similar to detrital zircon ages from underlying Cretaceous sedimentary rocks. These dates suggest that most of the infill of the Perth Basin was originally derived from the Albany–Fraser or Pinjarra Orogens, rather than the Yilgarn Craton to the east.

Further north, high-grade almandine garnet deposits are present in dune systems at Port Gregory, 85 km northwest of Geraldton, behind and north of Hutt Lagoon. Garnet was derived from garnet granulites of the nearby Neoproterozoic Northampton Inlier. Further north again, zircon-rich sands (up to 23% Zr) extend for 35 km along a strandline near Coburn, just south of Shark Bay.

Two new greenfields HMS provinces have emerged in the southeast and northwest of the State. One occurs along the northern margin of the Cenozoic Eucla Basin, in Eocene and Miocene strandlines, and includes the Cyclone (Wanna Lakes) and Serpentine Lakes deposits. Similar high-grade deposits in South Australia formed by eastward longshore drift of HMS along the basin margin. The second is on the Dampier Peninsula north of Broome. There, the Thunderbird–Argo deposits are large, fine-grained HM concentrations in shallowly dipping, deeply weathered sand units of the Cretaceous shallow-marine Jowlaenga Formation. Smaller, but locally high-grade, HMS deposits are found at James Price Point and at the mouths of the Fitzroy, May, and Robinson Rivers.

Production from HMS during 2013 contributed about 198 000 t of ilmenite, 32 000 t of leucoxene, 211 000 t of zircon, and 342 000 t of garnet. Operating HMS mines are spread along much of the Swan Coastal Plain, with a notable concentration in the Bunbury–Capel region, including Keysbrook, Burekup, Gwindinup, Wonnerup, and Tutunup South, and further north in the Eneabba–Gingin area (Twin Hills, Cooljarloo). Ilmenite ($FeTiO_3$) is the most abundant mineral produced, and much of this is kiln-leached to remove iron and form synthetic rutile (TiO_2).

Figure 22. Strandlines with heavy mineral sands in the Swan and Scott Coastal Plains. Photo (left) shows massive heavy mineral overlain by thin trough cross-bedded layer, Yoganup West pit (photo courtesy Iluka Resources Limited)

Figure 23. Major dunefields in Western Australia (after Pell et al., 1999, fig. 1)

Cycle 4 includes the events of the Pleistocene ice ages. There were no glaciers in Western Australia during the Pleistocene, unlike eastern Australia where mountain glaciers existed in the Eastern Highlands and Tasmania. Instead, the Pleistocene deposits of Western Australia record alternating periods of aridity and humidity, and low and high sea levels, reflecting the glacials and interglacials, respectively.

There are extensive coastal and inland dunefields, the former largely calcareous and the latter quartzose. The inland dunefields (Fig. 23) probably formed during the Neogene and the sands are derived from local bedrock with very little eolian transport. Two distinct generations can be recognized in the onshore Southern Carnarvon Basin:

- an older system now partly lithified and, on top of the Kennedy Range, dissected by headward erosion on the sides of the range;
- a younger non-lithified system last active at 25 to 18 ka.

The Pinnacles — silent sentinels

The Pinnacles, in the Nambung National Park about 15 km south-southeast of Cervantes (Perth Basin), developed from deep differential weathering on the surface of the Tamala Limestone. Much of the residual sand has been blown clear of the limestone columns by persistent winds, commonly exposing abundant calcified fossil rhizoliths (plant roots). Some residual sands with fossil soil horizons are present nearby.

Large taproots penetrated the eolian dune deposits while they were stabilized by vegetation and lithification. Dissolution and reprecipitation of calcium carbonate around the taproots alternated between wet winters and dry summers, thereby preferentially lithifying these areas. A subsoil calcrete developed at the base of the thin humic layer on the surface of the dunes. This was followed by cracking of the subsoil calcrete that allowed preferential leaching of the underlying friable limestone by surface waters. After prolonged weathering, only limestone pinnacles (originally lithified around taproots) remain, surrounded by residual quartz sand from the dune deposit. It has been suggested that very large pinnacles formed around the roots of tuart gums (*Eucalyptus gomphocephala*), and smaller pinnacles around other trees. Aboriginal artefacts (including flakes of chert) have been found in blowout depressions around the pinnacles and, in one instance, cemented to a pinnacle. Foraminifers in the chert indicate that the chert is Eocene in age. Chert artefacts are widespread in the Perth Basin and although chert-bearing rocks occur in the subsurface on the continental shelf, it is more likely that the chert came from the southern coast (Plantagenet Group, Norseman Formation, Wilson Bluff Limestone).

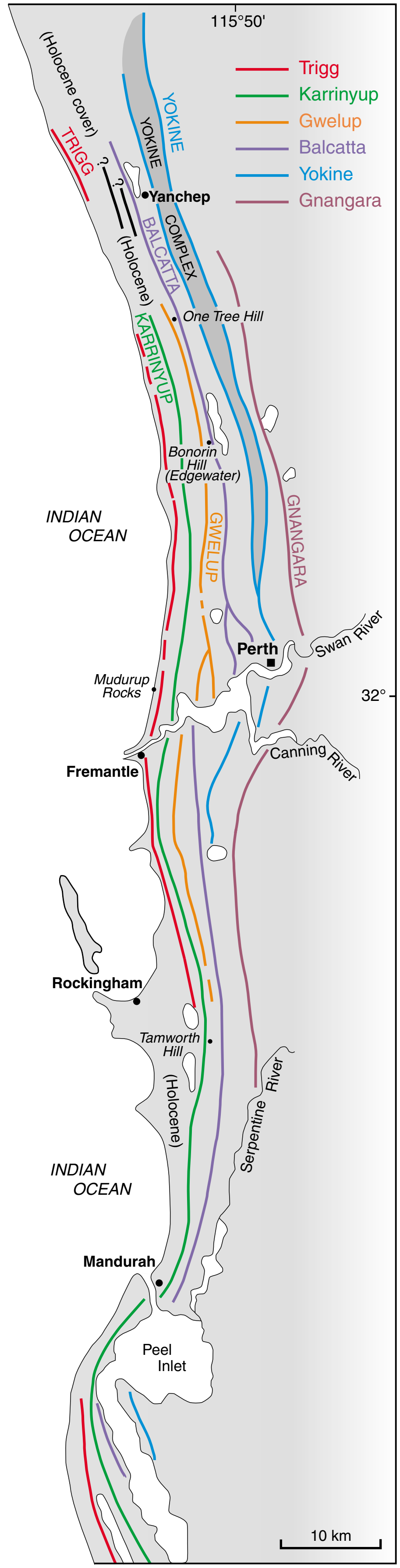
Active coastal dunes of the Quindalup Dune System border the beach along the road into the Pinnacles. A 31.7 × 23 cm egg of the large, flightless, now extinct, Madagascan elephant bird *(Aepyornis maximus)* was found in 1992 buried in one of these Holocene dunes, and was dated at about 2000 years BP. The egg probably drifted on ocean currents from Madagascar rather than having been transported by humans.

There is no reason to assume a different age for the other major unlithified but inactive dune systems (Great Sandy Desert, Great Victoria Desert, and Little Sandy Desert) in Western Australia, although well-vegetated small dunes in the extreme southeast Great Victoria Desert near Ceduna in South Australia are regarded as Holocene (Fig. 23).

The coastal dunes in the Perth region (Fig. 24) are aligned north–south, with the oldest dune system (Gnangara dunes) in the east being perhaps as old as early Pleistocene. All the dunes are of residual origin with the sand coming from weathering of the Tamala Limestone, rather than being transported over a long distance from central Australian deserts.

In the Perth region, shoreline notches and platforms around the coast of Rottnest Island and at the edge of salt lakes on the island show

Figure 24 (far right). Dune trend-lines in the Perth region (after Bastian, 1996, fig. 5)



The treeless plain

The Nullarbor Plain (Nullarbor means 'no trees') covers an area of 200 000 km^2, and lies inland from the single sealed road (Eyre Highway) that connects southern Western Australia to the remainder of Australia. The plain lies in the centre of the Bunda Plateau, which slopes gently from 250 m ASL elevation in the north to 75 m ASL in the Baxter Cliffs and Hampton Range. The extreme flatness of the plateau has been attributed to the uniformity of deposition of the Nullarbor Limestone on an essentially flat early Miocene sea floor over the entire Eucla Basin. However, it is more likely due to the regularity of weathering in preserving the Miocene sea floor. Rain is the principal agent of weathering and acts fairly uniformly over the plateau. There are numerous caves in the limestone underlying the plain, many going down to the watertable. The flooded tunnels in the Cocklebiddy Cave are more than 4 km long.

The aridity and sparse vegetation make the Nullarbor Plain one of the best regions in the world for the preservation and discovery of meteorites and many have been found. The Mundrabilla Meteorite is the largest found in Australia. It consists of several fragments, the largest, at 12.4 t, is now in the Western Australian Museum. The meteorite is an iron meteorite with a very low iridium and very high troilite content.

Because of the flatness of the plain, roads and railways can be built straight. The Trans-Australian Railway line holds the record for the longest straight section of railway in the world (478 km: Ooldea in South Australia to Loongana in Western Australia), and the Eyre Highway contains the longest straight stretch of tarred road in Australia (146.6 km: Balladonia to Caiguna), previously called the 90 Mile Straight. The flat plain is also home to the world's longest golf course, the Nullarbor Links, where the 18 holes cover a distance of 1365 km between Kalgoorlie and Ceduna (in South Australia). Distance between holes averages 66 km and par for the course is 72.

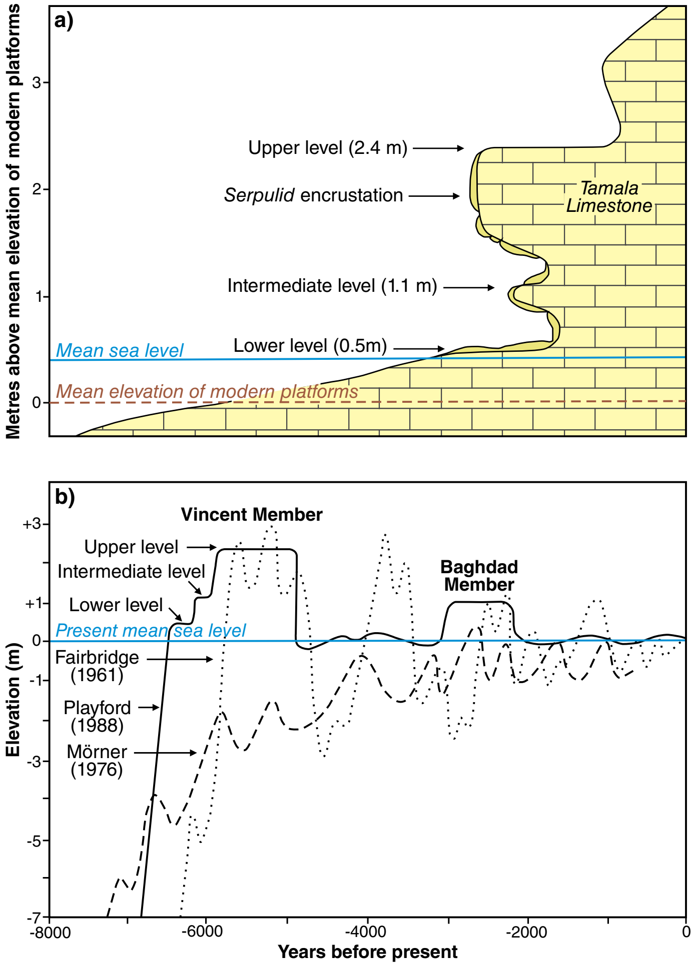
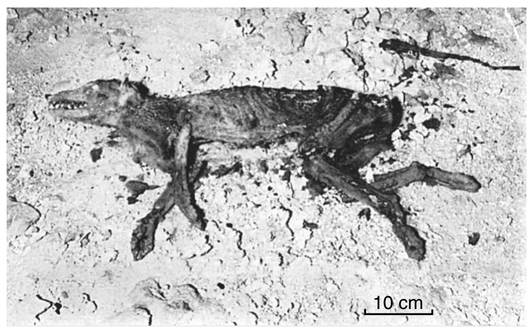


Figure 25. (a) Elevation of shoreline platforms and notches in Tamala Limestone around the margin of the Rottnest Island salt lakes; (b) Relative sea-level curve for the Rottnest area for the past 8000 years, according to Playford (1988), compared with the eustatic curves of Fairbridge (1961) and Mörner (1976). After Playford (1988, figs 50 and 60)

a complex pattern of sea-level change over the past 10 ka that can be correlated with marine shell-bed units (Vincent and Baghdad Members of the Herschell Limestone; Fig. 25). There is some evidence that these sea-level changes are, at least in part, tectonic. The *Acropora*-dominated Rottnest Limestone is a coral reef dated at 132 ± 5 ka when sea level must have been at least 3 m higher than at present. Further south, near Cape Leeuwin, corals in a *Goniastrea*-dominated reef 2–2.5 m above present-day sea level have been dated at 129–125 ka. These occurrences coincide with active reef growth in the Abrolhos Islands (Houtman Abrolhos) at this time (Last Interglacial highstand, 132–117 ka) when sea level may have been 6 m above present sea level. The presence of coral reefs as far south as Cape Leeuwin indicates that the warm Leeuwin Current was active in the Last Interglacial.

Most of the caves in the Miocene limestones of the Nullarbor Plain probably formed in the Quaternary (see box, *A treeless plain*). Caves in the Tamala Limestone are well known in the southwest of the State, especially in the Cape Leeuwin – Cape Naturaliste region, and must have formed in the late Pleistocene. These caves contain well-preserved fossils of the Pleistocene marsupial megafauna (Fig. 26, see adjacent page) that have been extensively studied from Mammoth Cave and Devils Lair, north of Augusta. The extinction of the megafauna has been variously attributed to climate change (increasing aridity) or hunting by humans, and both may be responsible. The extremely dry conditions in caves in the Nullarbor Plain enabled some marsupials to be mummified, one of the best preserved being the thylacine dated at 4600 years found in Thylacine Hole (Fig. 27).

Figure 27 (right). Mummified remains of a 4600 year-old thylacine (Tasmanian tiger) found in Thylacine Hole on the Nullarbor Plain in 1966 (from Lowry, 1970, fig. 41)



Mammals with pouches

Marsupials, or mammals with pouches (marsupiums), diverged from placental mammals at about 160 Ma and the earliest marsupial fossil is recorded from China at about 125 Ma. Marsupials spread rapidly into Europe, North Africa, and South America in the Cretaceous, but eventually became extinct in the northern continents in the Cenozoic, possibly due to adverse climatic influences and competition from placental mammals. Marsupials reached Australia via the Antarctic in the Late Cretaceous or early Paleogene; the oldest known Australian marsupial is *Djarthia murgonensis* from the early Eocene Tingamarra fauna of southeastern Queensland. Interchange continued between Australian and South American marsupial faunas (presumably via Antarctica), perhaps until the separation of South America and Antarctica in the Miocene. In the Pliocene–Pleistocene (~3 Ma) the Isthmus of Panama formed linking North and South America and led to the Great American Interchange with placental mammals from the north moving south and opossums invading Central and North America, so that nowadays marsupials are found only in Australia, New Guinea, and the Americas. The relative lack of large predators in Australia allowed the group to radiate in both size and body form, resulting in a diverse marsupial megafauna including the giant kangaroo *Sthenurus* (Fig. 26) and *Diprotodon*, a large (up to 2 m) browsing herbivore closely related to wombats, about 1.6 million years ago. Large mammals (e.g. mammoths, sabre-toothed cats) were common during the Pleistocene ice ages. Worldwide this megafauna became extinct by about 10 ka: the reason is widely debated and controversial, with climate change or hunting by humans being considered as possible causes.

***Figure 26.** Examples of some now-extinct vertebrates found as fossils in the caves of the southwest of Western Australia. Vertical scale bar is 2 m (after Merrilees, 1979, fig. 2). Published with permission of the Council of the Royal Society of Western Australia*

Tilting of Australia

The distribution of Cenozoic marine sediments across Australia shows a striking north–south asymmetry. Along the continent's southern margin sedimentary rocks in the Eucla Basin occur at up to 300 m ASL, whereas along the northern margin of Australia there is an almost complete lack of marine sediments of this age, let alone any at a significant height above present-day sea level. Additionally, Eocene and Miocene shorelines along the landward margin of the Eucla Basin are much higher along the northwestern margin of the basin than along the eastern margin of the basin in South Australia (Fig. 28; Table 2). Taken together, these lines of evidence suggest continent-scale (long-wavelength (10^3 km) deformation) tilting, aligned southwest-up, northeast-down since the late Eocene. This has been attributed to a dynamic topography response to the northward movement of the Australian Plate toward the subduction zones of Indonesia and southeast Asia (Fig. 28).

At a smaller scale (Fig. 29), lithospheric buckling due to intraplate stress can produce intermediate-wavelength (10^2 km) deformation. This can be seen in the western part of the Eucla Basin where Eocene sediments lie at significantly lower elevations than equivalent sequences in the central Eucla Basin and Lefroy Paleodrainage and reflects deformation along the east–west Jarrahwood Axis and associated Ravensthorpe Ramp. The warping of the terraces on the flanks of the Cape Range Anticline (Fig. 15) may also be due to this scale of deformation.

At even smaller scales (short-wavelength (10^1 km) deformation) intraplate stress related to plate-boundary forcing can produce fault movements of between 10 and 100 m, as seen in the paleoseismicity record for the Hyden Fault (see *Quakes and shakes*).

Table 2. Changes in paleoshoreline levels across the Eucla Basin

Epoch	North-western margin in Western Australia (m ASL)	Eastern margin in South Australia (m ASL)
Miocene (15 Ma)	~220	~60
Eocene (41 Ma)	~300	~150

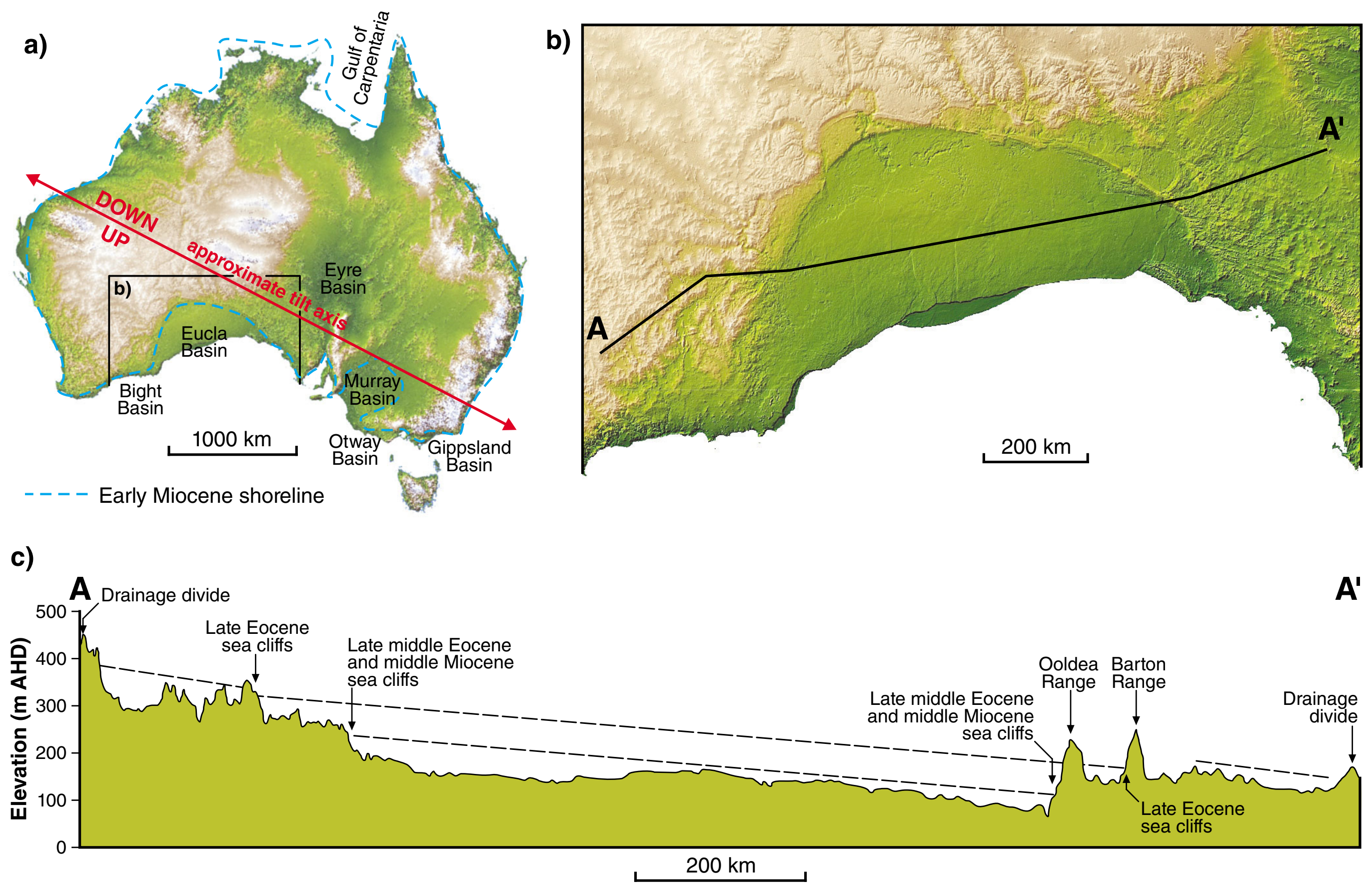


Figure 28. a) Australia showing approximate position of the early Miocene shoreline and tilt axis (after Sandiford et al., 2009, fig. 2 and Hou et al., 2011, fig. 3); b) and c) Topographic difference between western and eastern margins of the Eucla Basin (from Hou et al., 2011, fig. 3)

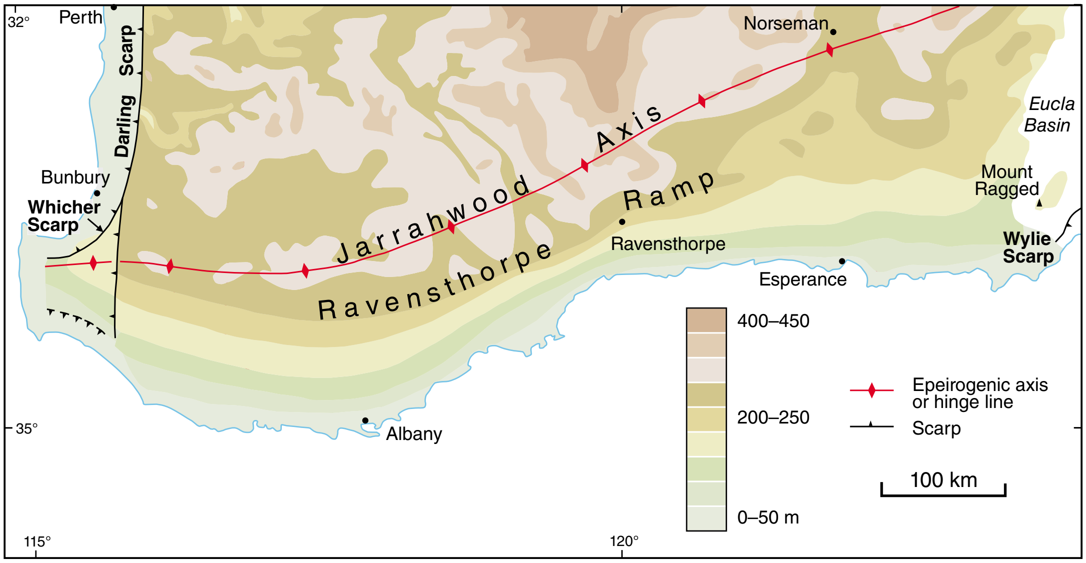


Figure 29. Outline topography of southwest Australia showing the Jarrahwood Axis and Ravensthorpe Ramp (after Cope, 1975, fig. 20)

Quakes and shakes

Australia is generally considered to be a stable continent in an intraplate position, but it is also the fastest moving continent, having moved north-northeast at a rate of 6–7 cm/yr, and is relatively highly stressed (Fig. 30). Furthermore, Western Australia is the continent's 'earthquake capital': of the 579 earthquakes recorded in 2013, 321 (55%) were in Western Australia. There is a significant concentration of seismic activity onshore and off the coast in the Northwest Seismic Zone, with another area of earthquakes in the southwest, called the Southwest Seismic Zone (Fig. 31). It is not clear why these regions should have above-average levels of seismicity.

Western Australia is the continent's 'earthquake capital', having 55% of Australia's earthquakes in 2013.

There have been four significant onshore earthquakes in the State since records were kept:

- Meeberrie, in 1941, magnitude 7.3, depth 33 km;
- Meckering, in 1968, magnitude 6.9, depth 7 km;
- Calingiri, in 1970, magnitude 5.9, depth 1 km; and
- Cadoux, in 1979, magnitude 6.2, depth 15 km.

Meeberrie is in the Northwest Seismic Zone, and the latter three in the Southwest Seismic Zone.

The Meeberrie earthquake was possibly the largest known earthquake to originate in Australia, although the only reported damage was cracking of the remote Meeberrie Homestead's walls. Subsequent mapping revealed a fault 10 km west of the homestead, which may have been the source of the earthquake. The Meckering earthquake destroyed many buildings in the town of Meckering and caused damage in towns within a 700 km radius, particularly in Perth, Northam, and York. The main fault scarp was an arcuate dextral thrust fault some 37 km long with a maximum vertical displacement of 3.5 m (Figs 31, 32). The Calingiri earthquake (Fig. 31) caused only minor damage; the main fault, an arcuate sinistral thrust fault, was about 3 km long with a throw of 0.4 m. The Cadoux earthquake (Fig. 31) caused considerable damage locally; the main fault was a dextral thrust about 10 km in length with a throw of 1.4 m.

The Darling Scarp is the present expression of the Darling Fault Zone (Fig. 22), which separates the Perth Basin from the Yilgarn Craton and has been historically aseismic. However, there are indications of paleoseismicity in Western Australia (Fig. 31), most associated with the Southwest Seismic Zone. It is possible that the Meckering earthquake was the result of the reactivation of an old fault line, possibly tens of thousands of years old. One of the best-studied areas of paleoseismicity is the Hyden Fault, where

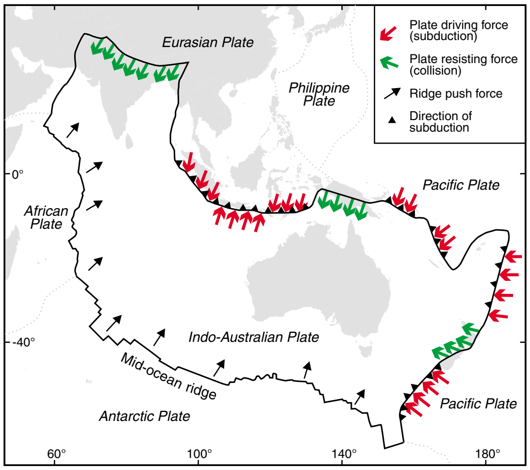
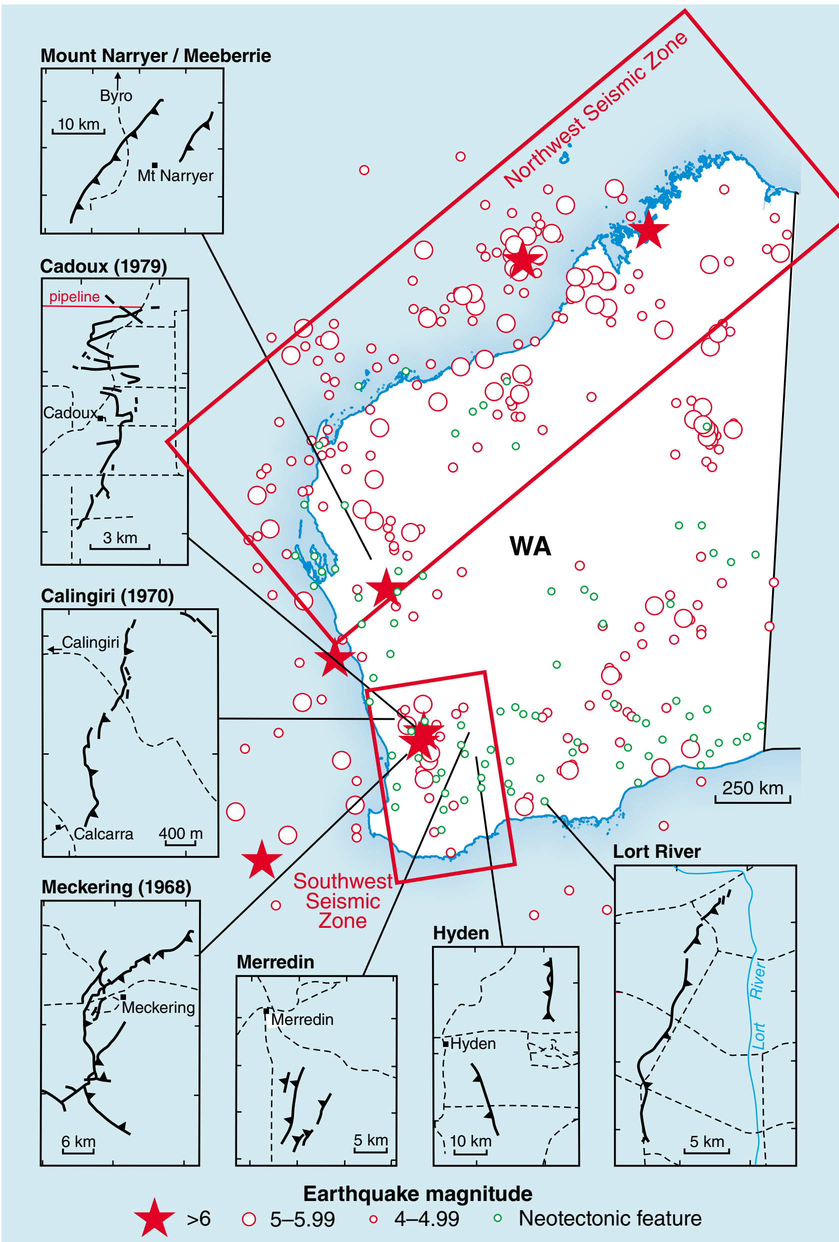


Figure 30 (left). Indo-Australian Plate showing present plate-boundary forces and direction of subduction (after Quigley et al., 2010, fig. 1)

Figure 31 (below left). Distribution of historical earthquakes with magnitudes greater than 4 (M>4) and selected fault scarps in Western Australia (after Quigley et al., 2010; Clark et al., 2008, fig. 8). The Mount Narryer fault scarp probably pre-dates the Meeberrie earthquake

Figure 32 (below right). Meckering Fault crossing the Great Northern Highway southwest of the town of Meckering (photo taken shortly after the earthquake on 14 October 1968).
Photo courtesy* The West Australian *newspaper



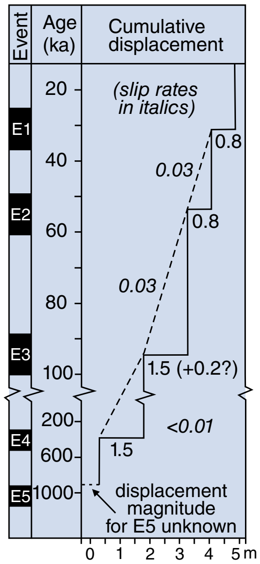


Figure 33. Summary of paleoseismicity data on the Hyden Fault (after Clark et al., 2008, fig. 8). Slip rates are millimetres per year (mm/yr)

up to five surface-rupturing earthquakes during the Quaternary have been identified (Fig. 33):

- E1 at c. 30 ka;
- E2 between 50 and 55 ka;
- E3 between 90 and 100 ka; and
- E4 and E5 at >200 ka.

Magnitudes of these paleoearthquakes were around 6.8.

Fault kinks are also known from the Pleistocene Tamala Limestone (Fig. 34). Some creeks in front of the Darling Scarp appear to be sag ponds. Creeks near some of the coastal anticlines north of Carnarvon are probably sag ponds and show drainage diversion, suggestive of relatively recent tectonism. A fault, with some drag and movement of at least a few metres, can be seen cutting the middle Miocene Trealla Limestone near Shothole Canyon in Cape Range. The Zuytdorp Cliffs are interpreted to be a fault-line scarp formed by recent movement along the Zuytdorp Fault (Fig. 21).

Long, arcuate, low-elevation fault scarps can be seen crossing the limestone surface of the Eucla Basin in many places. One fault scarp continues across the Roe Plains in front of the cliffs. These scarps coincide approximately with major basement structural trends apparent on aeromagnetic imagery, and so are taken as indications of fault reactivation since the Miocene and, for the scarp on the Roe Plains, in the Quaternary.

Figure 34. Small reverse faults in eolian cross-beds of the Tamala Limestone indicate faulting in the Quaternary, after the dunes were consolidated; Jurien HMS deposit

Evolution of a landscape

An ancient landscape

Australia has long been regarded as an ancient land with the land surface being one of the oldest on the globe and one that has not been covered by sea for a very long time. A contrary opinion states that land surfaces older than the Cretaceous are extremely unlikely, unless buried and subsequently exhumed. Although there can be little doubt that some landforms may relate to the Permian glaciation of Gondwana, fission-track dating and other studies show that several kilometres of uplift and denudation have taken place since that time. For example, fission-track dating suggests that ~3 km of Permian and Mesozoic strata were removed from the Yilgarn Craton before the Cenozoic.

On the other hand, the low maturity of Permian strata in the Collie Sub-basin (of the Perth Basin) and onlapping the margins of the Yilgarn, Pilbara, and Kimberley Precambrian terrains indicates less than 1500 m of section has been removed — in some cases less than 500 m — implying relatively little subsequent deposition and indicating that some present landforms are little changed since the Permian glaciation of Gondwana. Such observations apparently contradict the fission-track dating studies. Whereas it is clear that there has been burial and exhumation of the old landforms (followed by a long period of deep weathering), the timing and magnitude of this erosion is not fully resolved. Nevertheless, recent provenance studies from the Perth Basin and North West Shelf indicate that basement provinces — such as the Yilgarn and Pilbara Cratons, and the Kimberley Basin — had relatively little input into the Permian and Mesozoic successions. This implies that significant erosion of these provinces at least predated the Permian, and possibly the Phanerozoic.

Jutson summarized what was known of the physiography of Western Australia in a GSWA Bulletin published in 1914. His second edition in 1934 subdivided the State into nine

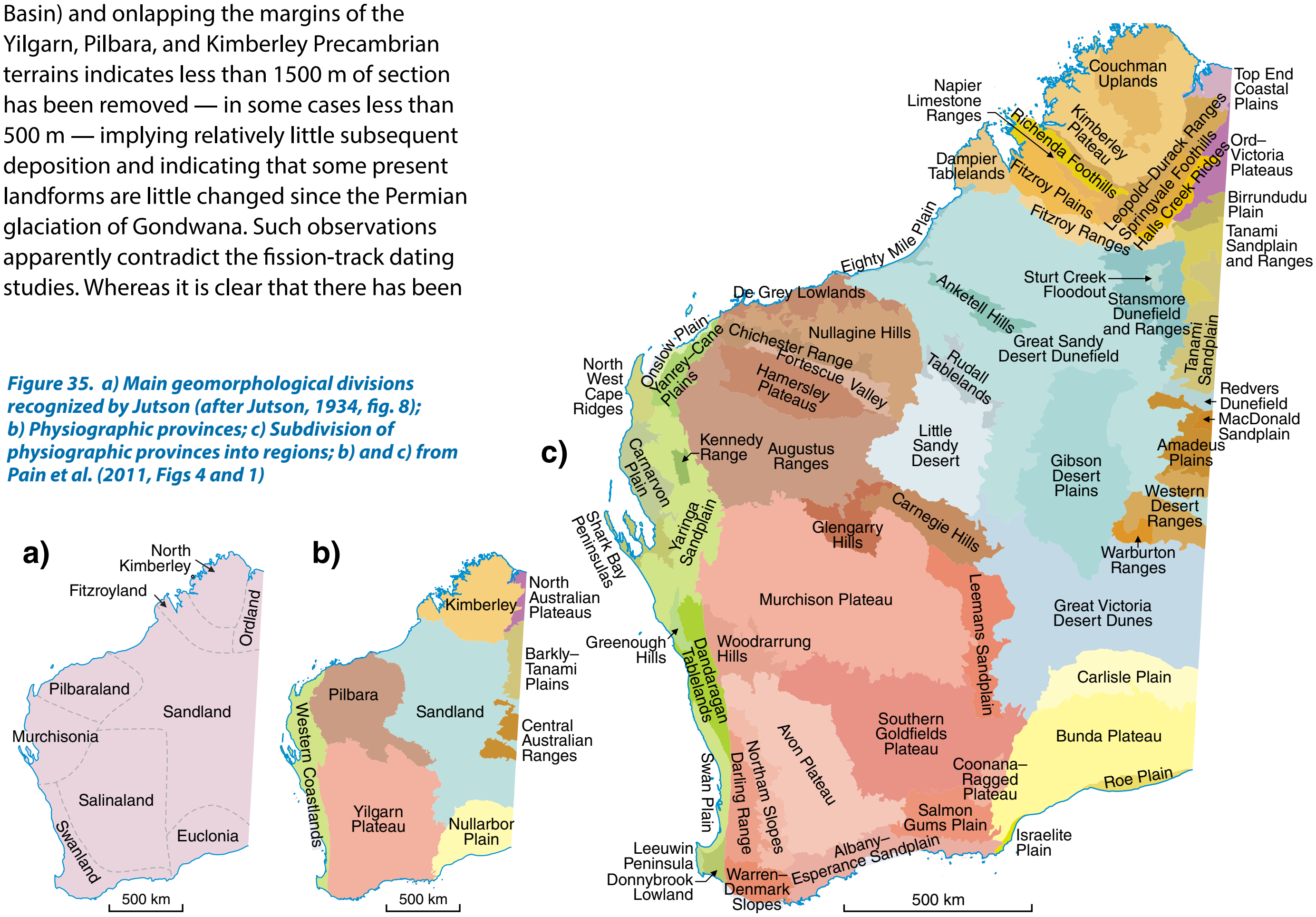


Figure 35. a) Main geomorphological divisions recognized by Jutson (after Jutson, 1934, fig. 8); b) Physiographic provinces; c) Subdivision of physiographic provinces into regions; b) and c) from Pain et al. (2011, Figs 4 and 1)

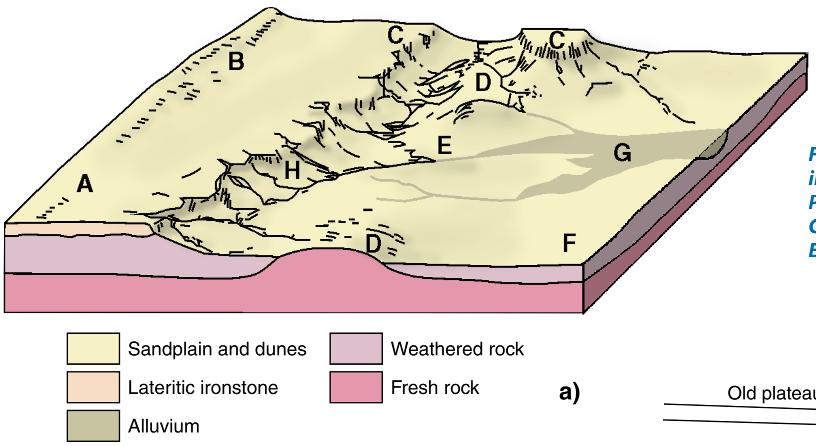


Figure 36. Examples of Yilgarn Craton landforms in the Wiluna–Meekatharra area (after Anand and Paine, 2002, fig. 8): A, sandplain; B, dunes and swales; C, partly stripped laterite; D, low rock hills; E, hill footslopes; F, plains; G, drainages; H, alluvial fans

geomorphological divisions (Fig. 35a) that have formed the basis for subsequent attempts to differentiate landform areas in Western Australia (Figs 35b, c).

The evolution of the landscape has been most closely studied in the Yilgarn Craton — essentially Jutson's Salinaland — with several scenarios being developed to explain the diversity of landforms (Fig. 36). One scenario envisaged an 'Old Plateau' capped by deeply weathered profiles, sand, and laterite that was eroded to form a 'New Plateau' at a lower level, without laterite (Fig. 37a). Another scenario considers that the duricrusts formed from transported material in old alluvial-channel systems and now occupy high ground through inversion of relief (Fig. 37b). Yet another view is the etchplain concept, involving differential stripping of a deeply weathered mantle; where stripping of the regolith progressed toward the interior in a stepped fashion from north and south (Fig. 37c). A more recent model recognizes four stages in the evolution of the landscape and regolith (Fig. 38):

i) Paleozoic and Mesozoic weathering;
ii) Late Cretaceous to mid-Cenozoic erosion and sedimentation;
iii) Neogene weathering; and
iv) Late Neogene to Quaternary sedimentation and weathering.

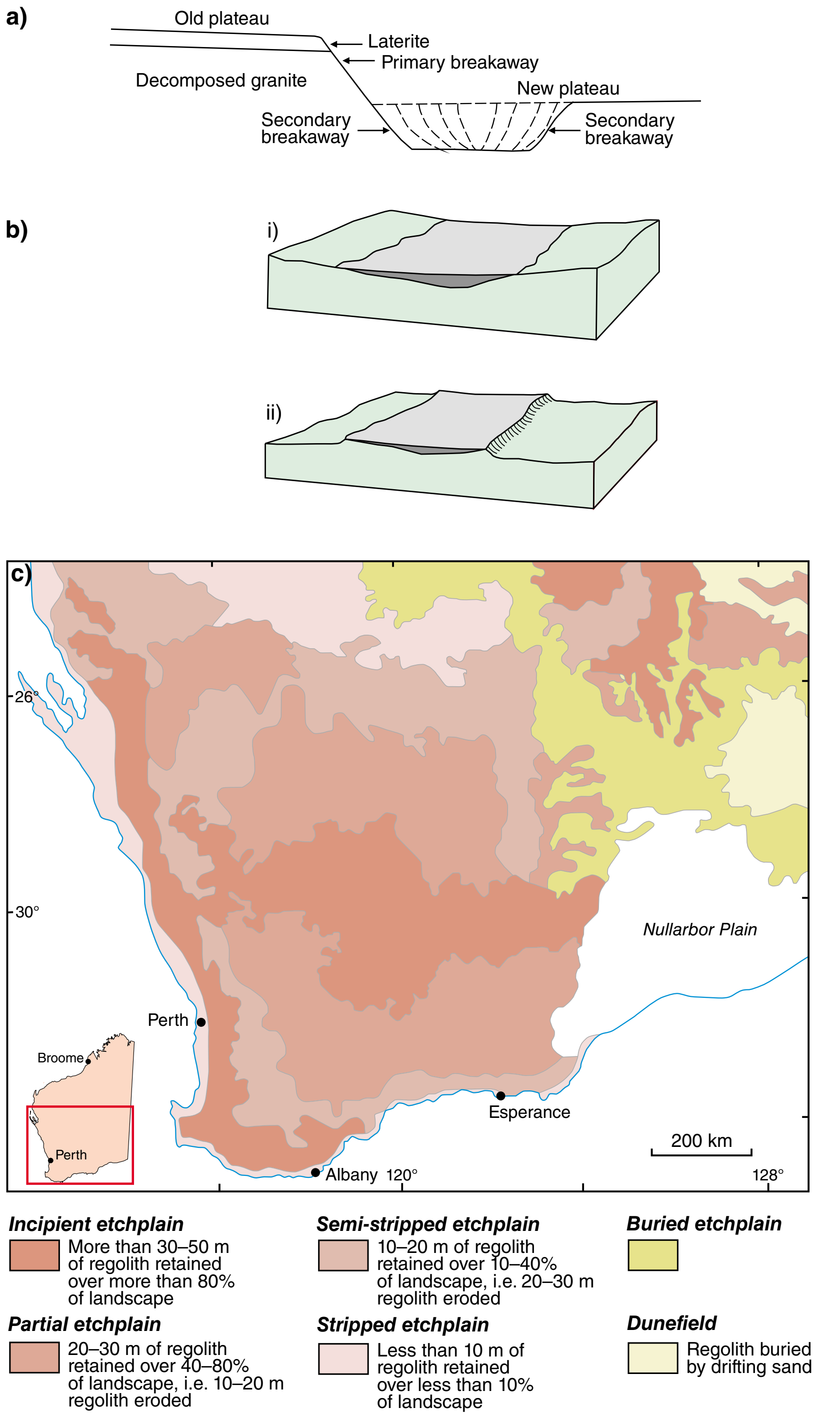


Figure 37. Various models of landscape evolution in the Yilgarn Craton:

a) Jutson model showing relationship between 'Old Plateau' and 'New Plateau' (after Jutson, 1934, fig. 99);

b) Ollier model with (i) duricrusts formed from transported material in old alluvial channel systems now (ii) occupying high ground after the relief became inverted (after Anand and Paine, 2002, fig. 3);

c) etchplain model of differential stripping of a deeply weathered mantle (after Anand and Paine, 2002, fig. 2)

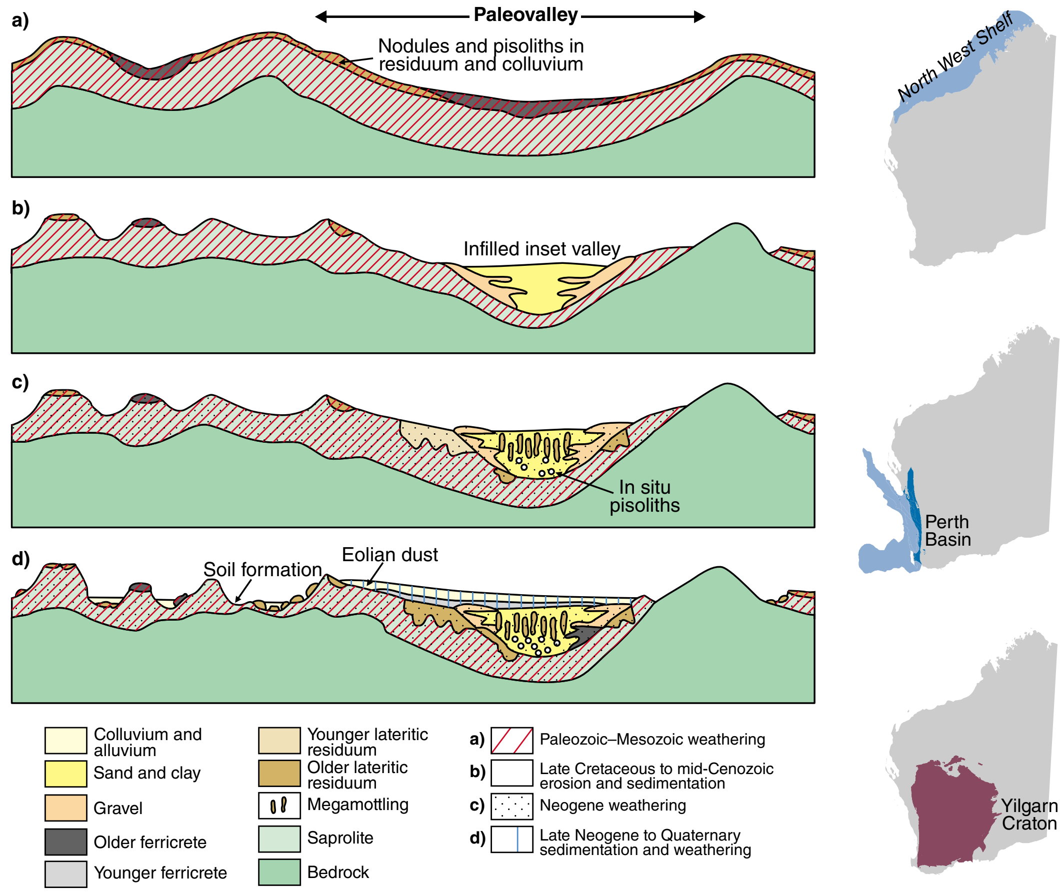


Figure 38. Landscape evolution for parts of the Yilgarn Craton. Although weathering and erosion were continuous, their relative rates changed over time (after Anand and Butt, 2010, fig. 4)

Regolith — the rich skin of continent

Regolith is the 'weathered skin' blanketing underlying bedrock. It includes transported or residual, fragmented, unconsolidated, or indurated material, and thus comprises fractured and weathered basement rocks, duricrusts, calcrete, eolian deposits, colluvium, alluvium, glacial deposits, and soil. Some refer to the regolith as 'everything between fresh air and fresh rock'. Such materials form the surface covering over most of Western Australia (Fig. 39). Regolith is difficult to date, as it is usually devoid of fossils and commonly composed of reworked older material. Some regolith deposits are clearly Quaternary, but many are much older, reflecting the long periods of weathering and erosion that have led to the development of the present-day landscape in Western Australia. There is debate as to whether weathering was continuous or episodic. Continuous weathering implies that the rates of weathering are independent of climate, whereas the episodic model implies that weathering reactions are related to water–rock interactions. Nevertheless, it is likely that weathering processes are continuous but at rates that are related to changes in climate.

> *Some refer to the regolith as 'everything between fresh air and fresh rock'.*

Many geochronological methods have been applied to determining the age of regolith (Fig. 40). The various geochronology results indicate that weathering history extends back to the Late Cretaceous, with even a couple of Paleozoic dates from clays in mining pits in the Northern Goldfields of the Yilgarn Craton. Although paleogeographic reconstructions suggest that parts of the State have probably been subaerially exposed since the Neoproterozoic, the geochronological evidence suggests that the weathering profiles certainly record a history extending into the Mesozoic and, locally, the Paleozoic. This implies that some weathering profiles in Australia were forming when the continent was at cold high latitudes and attached to Antarctica, conditions not generally conducive to weathering. It is not clear what conditions enabled the formation of weathering profiles at high latitudes, perhaps:

- humid warm climates extended to higher latitudes in the past; or
- higher atmospheric CO_2 with enhanced biological activity could result in weathering at low temperatures.

In the Yilgarn Craton, where the weathering history is best documented, a number of climatic episodes are recognized (Table 3). Whereas there may have been significant weathering in the Paleozoic, most of the evidence has been removed by Permian glaciation. During the Mesozoic, when the major drainage systems were established, chemical weathering took place under humid and temperate to sub-tropical conditions. In the Paleogene erosion and weathering took place under subtropical to tropical humid conditions that were probably seasonal: clay units in the infill valley sediments (see below) were strongly weathered. Sub-tropical conditions continued into the Neogene with a change to arid and semi-arid conditions in the late middle Miocene that have since been dominant. With increasing aridity the groundwaters became saline and the inland drainages shrank to become chains of salt lakes.

The weathered regolith profile can be several tens of metres thick (even up to 150 m), but is variable, and a 'typical' profile is divided into a number of zones (Fig. 41). The type of duricrust that develops at the top of the profile depends on a number of factors. In general, laterite or ferricrete tends to occur in areas of higher rainfall, whereas silcrete is dominant in arid areas or areas with a strongly seasonal climate, although bedrock and local topography are also important controls. Laterite is most extensive in the southwest of Western Australia, where it extends from the south coast, east of the Darling Scarp, to the Wooramel River, a distance of some 1000 km. Silcrete is most extensive in the Gibson and Great Victoria Deserts (Fig. 23), where widespread Cretaceous radiolarian siltstones provide an additional source of silica.

The age of the duricrusts is varied. Laterite is forming today in the southern part of the Perth Basin, and paleomagnetic results from Perth Basin sedimentary rocks suggest the age of formation could extend back to the Miocene or Pliocene (depending on which apparent polar wander path is used). In the Yilgarn Craton two periods of ferricrete formation are recognized: an 'older ferricrete' in the Mesozoic drainage systems and a 'younger ferricrete' formed in the inset valleys in the Miocene. The main phase of duricrust development in the Northern and Southern Carnarvon Basins was Eocene to Oligocene.

Two main types of calcrete are recognized in Western Australia:

- pedogenic calcrete or 'kankar'; and
- non-pedogenic groundwater ('valley') calcrete.

Pedogenic calcrete develops as a duricrust over calcareous rocks and is found over much of the Eucla Basin as well as parts of the Northern and Southern Carnarvon Basins. It also forms over non-calcareous rocks such as ultramafic

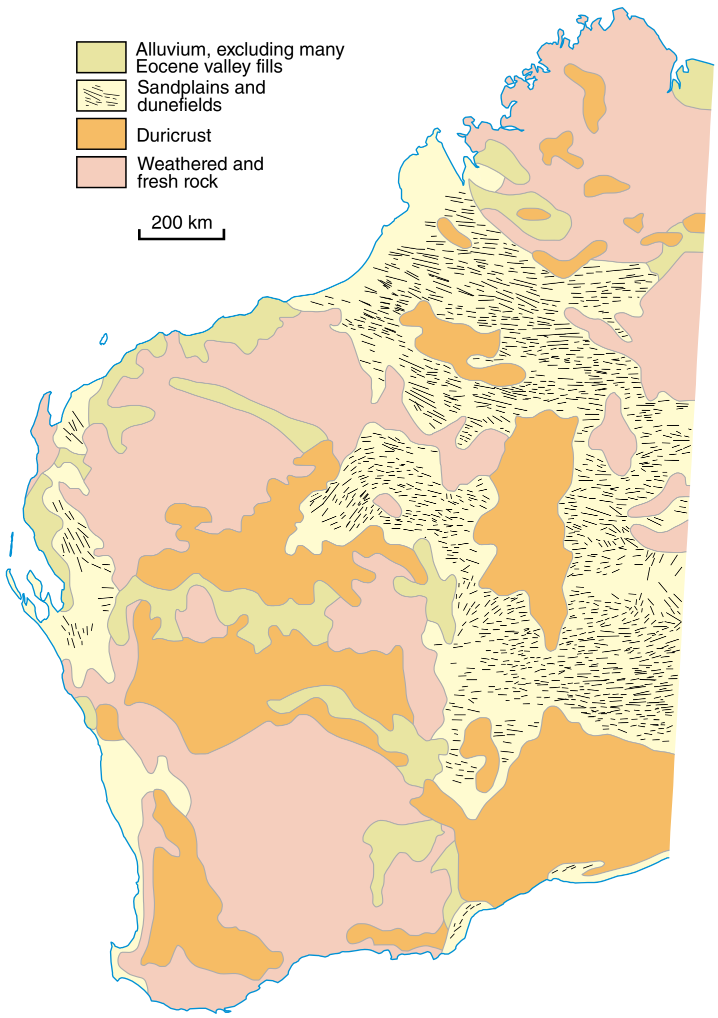


Figure 39. Distribution of regolith materials over Western Australia (from Hocking and Cockbain, 1990, fig. 6-1)

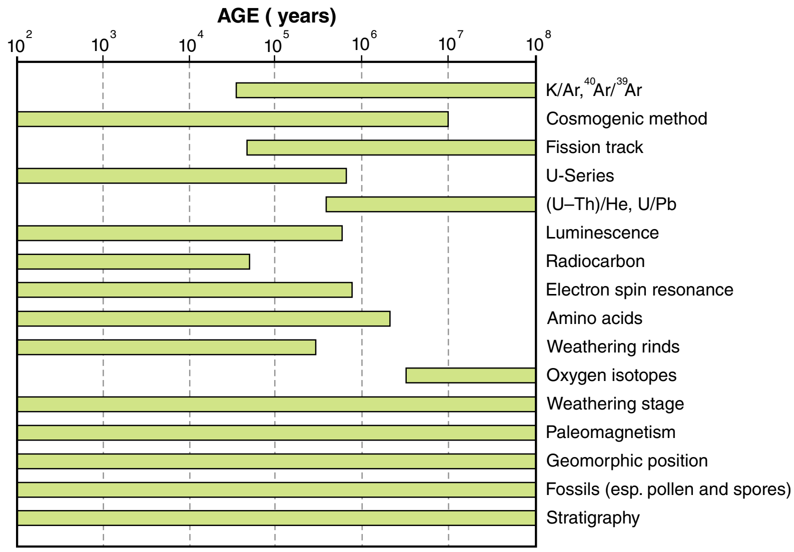


Figure 40. Regolith dating methods and their age ranges (after Pillans, 2004, fig. 2)

Table 3. Principal climatic episodes in the southern Yilgarn Craton

	Age (Ma)	Climate
Quaternary	1.8–0	Temperate to warm; semi-arid to arid (23–13 ka peak aridity; glacial maximum)
Middle Miocene to Pliocene	15–1.8	Subtropical; aridity increasing; cooler after 2.5 Ma
Paleocene to middle Miocene	65–15	Subtropical to tropical; humid; probably seasonal
Mesozoic	230–65	Temperate to warm; humid
Early Permian	280–270	Glaciation

Source: Anand and Paine (2002, table 15); after Ollier (1978)

rocks. Groundwater calcrete occurs in many of the paleodrainages as linear tabular bodies of calcreted alluvium, and delineates some drainages otherwise not obvious on the ground or on imagery. Both types of calcrete form under arid conditions, and the 500 mm isohyet marks the boundary of present-day calcrete formation. The main period of calcrete development was probably in the Pliocene and Pleistocene, after the onset of aridity in Western Australia in the mid-Miocene (Table 3).

There are two major areas of inland dunefields — in the Southern Carnarvon Basin north of the Wooramel River, and the larger dunefield covering most of the Canning, Officer, and Gunbarrel Basins, and extending into South Australia as far as Ceduna (Fig. 39). Longitudinal dunes predominate, with network dunes in depressions and in wind traps around hills. The dunes are made primarily of red-brown quartz sand, and are largely unconsolidated with poorly lithified soil horizons (Fig. 42).

The largest area of alluvial valley-fill is in the Fortescue River valley, an obvious feature on all State geological maps. Originally formed in the Early Cretaceous or possibly the Late Jurassic, the valley has been through several stages of alluvial infill, in the Early Cretaceous, Eocene, and Pliocene–Quaternary. Although unconsolidated

Uranium — a new era

Western Australia contains about six percent (234 kt U_3O_8) of Australia's known uranium resources. Eighty-seven percent of this mineralization is contained in Cenozoic, Cretaceous, and Carboniferous paleochannels that drain from or across relatively uranium- and vanadium-rich Archean and Proterozoic source regions into younger sedimentary basins.

The largest uranium deposits in Western Australia are hosted by surficial calcretes in Cretaceous to Cenozoic paleochannels. These constitute 55% of Western Australia's known resources of U_3O_8, and are most common across the northern Yilgarn Craton and Gascoyne Province. Typical examples include Yeelirrie, the largest uranium deposit in Western Australia and the largest surficial uranium deposit in the world (total resources of 66.22 kt U_3O_8), and Lake Way, near Wiluna, which may become the first new uranium mine in Western Australia since closure of the Kintyre operations in 1998.

Uranium began accumulating in calcrete during the Pliocene, when arid conditions, infrequent heavy rains, and inland drainage systems provided suitably high rates of evaporation and the natural traps required to form large, localized deposits of channel calcrete. Oxidized, low-temperature groundwater leaches and transports uranium from weathered Archean granites (containing 2–25 ppm U), and precipitates it as carnotite [$K_2(UO_2)_2(VO_4)_2.3H_2O$] in cracks, selvages, and pore spaces within the calcrete at the redox boundary with the underlying fluvial sediment.

Western Australia also has paleochannel sandstone-hosted or 'roll front' uranium deposits. These are typically buried beneath tens to hundreds of metres of cover, hence fewer are known. Prominent examples include: the lignite-hosted Mulga Rock and sandstone-hosted Ponton deposits in Cretaceous to Cenozoic paleochannels draining into the western Eucla Basin from the Yilgarn Craton; the Theseus deposit, in an Eocene paleovalley draining from the crystalline Arunta Province into Lake MacKay; the roll-front and tabular Manyingee, Bennett Well, and Carley Bore deposits in Cretaceous fluviodeltaic paleochannels that drain westward from the Proterozoic Gascoyne Province into the Carnarvon Basin; and the sandstone-hosted Oobagooma deposit north of Derby, in an Early Carboniferous paleochannel that drains from the King Leopold Orogen into the northern Canning Basin.

Uranium in sandstone-hosted deposits is believed to be transported by oxidized groundwaters. It is precipitated — predominantly as uraninite (UO_2) and coffinite ($(U(SiO_4)_{1-x}(OH)_{4x})$) — where these groundwaters react with H_2S derived by biogenic or non-biogenic breakdown of organic or inorganic material (e.g. fossil plant debris, pyrite) within the host rock, or with other reduced fluids or gases (e.g. H_2S, hydrocarbons) passing along favourable structures.

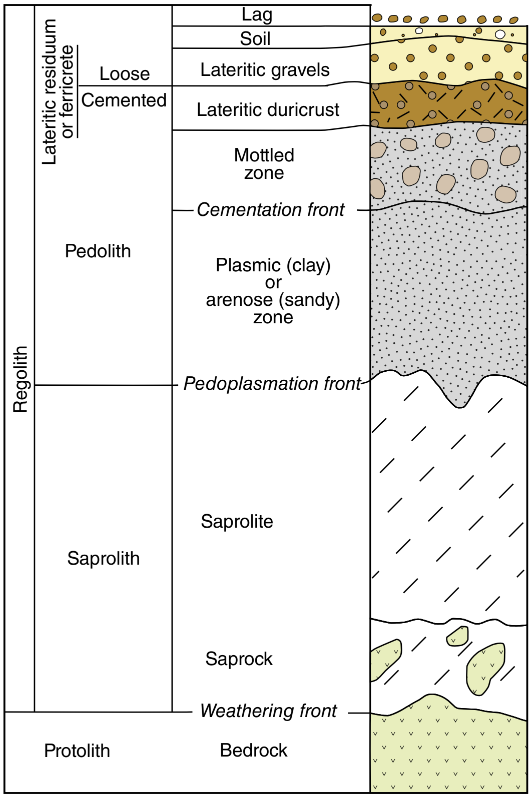


Figure 41. Terminology of a deeply weathered regolith profile (after Anand and Paine, 2002, fig. 10)

Bauxite and jarrah

Bauxite was identified in the Darling Range of Western Australia as early as the 1940s, and mining commenced at Jarrahdale in the southern forests in 1963. This marked the birth of the aluminium industry in Australia, which now encompasses bauxite mining, refining, and smelting into aluminium ingots for world markets.

Bauxite-grade laterite covers a huge area of the southwestern edge of the Yilgarn Craton — also home to the State's unique jarrah forests.

Alcoa is currently mining at Huntly and Willowdale and this involves drilling and blasting a caprock layer of bauxite about 4 m thick. BHP Billiton Ltd and partners have similar mining operations at Boddington and a refinery at Worsley. Alumina production in Western Australia reached a record 13.6 Mt alumina with a value of A$4.1 billion in 2013.

Economic bauxite mineralization is confined to the western lateritic upland margin of the Archean Yilgarn Craton. Deposits are lenticular, alumina-enriched laterites. Although generally low-grade (about 30% available aluminium), the deposits are economic because of proximity to infrastructure and shipping facilities. At the time of lateritization and bauxite formation in the late Eocene and early Oligocene, this region possessed a favourable combination of high rainfall, high temperatures, chiefly granitic bedrock, moderate relief, appropriate groundwater Eh–pH conditions, adequate drainage, and dense vegetation. Deep chemical weathering and removal of deleterious components and the alteration of clay minerals to bauxite minerals in the homogeneous Archean granites have resulted in a world-class aluminium province in southwest Australia.

A second bauxite province lies on the Mitchell Plateau in the Kimberley region in the far north of Western Australia. Deposits remain undeveloped because of their remoteness and lack of regional infrastructure. They, too, resulted from deep weathering under hotter, more humid conditions, but may be much younger.

to semiconsolidated sandy alluvium lies along most major drainages, there are few areas of active alluvial deposition in Western Australia. Major subaerial deltaic deposits are associated with the Gascoyne, Ashburton, Robe, Fortescue, and De Grey Rivers, where most of the delta building took place in the late Pleistocene. Some coastal plains are alluvial in origin, for example the lower Fitzroy River and lower Ord River (which also has extensive subaqueous deltaic deposits), but most result from coastal processes.

A highly indurated, locally silicified or carbonate-cemented, alluvial and/or colluvial sheet, collectively named the Wiluna Hardpan (Fig. 43), spreads over a large area of arid and semi-arid country in the Gascoyne and Yilgarn regions, from the southern Pilbara in the north, west to the Byro and Lyons River area, east to the Gibson and Great Victoria Deserts, and south to Kalgoorlie. It varies from 1 m to 10 m thick and is typically red-brown. Deposition post-dated siliceous and ferruginous duricrust formation, and initial induration was probably contemporaneous with the development of calcrete. Hardpan appears to be still forming.

The soils of Western Australia are both old and young, often in close proximity, with, in some cases, the old soil materials being incorporated into the young soils. Australian soils have less organic matter and poor structure compared with soils in the Northern Hemisphere. Four broad soil–landscape regions have been recognized (Fig. 44): Kimberley, Sandy Desert, Western, and Central Southern. The Kimberley region contains mainly stony soils with red

Figure 42. Longitudinal (seif) dune in the remote Great Sandy Desert

More than half of the total value of the mineral production of the State comes from regolith processes.

and yellow deep sands and some red and yellow loamy earths, sandy earths, and self-mulching cracking clays. The Sandy Desert region has red deep sands and sandy earths, with some shallow gravels and red loamy earths. In the Western region there are deep sands, loamy earths, and shallow loams (all mostly red), together with sandy duplexes, stony soils, and red sandy earths. The soils of the Central Southern region are all calcareous, comprising shallow loams, loamy earths, and stony soils.

An interesting feature of the regolith is the presence of tektites (see box, *Tektites*) on the surface of the landscape, especially on salt lakes and little-vegetated plains, where they are easily seen. One of the greatest concentrations is in an elongate strewnfield across the Eastern Goldfields region of the Yilgarn Craton.

More than half of the total value of the mineral production of the State comes from regolith processes (see boxes, *Giant iron resources in old river systems*; *Uranium — a new era*; *Bauxite and jarrah*; *REE surprises in the regolith*; *Gold — yet another source*; *Wingellina nickeliferous laterite*). The regolith is the sole source of bauxite and heavy mineral sands, and many industrial minerals (clays, garnet, gypsum, salt, silica sand, and limesand). In addition the regolith contains substantial amounts of gold, iron ore (as channel-iron deposits), nickel, uranium, alluvial diamonds, and tin.

Figure 43. Inferred extent (in orange) of the Wiluna Hardpan (from Krapf, 2011, fig. 22)

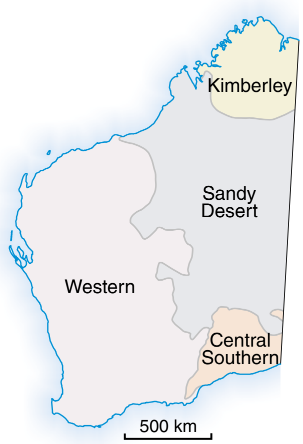


Figure 44. Soil–landscape regions of Western Australia (after Tille, 2006, fig. 2.2)

REE surprises in the regolith

The Mount Weld carbonatite is a 3.5 km-wide, near-vertical plug that intruded Archean volcano-sedimentary rocks of the Laverton Domain of the eastern Yilgarn Craton during the Paleoproterozoic. The carbonatite hosts Western Australia's largest, and one of the world's richest, deposits of light rare earth elements (REE), totalling around 23.9 Mt at 7.9% rare earth oxides. The REE resource lies entirely within the saprolitic and lateritic regolith cap that formed over the carbonatite during extensive weathering after Permian glaciation in the region. REE are largely contained in secondary rhabdophane, monazite, and churchite. Pronounced REE mobility and concentration were favoured by the presence of abundant acid groundwaters with long residence times, abundant REE-complexing agents, and lateral groundwater flow towards a topographic low. Mining at Mount Weld began in 2009, and the first production of downstream rare earth products was in early 2013.

Another residual regolith-hosted REE deposit lies over the c. 905 Ma Cummins Range carbonatite plug in the East Kimberley region, although this is somewhat smaller and of lower grade (~4.9 Mt at 1.74% rare earth oxides, including yttrium).

Western Australia was for many years a major producer of REE from monazite obtained as a byproduct of ilmenite, rutile, and zircon mining from heavy mineral sand deposits along the coastal plain of the Perth Basin. In 1995, amid concerns about the radiation risks from the thorium and uranium also contained in the monazite, all shipments of monazite from mineral sands ceased. HMS-mining companies are now required to return any monazite to the mine site for reburial during back-filling and remediation.

Mount Weld pit

Tektites

Tektites are natural glass objects, up to a few centimetres in size, produced by the melting and ejection of crustal material into space during a large impact event. They are only found in four strewnfields (Central European, North American, Ivory Coast, and Australasian strewnfields), three of which are associated with known impact craters. The Australasian strewnfield is the largest, extending from southern China to Antarctica and from the western Pacific to the southwestern Indian Ocean. Although no associated impact crater has been found it is generally assumed to be located somewhere in Indochina, where the tektites are more abundant and larger. Australian tektites are called australites; they have a wide range of shapes including discs, dumb-bells, and bowls that are not seen in other tektites. The aerodynamic shape of the perfect flanged buttons has been precisely duplicated in laboratory wind tunnel experiments; NASA studied them to devise the best shapes for re-entry modules.

Tektites were known to the Aboriginal people, who used them as artefacts and ritual objects. Europeans found out about them in 1857, when explorer Thomas Mitchell gave one to Charles Darwin who thought it was of volcanic origin. Tektites are not evenly distributed across Australia but appear to be found in local concentrations, mainly across the southern half of the continent, south of 25°S.

The ages of the strewnfields range throughout the Cenozoic: North American, 34 Ma; Central European, 15 Ma; Ivory Coast, 1 Ma; Australasian, 0.8 Ma. A precise date of 796 ± 10 ka, obtained using the ^{40}Ar–^{39}Ar step-heating method at the John de Laeter Centre for Isotope Research at Curtin University, was determined for an australite collected from a salt lake some 140 km east of Kalgoorlie.

Gold — yet another source

Australia's gold industry went through a revival in the 1980s, on the back of an improving gold price, a falling Australian dollar, and new processing techniques that substantially lowered the economic cutoff grades for gold mining. Such developments allowed the profitable exploitation of the near-surface, heavily weathered, uppermost portions of the broader, lower grade haloes of gold mineralization commonly surrounding high-grade ores. This contributed to increasing Australia's economically demonstrated gold resources from 332 t in 1980 to 1486 t by 1989.

The grades in these regolith-hosted gold deposits increased because of the weathering process. The chemical breakdown of the host rocks released gold into local groundwaters, from which it then reprecipitated in broad, flat-lying, supergene nuggetty sheets in either near-surface laterite or deeper saprolite, depending on the prevailing climate. Lateritic gold deposits are believed to have formed in a humid environment, when gold was carried as organic complexes moderated by weakly acidic, oxidizing groundwaters, and redeposited when these groundwaters were diluted and reduced by reaction of Fe^{2+}, typically between 2–5 m below the surface. Saprolitic gold deposits probably formed in arid environments when highly oxidizing, acidic, saline groundwaters transported gold as halide complexes downwards to the prevailing watertable or other redox fronts — such as the interface between paleochannel sediments and the underlying saprolite — generally at depths of between 10 and 70 m.

Regolith-related gold deposits can be very large. The Boddington gold mine in the Saddleback greenstone belt was the largest gold producer in Australia in 2012. Gold was discovered there in 1979 during a geochemical stream sediment and soil sampling program conducted by GSWA. Primary gold mineralization is hosted by felsic–intermediate volcanic rocks and is associated with silicification and potassic and calc-silicate alteration, but there was also significant supergene gold contained in saprock, saprolite, bauxite, ferruginous duricrust, and pisolitic laterite. This supergene component was estimated in late 1995 to contain a demonstrated resource of about 83 Mt at 1.08 g/t Au and inferred resources of 74 Mt at 1.0 g/t Au, with a combined total of 163 t or 5.3 M troy ounces of contained gold.

In 2013, the total gold production from Western Australia (including regolith-hosted Au and other Au) was 186.7 t with a value of A$8.7 billion. GSWA estimates that about 10% of this total gold output relates to regolith processes.

Nuggets

GOLD! For some, the very word fires the imagination. Gold has been sought after and fought over, and ranks as the world's most hoarded, yet most under-utilized metal. Most of the gold ever found or mined is still in circulation — or hidden in vaults — although today gold is utilized in the aircraft and space industries and in computers and electronics.

Plenty of large gold nuggets have been discovered in Australia, particularly during the 1850s in the early days of the gold rushes to Victoria and New South Wales. The largest was the massive 'Welcome Stranger' nugget, found near Moliagul in Victoria in 1869, lying just below the surface and weighing 71.5 kg (2300 troy ounces).

In Western Australia, in January 1931, James Larcombe and his son made a sensational discovery — the largest nugget ever found in the State. Called the 'Golden Eagle' it weighed in at 38.435 kg (1235.7 troy ounces) and measured 67 × 29 × 6 cm (see photo and Table 4). It came from Larkinville, near Londonderry, about 60 km south-southeast of Coolgardie, and was about 50 cm below ground.

The Department's incomplete list of Western Australian nuggets commences with the small nugget found in 1882 in the Cossack–Roebourne area. Discoveries quickly followed in the Pilbara, Murchison, and Ashburton, particularly of alluvial gold. Prospectors pushed eastward from Southern Cross to discover extensive alluvial deposits at Coolgardie in 1892, and later the famous deep leads in soft clay (known as pug) were found at Kanowna.

Specking and dry blowing rather than panning and puddling were favoured on the Western Australian diggings because of the scarcity of water. Today metal detectors, some that can penetrate to 3 m depth, are the preferred prospecting tool.

There is still controversy about the origin of nuggets. Are they essentially unaltered hypogene gold masses shed by erosion from quartz veins or lodes and transported by streams or downslope processes, or do some represent modification of hypogene nuggets by surface processes (such as weathering) shown, for example, by changes in the Au/Ag ratio?

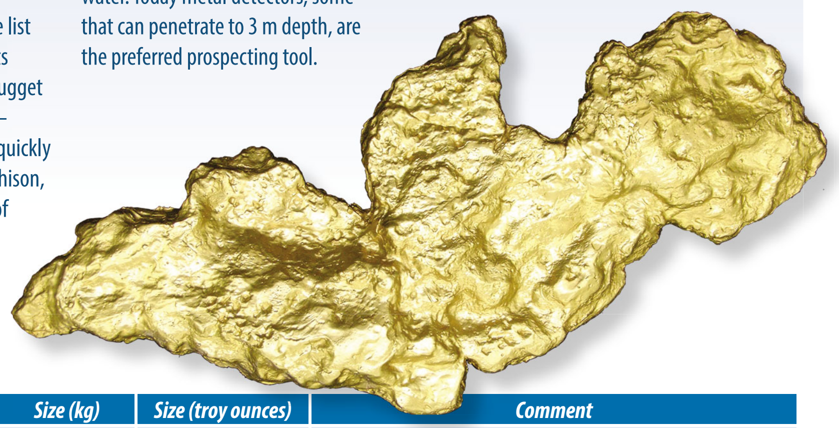


Table 4: Some interesting gold finds and nuggets

Date	Locality	Name of nugget or finder	Size (kg)	Size (troy ounces)	Comment
1882	Cossack–Roebourne, W Pilbara		0.44	14	First 'official' nugget noted by DMP
1888	Pilbara Creek, Pilbara		3.95	127	Slugs, nuggets, and coarse gold
1890	Sharks Gully, Pilbara	'Little Hero'	4.1	133	Well-known locality for alluvial gold and large and small nuggets
1890	Top Camp, Ashburton		4, 3.8, 2.8, 2.1	130, 123, 90, 68	First alluvial gold discovery in Ashburton, good sized nuggets
1891	Nannine, Murchison		12.44	400	
1892	Cue, Murchison		3.11	100	
1892	Austin, The Island, Murchison		2.8, 2.8	90, 90	
1892	Southern Cross, EGF	Bayley and Ford	1.5	50	Prospectors discovered Coolgardie in same year
1892	Pilbara Creek		5.23	165	
1893	Kanowna, EGF		311	10 000	From both alluvial workings and deep leads
1893	Kalgoorlie, EGF	Patrick Hannan, Tom Flanagan, and Dan O'Shea	0.74	24	Discoverers of Kalgoorlie goldfield. This was their first nugget
1893	Top Well, Murchison		9.27	298	
1895	Black Flag, Kalgoorlie	Devon mine	12.44	400	Solid slab of gold. Not a nugget, ?from reef
1897	Wiluna, north EGF	'Monarch'	14.4	463	
1898	Kurnalpi, EGF		3.39	109	
1898	Kanowna, EGF		3.2	103	
1899	Sharks Gully, Pilbara	'Bobby Dazzler'	15.15	487	
1899	Sharks Gully, Pilbara	'General Gordon'	11.57	372	
1899	Hogans Find, EGF		3.89	125	
1900	Kurnalpi, EGF		6.13	197	
1901	Coolgardie, EGF	Coolgardie	4.51	145	
1902	Friendly Creek, Pilbara		5.13	165	
1903	Shark Gully, Pilbara		6.5	209	
1912	Kurnalpi, EGF		7.15	230	
1931	Larkinville, EGF	'Golden Eagle'	38.435	1235.7	Other large nuggets found here in same year
1976	Mount Margaret	Mark Creasy	2.7, 1.5	86, 47	
1980	Feysville, EGF	'Golden Aussie'	8.3	267	Grader used to 20 cm depth
1980	Leonora, EGF		3.67	118	Largest of 200 troy oz of nuggets

Note: List compiled from unpublished Department of Mines and Petroleum sources and from newspaper reports. Abbreviation: EGF, Eastern Goldfield

Wingellina nickeliferous laterite (ochres)

The world-class Wingellina lateritic nickel–cobalt ore deposit — discovered in 1956 — was Western Australia's first nickel discovery. Nickel and cobalt are contained in a yellow-brown to dark-brown ochreous laterite (see photo, exploration costean) consisting of goethite, manganese oxides, gibbsite, and kaolinite. The laterite is locally cut by veins of semiprecious pale-green chrysoprase. The ochreous material was derived by selective leaching of SiO_2 and MgO, and passive concentration of residual alumina, iron oxides, nickel, and cobalt during weathering of dunite and peridotite layers in the Wingellina Hills intrusion. This ochreous material is especially prominent along shear zones, and is best developed at the base of the Wingellina Hills, where weathering extends to a depth of at least 200 m. The orebody averages 80 m in thickness but, in places, is up to 200 m thick. The deposit is exposed at surface, and has a high aspect ratio and very low strip ratio, so would be easily mined. Metals X calculated in 2008 a total measured, indicated, and inferred resource of 183 Mt at ~0.98% Ni and 0.08% Co, for 1.8 Mt of contained metal, and proposed a 40-year mine life based on an annual production of 40 000 t of nickel and 3500 t of cobalt.

Western Australia has many other large lateritic nickel–cobalt deposits, such as at Murrin Murrin, Cawse, Bulong, and Ravensthorpe. In most, Ni–Co enrichment in the regolith profile persists from the uppermost ochreous zone downward through the transition and saprolitic zones. Each regolith zone presently requires a different processing technique to extract metals, which commonly results in exploitation of only one part of the deposit where mining is feasible, and in some cases can render an entire deposit uneconomic. Process metallurgists are presently seeking to develop a single technique for processing an entire resource, which will improve the economics of existing mines, and potentially unlock nickel and cobalt resources contained in the many other marginally economic or sub-economic lateritic nickel–cobalt deposits in Western Australia.

The world-class Wingellina lateritic nickel–cobalt ore deposit was Western Australia's first nickel discovery.

Rivers ancient and modern

There are few large rivers in Western Australia. However, the chains of salt lakes marking the courses of paleodrainages suggest that at one time there were many more large rivers, indicative of a wetter climate. The significance of the chains of salt lakes was recognized as early as 1898 by the explorer David Carnegie.

The present-day rivers are an important source of drinking water and those with sufficient flow have been dammed. The largest dam is on the Ord River in the Kimberley, where Lake Argyle, the second largest man-made lake in Australia has a storage capacity of 10.8×10^3 GL (equivalent to 21 sydharbs, where 1 sydharb (the volume of water in Sydney Harbour) $\approx$ 500 GL). Other dammed rivers are mainly in the southwest of the State to supply Perth (the Mundaring, Canning, and Serpentine Dams on the Helena, Canning, and Serpentine Rivers), although many of these have been far from full due to below-average rainfall in recent years. Elsewhere, rivers have intermittent flows but have large quantities of groundwater in their channels (Fortescue, Robe, Gascoyne, and Fitzroy Rivers). The paleodrainages are also valuable sources of groundwater in both alluvium and calcrete. Nevertheless, potable water remains a scarce resource in the interior of Western Australia, to be shared amongst town water supplies, agriculture, and mining. For instance, the mining town of Kalgoorlie, some 550 km east of Perth, is supplied by a pipeline from Mundaring Dam in the Perth hills.

The widespread Carboniferous–Permian glaciation eroded and smoothed the pre-existing landscape, so that the paleodrainage sediment fill is generally post-Permian. Some paleovalleys (Ponton Creek) may have followed Permian glacial valleys, and Permian fill is known locally. On the Yilgarn Craton the south- and east-flowing paleovalleys consist of broad 'primary valleys' of Mesozoic age that have been incised by secondary 'inset valleys' in the Cenozoic (Fig. 45). This incision was due to uplift in the early middle Eocene, no doubt associated with the plate reorganization that took place around 43 Ma. The continent-wide paleodrainage systems must have developed under pluvial conditions with large amounts of runoff.

Sediments infilling paleovalleys in the central and eastern Yilgarn typically consist of Cycle 2 Eocene channel or estuarine coarse-grained

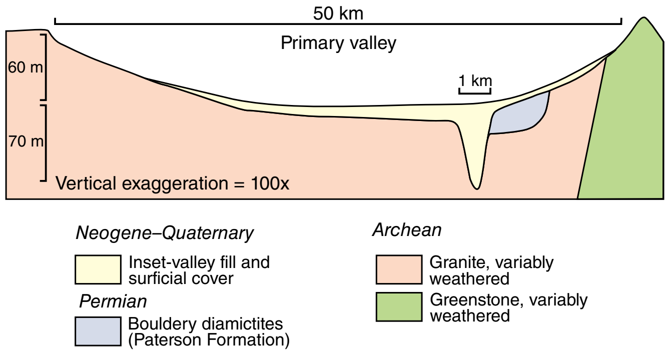


Figure 45. Cross section showing relationship between broad 'primary valleys' of Mesozoic age that have been incised by secondary 'inset valleys' in the Cenozoic (after Magee, 2009, fig. 1.3)

fluvial sands laid down by braided rivers under a wet climate with widespread rainforests. The basal gravels and sands are commonly carbonaceous and contain lignite. These are disconformably overlain by Cycle 3 late Oligocene – Miocene fine-grained sediments, including dolomite and calcrete, deposited in valley lakes and wetlands under somewhat drier conditions than the underlying unit. Quaternary sand sheets and dunefields may cover part of the paleovalleys, and

Chains of salt lakes across inland Western Australia are relics of former rivers.

developed after external drainage and associated deposition ceased. Salt pans and salt lakes are also present in many paleodrainages as saline groundwaters developed.

Paleodrainages have been little studied in areas with present-day active, but still intermittent, drainage systems, such as in the Kimberley, Murchison, Gascoyne regions, and much of the Pilbara (except for areas with groundwater or iron ore resources, particularly CID, see box *Giant iron resources in old river systems*). Undoubtedly they do occur, and many present-day river courses are presumably inherited. The best-known paleovalleys (Fig. 46) are in the Canning Basin (Mandora and Canning Paleovalleys), Pilbara (Fortescue–Robe, Yandi–Marillana, and De Grey Paleovalleys), western Yilgarn (Salt River – Yilgarn Paleovalley), eastern Yilgarn and Eucla Basin (Roe, Cowan–Lefroy, Throssell, and Baker Paleovalleys).Although the paleodrainage systems are extensive, at the present time most are no longer active and there is little or no long-term movement of sediment or surface water. Nevertheless, they can flood after exceptionally heavy rainfall as witnessed by the flow down Ponton Creek in the Eucla Basin, which washed away the Trans-Australian Railway line in the aftermath of Cyclone Trixie on 20 March 1975.

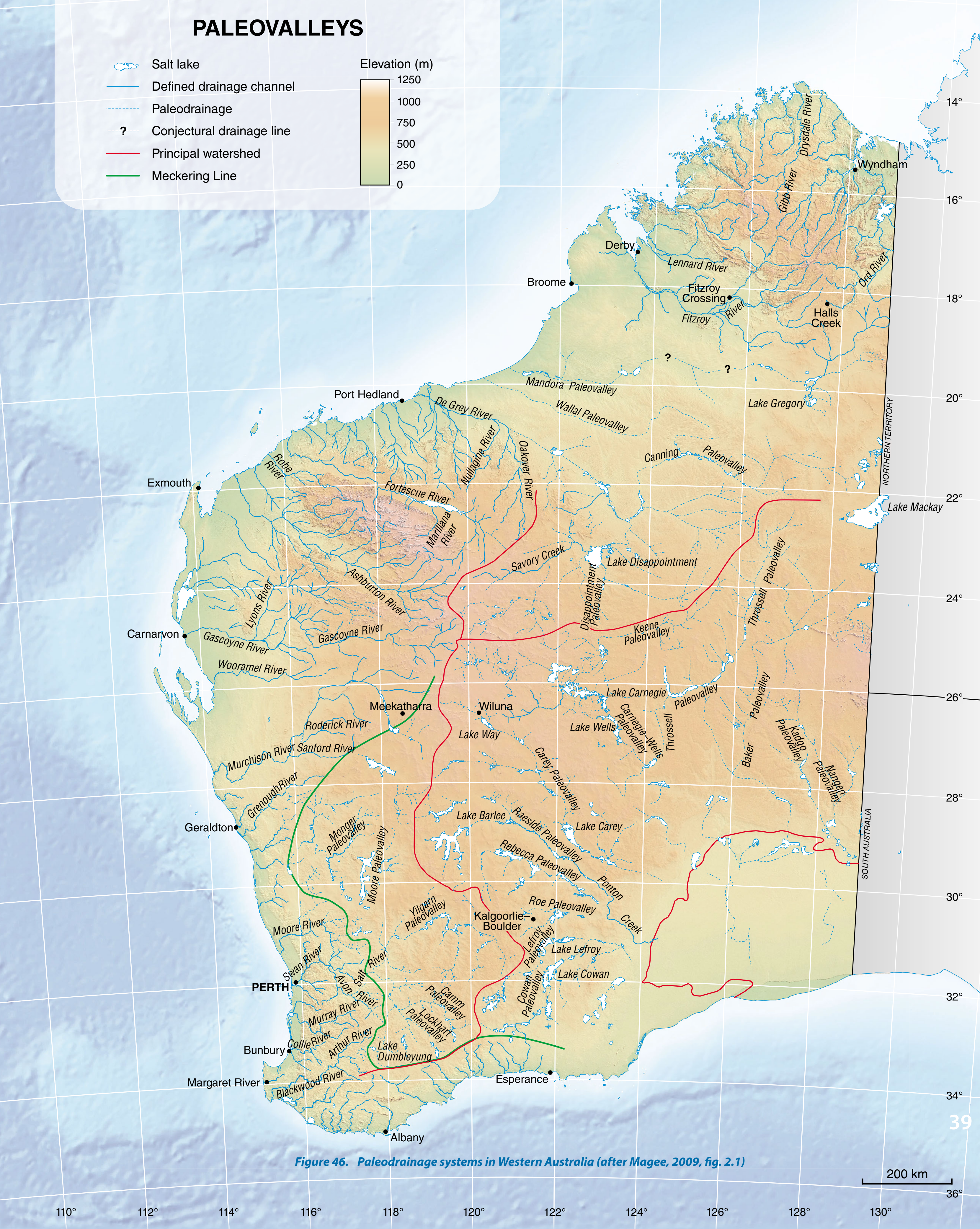


Figure 46. Paleodrainage systems in Western Australia (after Magee, 2009, fig. 2.1)

Although the paleodrainage systems are extensive, at the present time most are no longer active.

Figure 47. West entrance to Windjana Gorge on the Lennard River as sketched by Government Geologist ET Hardman in 1883 (Hardman, 1884)

The rivers in northern Australia commonly flood in the summer wet season. Dated slackwater deposits on rivers in the Kimberley region record six floods between 5000 and 30 000 m^3/s along the Fitzroy River in the last 2000 years, and some 13 floods between 2000 and 20 000 m^3/s along the upper Margaret River in the last 4000 years:

Figure 48. Murchison River gorge at the Z-bend looking north (reproduced by permission of Western Australian Land Information Authority C/L 47-2011)

these values are at the upper limit of floods recorded in northern Australia.

The main watershed runs north–south in the Yilgarn region and now separates west-draining rivers from those draining to the south. The now west-draining Yilgarn Paleoriver once drained to the south and has been diverted by river capture. The south-flowing rivers crossed the newly formed continental shelf and cut canyons in the shelf edge in the Late Cretaceous (see below). Subsequent uplift of the continent and downwarping along the Jarrahwood Axis formed the Ravensthorpe Ramp (Fig. 44) along the southern coast, creating a new southwest–northeast watershed and truncating the south-flowing rivers, which are now very short.

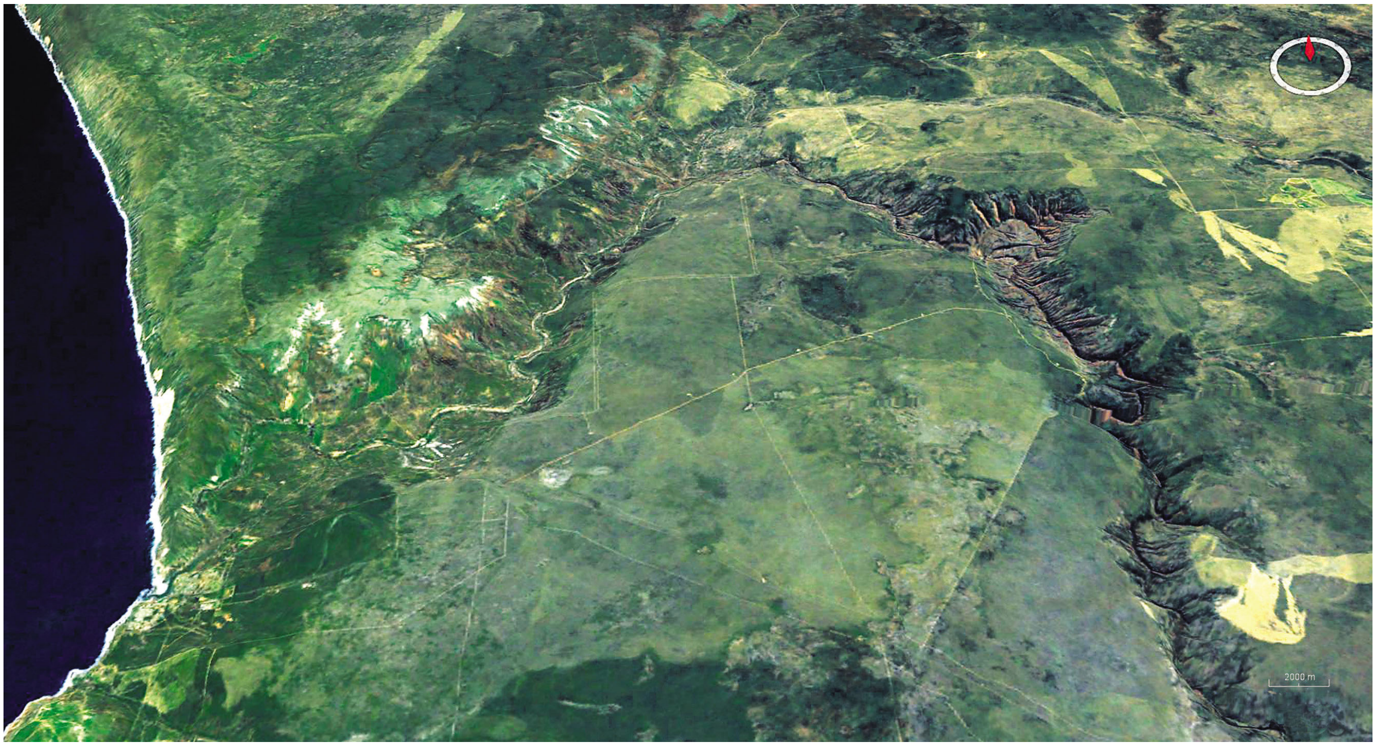
Uplift of the Yilgarn plateau and consequent rejuvenation of rivers is also seen in the rivers draining the southwest of the State, where the downstream reaches have more-incised valleys than those upstream, the change being along the Meckering Line (Fig. 46).

Some rivers in the Kimberley flow through gorges cut into the Devonian reef complexes. The Lennard River at Windjana Gorge (Fig. 47) and the

Fitzroy River at Geikie Gorge are fine examples. These gorges are thought to be exhumed Early Permian subglacial channels. Permian channels can also be seen in the east Pilbara region, where Permian Paterson Formation is preserved in broad channels, and U-shaped valleys are locally apparent.

Other gorges have been cut by the rivers themselves — a good example being the Murchison River gorge near Kalbarri, which cuts through Ordovician Tumblagooda Sandstone (Figs 48, 49). The steep-sided gorge is flanked by a broad gently sloping valley that rises to a lateritized plateau, the Victoria Plateau. There are Lower Cretaceous marine rocks locally in the valley below the level of the plateau. This suggests that the valley formed in the Jurassic or earliest Cretaceous, was later drowned, and incision of the gorge took place in the Neogene and Quaternary after lateritization of the plateau and upper valley. Uplift of the area is associated with reverse movement along the Hardabut Fault.

Figure 49. Oblique 3D view from satellite data, north from Kalbarri, of the Murchison River gorge and consolidated Quaternary dunes in cliffs along the coast. National Aeronautics and Space Administration (NASA) World Wind Image



Submarine canyons

Submarine canyons exist on the upper continental slope and extend onto the abyssal plain around the coast of Western Australia. The best known is the Perth Canyon (Fig. 50) with an area of 1820 km^2, making it second in size to the Bass Canyon, the largest in Australia. The Perth Canyon is possibly related to the ancestral Swan River, which was incised and filled with sediment in the Paleocene (see Cycle 1, in *100 million years of history*).

Canyon cutting on the North West Shelf began in the late middle Miocene. However, along the southern margin of Western Australia, river canyons developed where paleorivers debouched into the emerging ocean during uplift and erosion prior to Santonian breakup; with subsequent breakup and formation of a continental shelf these canyons became submerged. It is possible to relate the paleorivers to some of the canyons (Fig. 51); the best-known paleorivers are those south from Albany (Fig. 52). Major canyon cutting probably did not occur until the middle Eocene (c. 43 Ma) when rapid sea-floor spreading and subsidence began. Glacio-eustatic sea-level changes since the early Oligocene may have contributed to continuing canyon development as could a drop in sea level of up to 120 m in the Quaternary. More recently, knowledge has been gained from dredging and swath mapping of the canyons (Figs 52–54).

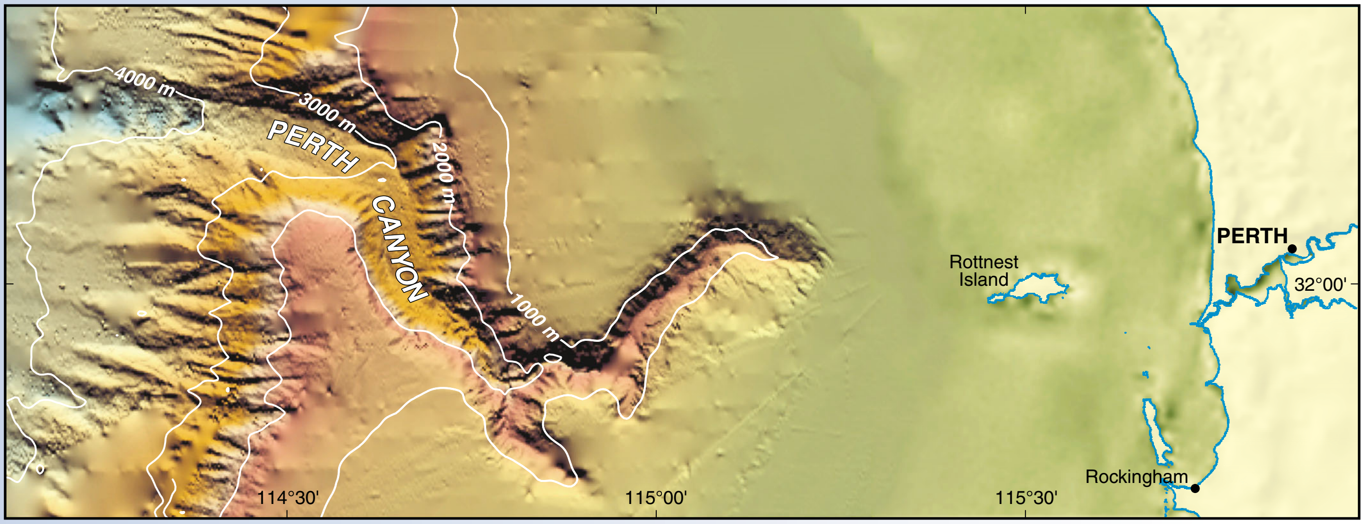


Figure 50. Bathymetry of the Perth Canyon (published with permission of Geoscience Australia)

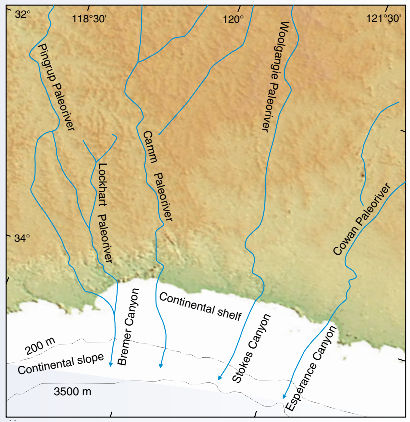


Figure 51. Possible relationship between paleodrainage systems and submarine canyons (after Beard, 1999, fig. 3)

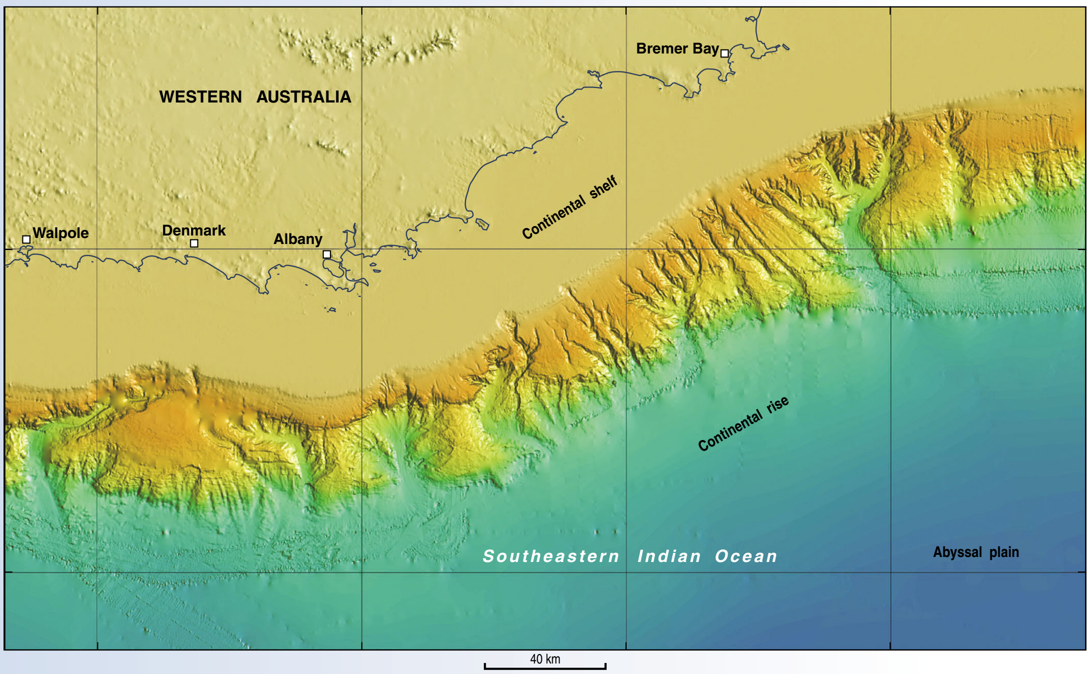


Figure 52. Relief map of the Albany Canyons based largely on multibeam bathymetry (after Exon et al., 2005, fig. 3)

Figure 53. Dredge basket of rocks from submarine canyon walls off Western Australia's southern margin. Rocks collected during 2004 geological cruise

Figure 54. Plant imprints in grey siltstone dredged from submarine canyons off Western Australia's southern margin between Denmark and Esperance

Groundwater — a vital resource

Groundwater is present in the pore space in rocks; the pore space may be primary (the intergranular space between sedimentary grains) or secondary (in fractures in igneous and metamorphic rocks). There are three main types of aquifers that hold the groundwater (Fig. 55):

i) fractured-rock aquifers, mainly in the Precambrian rocks of the Kimberley, Pilbara, and Yilgarn regions;

ii) sedimentary aquifers, in the Phanerozoic sedimentary basins, especially the Canning, Southern Carnarvon, and Perth Basins; and

iii) surficial aquifers in the coastal plains, alluvial deposits, and paleochannels overlying the sedimentary basins and fractured rock provinces.

Fractured-rock aquifers

Precambrian fractured rocks underlie about 60% of Western Australia. Groundwater is in the secondary fracture porosity resulting from weathering and tectonic processes. Such aquifers provide small but significant amounts of groundwater in arid to semi-arid parts of the State for pastoral purposes, and are a significant source of water for mining and local communities. The salinity of groundwater in the fractured-rock provinces varies markedly, irrespective of annual rainfall, but is generally high where drainage is internal, and lower where drainage is external. Due to the wide range of rock types that can form fractured-rock aquifers the groundwater may have unacceptable concentrations of sulfate, magnesium, lead, arsenic, boron, fluoride, aluminium, radon, or uranium; in addition, high levels of nitrate resulting from biological activity can exceed the recommended limits. The majority of bores used for pastoral purposes yield about 5 kL/day, but individual bore or well yields are commonly <100 kL/day but can range up to 2600 kL/day.

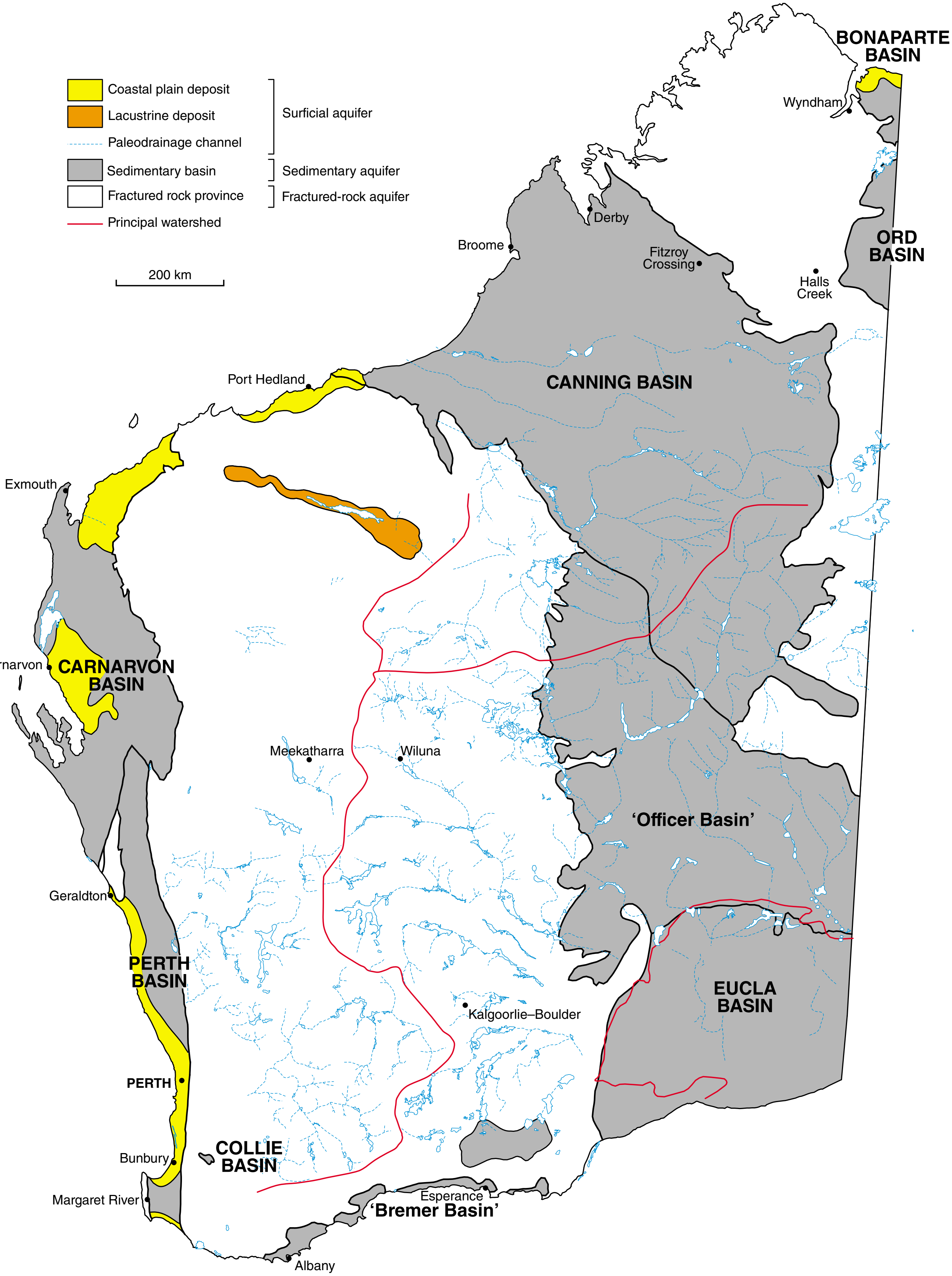


Figure 55. Distribution of the main types of groundwater aquifers (after Allen, 1997, fig. 21). Allen's (1997) basin terminology is retained here

Era	Geological systems/period	Perth	Southern Carnarvon	Canning/ 'Officer'	Eucla/ 'Bremer'
CENOZOIC	QUATERNARY	Alluvium	Alluvium	Alluvium	
CENOZOIC	NEOGENE				Abrakurrie Ls.
CENOZOIC	PALEOGENE				Wilson Bluff Ls.; Werillup Fm.
MESOZOIC	CRETACEOUS	Leederville Fm.	Birdrong Ss.	Broome Ss.	Loongana Ss.
MESOZOIC	JURASSIC	Yarragadee Fm.; Cockleshell Gully Fm.		Wallal Ss.	
MESOZOIC	TRIASSIC	Lesueur Ss.		Erskine Ss.; Millyit Ss.	
PALEOZOIC	PERMIAN	Collie CM.	Mallens Ss.; Moogooloo Ss.	Poole Ss.	
PALEOZOIC	CARBONIFEROUS			Grant Gp/ Paterson Fm.	
PALEOZOIC	DEVONIAN		Kopke Ss.	Lennis Ss.	
PALEOZOIC	SILURIAN				
PALEOZOIC	ORDOVICIAN		Tumblagooda Ss.		
PALEOZOIC	CAMBRIAN				

Figure 56. Main groundwater aquifers in some Phanerozoic sedimentary basins (after Allen, 1997, fig. 22)

Sedimentary aquifers

The sedimentary aquifers contain the greatest volumes of groundwater and are capable of providing the largest supplies, with individual bores yielding up to 20 000 kL/day. The principal aquifers in the Phanerozoic sedimentary basins are sandstone, interbedded sequences of sandstone, shale and siltstone, and limestone. The major aquifers are shown in Figure 56. Some of these aquifers extend over very large areas and vary greatly in thickness, e.g. the Yarragadee Formation aquifer in the Perth Basin is >40 000 km^2 in area and about 2500 m thick; and the Birdrong Sandstone aquifer in the Southern Carnarvon Basin is >77 000 km^2 in area and some 30 m thick.

Groundwater salinity varies considerably between basins depending on location, topography, and climate, and varies with depth in individual aquifers, and between different aquifers. In general, the freshest groundwater is in the unconfined aquifers, but in the Perth Basin there is also low-salinity groundwater in the Yarragadee Formation. The groundwater contains mainly sodium and chloride, with lesser amounts of calcium, magnesium, potassium, sulfate, and bicarbonate, and may contain various trace elements, heavy metals, and dissolved gases. Groundwater temperature increases with depth from 2–5°C/100 m.

The sedimentary aquifers contain the greatest volumes of groundwater and are capable of providing the largest supplies.

Historically, artesian groundwater from the sedimentary aquifers was sought after as it minimized the need for pumping. In the Southern Carnarvon Basin, most artesian pastoral bores, which used to flow freely, are now controlled, and in other areas, principally around Perth, pressures have declined and the bores have become subartesian, needing to be pumped.

Surficial aquifers

Although surficial, mainly Cenozoic, sediments are widespread, they generally form aquifers only along drainage lines and on the coastal plains where they are relatively thick. In many areas they may contain local perched groundwater that can facilitate recharge into underlying fractured-rock or sedimentary aquifers. Large surficial aquifers are in the paleodrainage channels, on the Swan Coastal Plain in the Perth Basin, and in alluvial and deltaic deposits, particularly on the Ord, Fitzroy, De Grey, Yule, Fortescue, Robe, and Gascoyne Rivers. The salinity of the groundwater in the surficial aquifers is generally fresh to brackish, except in the paleodrainage channels where some groundwater may reach 300 000 mg/L TDS.

The surficial aquifers have been the most readily accessible sources of groundwater. Groundwater from surficial aquifers in Perth (Gnangara and Jandakot Mounds), Kununurra, Port Hedland, Newman, Carnarvon, and Esperance is used for public water supplies. These aquifers are also utilized as sources of groundwater for irrigated agriculture (at Carnarvon and in the Perth region), and as the major source of water for the mining industry, particularly in the Kalgoorlie region. Individual bores may yield up to 5000 kL/day.

In recent years, desalinated seawater has been used to supply about half of Perth's water requirements.

Water sources and resources

Water supply in Western Australia comes from three sources: surface water (rivers and lakes), groundwater, and desalination of seawater. The relative contribution from each source has changed over the years. Surface water and groundwater met the requirements in the early years of settlement, with the building of dams and sinking of bores, many of them artesian. Water from the Mundaring Dam supplied communities in the Eastern Goldfields around Coolgardie and Kalgoorlie via a pipeline. Other dams (Serpentine and Canning) supplied water to the Perth Metropolitan area. The more-recent damming of the Ord River to form Lake Argyle supplies water for agricultural development in the Kununurra area. An important source of water in the Perth area is groundwater from the Leederville and Yarragadee aquifers, and from the surficial aquifers in the Gnangara and Jandakot Mounds. Groundwater at Millstream and in the surficial aquifers in several rivers in the Pilbara has been utilized for domestic and mining supplies to service the iron ore industry in the region. In recent years, desalinated seawater has been used to supply about half of Perth's water requirements in response to the growth in population, decreasing rainfall, and increasing concern for overpumping and its effect on Perth's wetlands. Environmental concerns have also affected the proposed development of the Yarragadee aquifer in the southwest of the State.

Groundwater is a renewable resource, and the long-term sustainable yield depends on the rate of recharge from rainfall or streamflow. The State is divided into groundwater areas with allocation limits — the amount available to be licensed for consumptive use — set for each aquifer. In the sedimentary basins, allocation limits generally reflect what is assessed to be a sustainable yield. In the fractured-rock provinces, where it is not possible to determine regional sustainable yields, projects are assessed on an individual basis, and allocation limits reflect what has been licensed. In some areas, such as the Eastern Goldfields, depletion of saline groundwater with very low recharge rates is allowed. The 2008 total allocation limit for all groundwater in the State was set at 3864 GL, of which 2358 GL are in surficial and sedimentary basin aquifers and 1506 GL in fractured-rock aquifers.

Intermittent flooding of the Gascoyne River rejuvenates surficial aquifers

Dreamtime and after: finding *Terra Australis Incognito*

Terra Australis Incognito — the unknown land of the south — was shown on many European maps of the Middle Ages (Fig. 57). The concept of a hypothetical continent in the Southern Hemisphere to balance the landmasses in the Northern Hemisphere goes back to the Ancient Greeks, although the geographer Ptolemy did not actually show it on his map. The voyages of various explorers failed to find the continent, and on his second journey James Cook sailed around the globe at very high southern latitudes demonstrating that the continent, if it existed, must be small and separate from Australia and New Zealand.

We owe the name Australia to Matthew Flinders, who in 1814 wrote, 'There is no probability that any other detached body of land, of nearly equal extent, will ever be found in a more southern latitude; the name *Terra Australis* will, therefore, remain descriptive of the geographical importance of this country, and of its situation on the globe' and in a footnote, 'Had I permitted myself any innovation upon the original term, it would have been to convert it into Australia; as being more agreeable to the ear....' The hypothetical southern continent was finally sighted by Bellinghausen six years later and was eventually called Antarctica by the Scottish cartographer John Bartholomew.

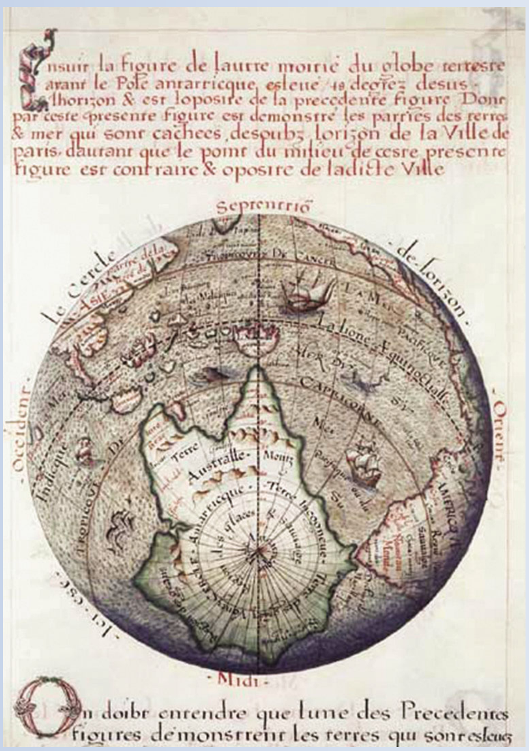


Figure 57. 1583 map of Terra Australis (open-source map)

The Aboriginal people were unperturbed by the arguments as to whether their continent existed. They had been living here for at least 50 000 years — some would say 125 000 years — and spread across the continent, speaking some 250 different languages. Aboriginal beliefs have a period known as the Dreamtime that stretches back into the distant past when their ancestors travelled across the land, creating and naming as they went. For example, in Perth, the Noongar people believe that the Darling Scarp represents the body of a Wagyl — a serpent being that meandered over the land creating rivers, including the Swan River, waterways, and lakes (Fig. 58). It is possible that the Wagyl story may represent the racial memory in oral tradition of the extinct giant (5–6 m long) python, *Wonambi naracoortensis* (Fig. 26), remains of which lie in caves such as Devil's Lair in the southwest of the State.

Figure 58. Rock painting showing the Wagyl (open-source image)

The first European known to land on Western Australia was Dirk Hartog, who landed at Cape Inscription on Dirk Hartog Island, Shark Bay, in 1616. European settlement dates from 1826, when Edmund Lockyer established an outpost, later to be named Albany, on King George Sound on the south coast. The founding father of modern Western Australia was James Stirling who, in 1827, explored the Swan River area.

The colonial gold rushes

Western Australia was 'the poor relation' of the Australian colonies in the mid-1800s. In 1872, to boost the population and growth of the colony, the Government offered a reward of £5000 (roughly A$750 000 today) for the discovery of the colony's first payable goldfield — equivalent to the production of 10 000 troy ounces (311 035 g) of gold.

Alexander Forrest led an exploring party through the Kimberely in 1879, and similarities between the region and gold-bearing rocks of Pine Creek, Northern Territory attracted the first prospecting parties into Western Australia. In 1882 Phil Saunders and Adam Johns traversed the area of the future Halls Creek finding traces of gold. Geologist Edward Hardman accompanied HF Johnston's survey party and panned gold in several rivers, particularly in the Elvire River. Hardman's report and map were released in 1884, encouraging exploration in the east Kimberley; and finally Charles Hall, John Slattery, and party found payable gold at a place they named 'Halls Creek' on 14 July 1885 to start the Kimberley gold rush. It was extremely remote: for prospectors to even get to Halls Creek entailed a walk of 600 km from the port of Derby!

However, the alluvial gold soon petered out and the early promise of the underground mines did not eventuate. Remote Halls Creek never really flourished. Official recorded production from Halls Creek amounted to 8668 troy ounces, short of the required 10 000 troy ounces for the reward. However, production must have been larger, perhaps nearer 20 000 troy ounces as claimed by Charles Hall. Western Australia, alone among the colonies, placed a duty on gold and some miners preferred to smuggle out their gold. The Government never paid the full reward.

The Kimberley gold rush was an important watershed for Western Australia. It marked the beginning of the mining industry (despite modest amounts of base metals and coal already being mined), drawing attention to the colony and its gold potential. Prospectors attracted to the Kimberley rush went on to make discoveries elsewhere in Western Australia. Rich alluvial gold was discovered in the Pilbara. Southern Cross was discovered in 1888, the Murchison in 1891, and Coolgardie in 1892. The famous Hannans rush of 1893 set-up the town of Kalgoorlie and ultimately carried Western Australia into the Commonwealth in 1901.

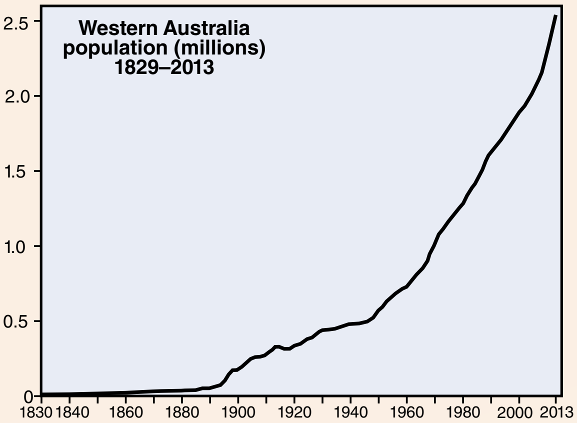


Figure 59. Growth of the population of Western Australia between 1829 and 2013 (Australian Bureau of Statistics, 2013a)

Shortly afterwards the Swan River Colony was established by Charles Fremantle in 1829. Initial growth of the colony was slow, with many setbacks, not least the difficulty of clearing land for agriculture. Originally a 'free settlement', it became a penal colony in 1850 in an effort to build more public infrastructure. The early settlers explored extensively, looking for farming land and minerals, and became the first to investigate the geology of the State.

Lead was discovered at Galena in the lower Murchison River in 1848, and coal was discovered at Collie in 1883. Although gold was found at Halls Creek in 1885 (see box, *The Colonial gold rushes*), it was not until Paddy Hannan discovered gold near Kalgoorlie, in 1893, that gold fever came to Western Australia and the population rapidly increased (Fig. 59, see box on page 30, *Nuggets*). The State's mineral resources have been the backbone of the economy ever since (Fig. 60). Although 'Our land abounds in nature's gifts' it is the work of many generations of geologists, including those of the Geological Survey of Western Australia (see box, *About GSWA*) that has made it indeed 'The Lucky Country'.

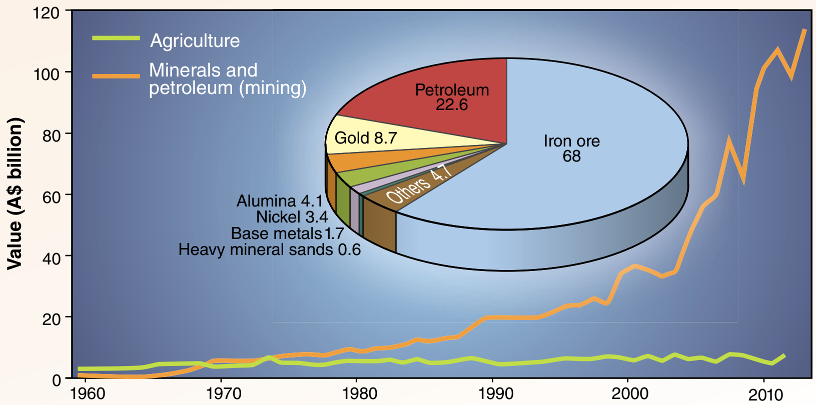


Figure 60. Review of agricultural and mining production from 1960 to 2011–12 and 2013; and value of production to end 2013 of Western Australia's major resource commodities in A$ billion (Australian Bureau of Statistics, 2013b and Department of Mines and Petroleum, 2014). Petroleum includes all petroleum products, Others includes salt, coal, cobalt, diamond, manganese

About GSWA

The Geological Survey of Western Australia (GSWA) was founded in 1888 with the appointment of Harry Page Woodward to the newly created permanent position of Government Geologist to the then colony of Western Australia. GSWA — the first scientific organization in Western Australia — has ever since been at the forefront of the mapping and assessment of the State's geology, mineral, energy, and basic raw material resources to provide a basis for encouraging private sector mineral and energy exploration, decision making by all levels of government, and to respond to a variety of community needs.

GSWA research is strongly field-oriented, and includes regional geological mapping, terrane and basin analysis, geochronology, and mineralization studies. Systematic, State-wide bedrock geology mapping at 1:250 000 scale over more than three decades is summarized in the latest State Geological Map (the thirteenth published by GSWA), and about 30% of Western Australia has been mapped at 1:100 000 scale. Regolith, geochemistry, hydrogeology, and urban geology maps have been produced at various scales for selected parts of the State.

GSWA's activities stimulate exploration, particularly in underexplored areas, for the long-term sustainability of the State's resources sector. In conjunction with universities, industry, CSIRO, and Geoscience Australia, GSWA is documenting the geology of the State to develop robust interpretations of tectonic setting, crustal architecture, and geological evolution for regional metallogenic modelling and prospectivity analyses. Some specific projects being undertaken are: seismic reflection profiling across the margins of the cratons; aeromagnetic surveys across large swaths of the State; 3D architectural modelling studies; prospectivity studies of under-explored regions; and a geochemical sampling project covering the Kimberley region.

Further reading

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Maps of Western Australia

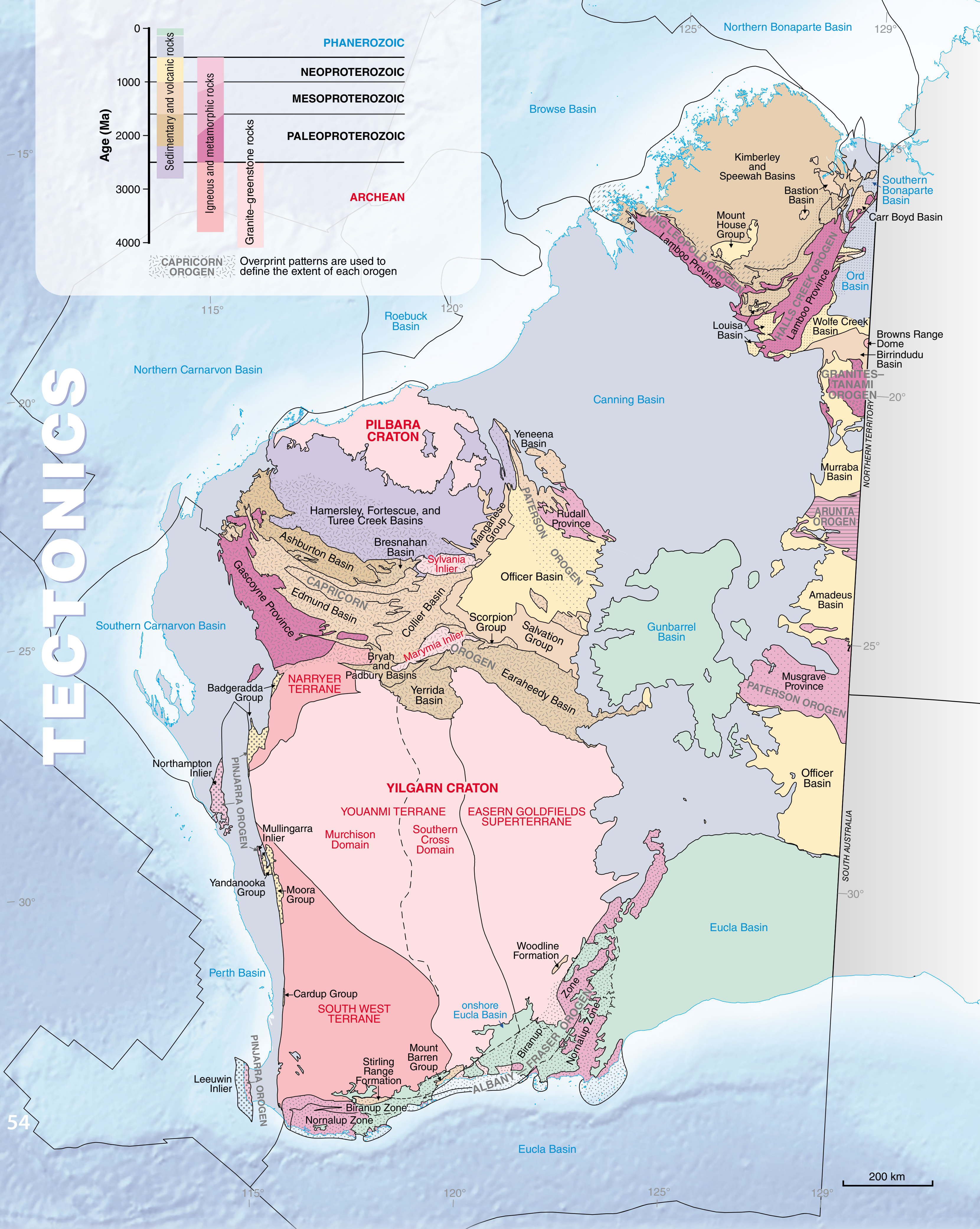
Tectonics of Western Australia

Geology of Western Australia

Cenozoic and regolith-enriched mineralization in Western Australia

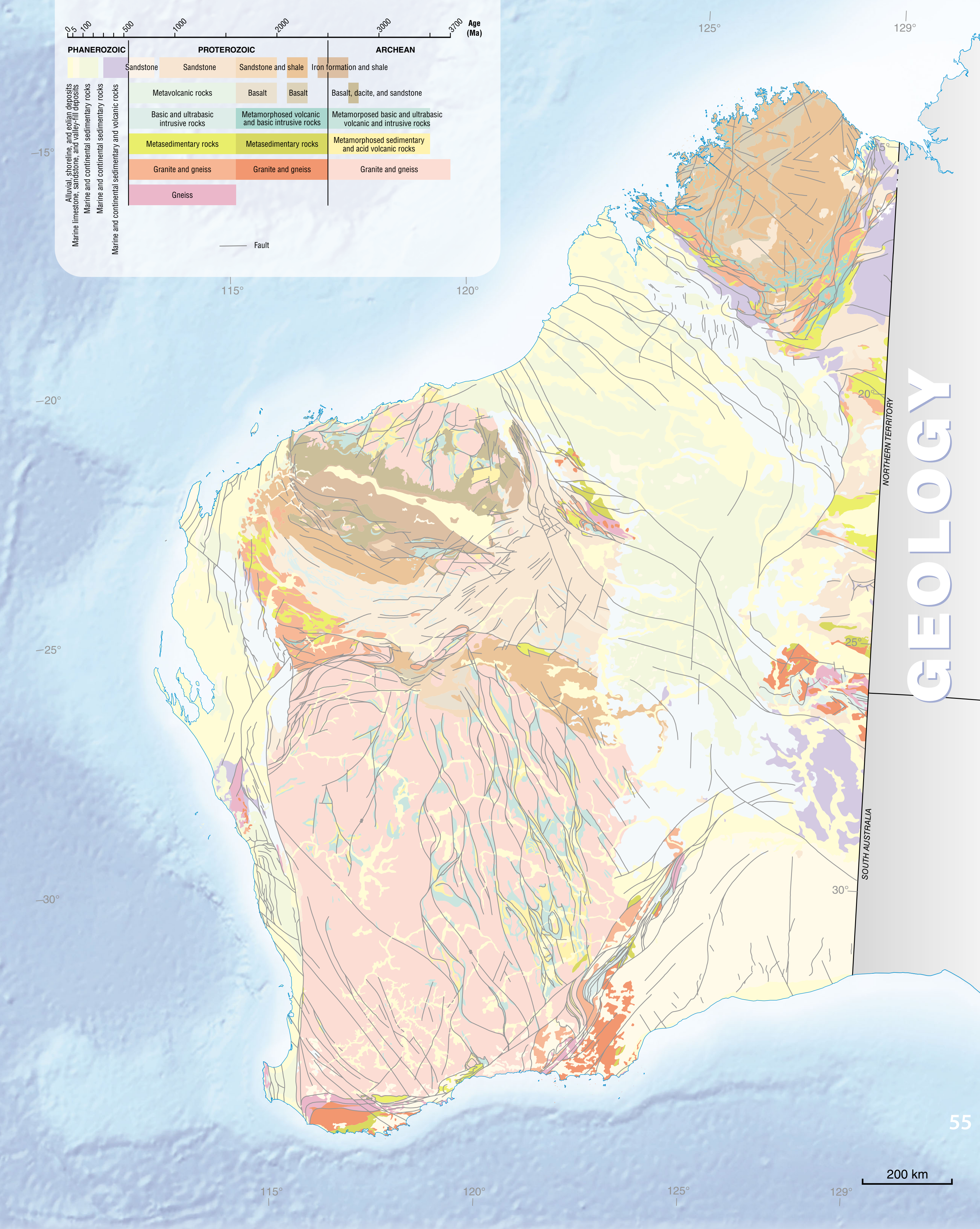
Localities mentioned in text

TECTONICS

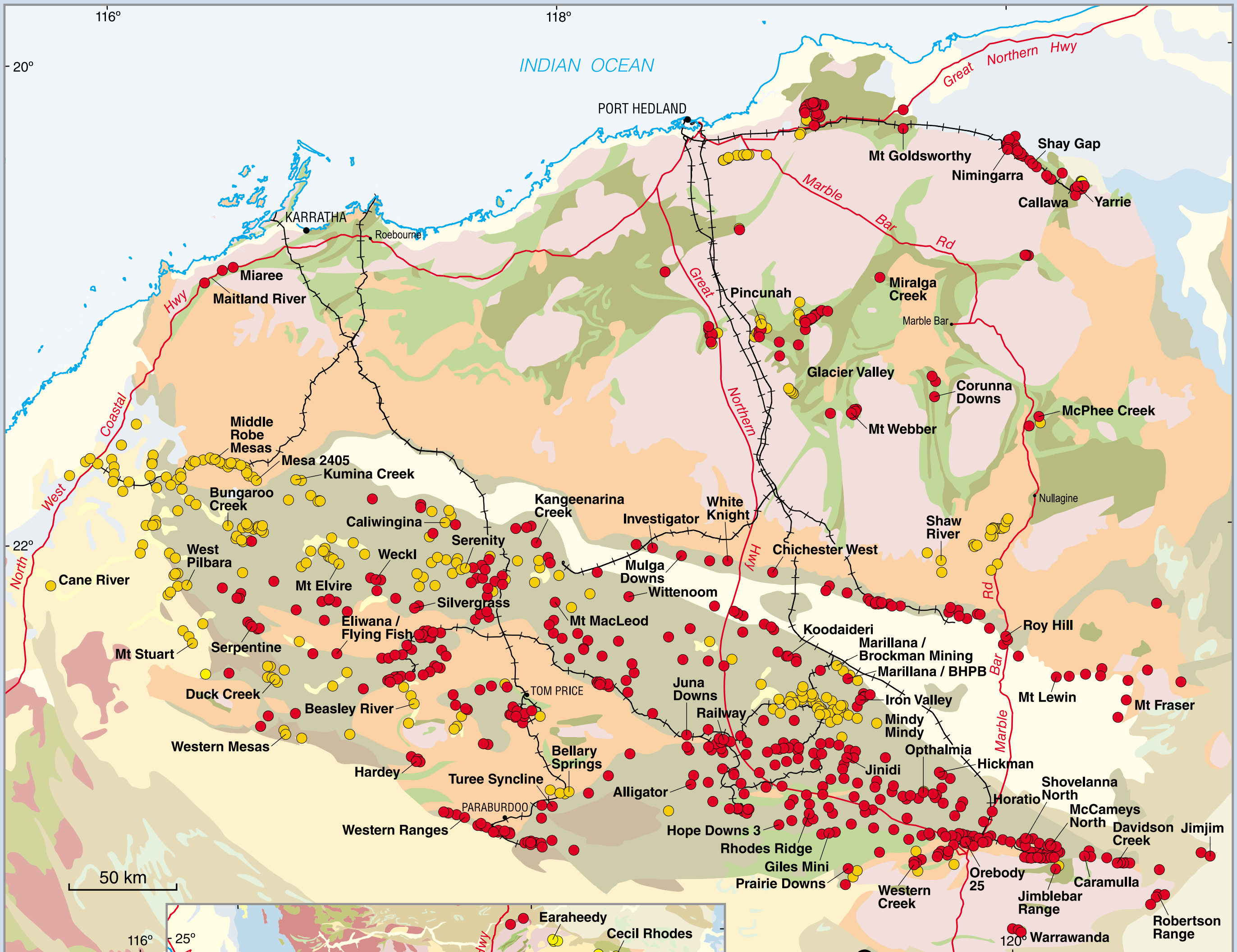


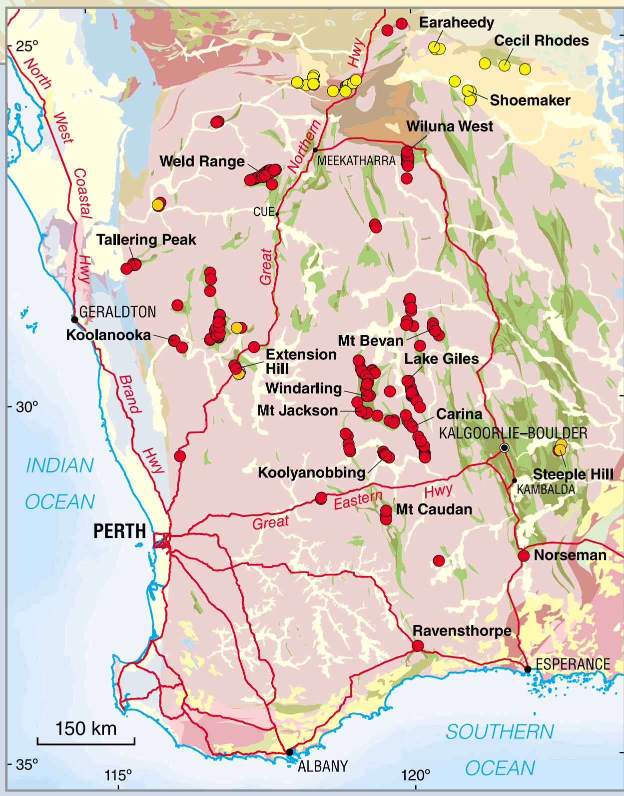
Age (Ma)
0
1000
2000
3000
4000
Sedimentary and volcanic rocks
Igneous and metamorphic rocks
Granite–greenstone rocks
PHANEROZOIC
NEOPROTEROZOIC
MESOPROTEROZOIC
PALEOPROTEROZOIC
ARCHEAN
CAPRICORN OROGEN
Overprint patterns are used to define the extent of each orogen
Northern Bonaparte Basin
Browse Basin
Kimberley and Speewah Basins
Bastion Basin
Mount House Group
Southern Bonaparte Basin
Carr Boyd Basin
KING LEOPOLD OROGEN
Lamboo Province
HALLS CREEK OROGEN
Lamboo Province
Ord Basin
Louisa Basin
Wolfe Creek Basin
Browns Range Dome
Birrindudu Basin
GRANITES–TANAMI OROGEN
Roebuck Basin
Northern Carnarvon Basin
Canning Basin
PILBARA CRATON
Yeneena Basin
Hamersley, Fortescue, and Turee Creek Basins
Rudall Province
Manganese Group
PATERSON OROGEN
Murraba Basin
NORTHERN TERRITORY
ARUNTA OROGEN
Bresnahan Basin
Ashburton Basin
Sylvania Inlier
Gascoyne Province
CAPRICORN OROGEN
Edmund Basin
Collier Basin
Officer Basin
Amadeus Basin
Scorpion Group
Salvation Group
Gunbarrel Basin
Southern Carnarvon Basin
Marymia Inlier
Bryah and Padbury Basins
Earaheedy Basin
Musgrave Province
PATERSON OROGEN
NARRYER TERRANE
Badgeradda Group
Yerrida Basin
Officer Basin
Northampton Inlier
PINJARRA OROGEN
YILGARN CRATON
YOUANMI TERRANE
EASERN GOLDFIELDS SUPERTERRANE
Mullingarra Inlier
Murchison Domain
Southern Cross Domain
SOUTH AUSTRALIA
Yandanooka Group
Moora Group
Eucla Basin
Woodline Formation
Perth Basin
Cardup Group
onshore Eucla Basin
SOUTH WEST TERRANE
Zone
FRASER OROGEN
Biranup
Nornalup Zone
Mount Barren Group
Stirling Range Formation
ALBANY
Leeuwin Inlier
PINJARRA OROGEN
Biranup Zone
Nornalup Zone
Eucla Basin
200 km
115°
120°
125°
129°
15°
20°
25°
30°

GEOLOGY



0 5 100 500 1000 2000 3000 3700 Age (Ma)
PHANEROZOIC
PROTEROZOIC
ARCHEAN
Alluvial, shoreline, and eolian deposits
Marine limestone, sandstone, and valley-fill deposits
Marine and continental sedimentary rocks
Marine and continental sedimentary rocks
Marine and continental sedimentary and volcanic rocks
Sandstone
Sandstone
Sandstone and shale
Iron formation and shale
Metavolcanic rocks
Basalt
Basalt
Basalt, dacite, and sandstone
Basic and ultrabasic intrusive rocks
Metamorphosed volcanic and basic intrusive rocks
Metamorposed basic and ultrabasic volcanic and intrusive rocks
Metasedimentary rocks
Metasedimentary rocks
Metamorphosed sedimentary and acid volcanic rocks
Granite and gneiss
Granite and gneiss
Granite and gneiss
Gneiss
Fault
NORTHERN TERRITORY
SOUTH AUSTRALIA
115°
120°
125°
129°
–15°
–20°
–25°
–30°
200 km

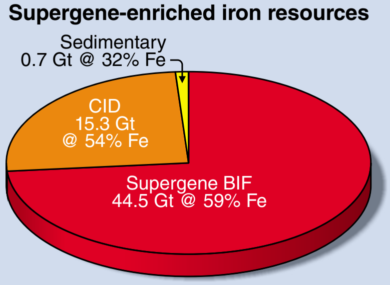




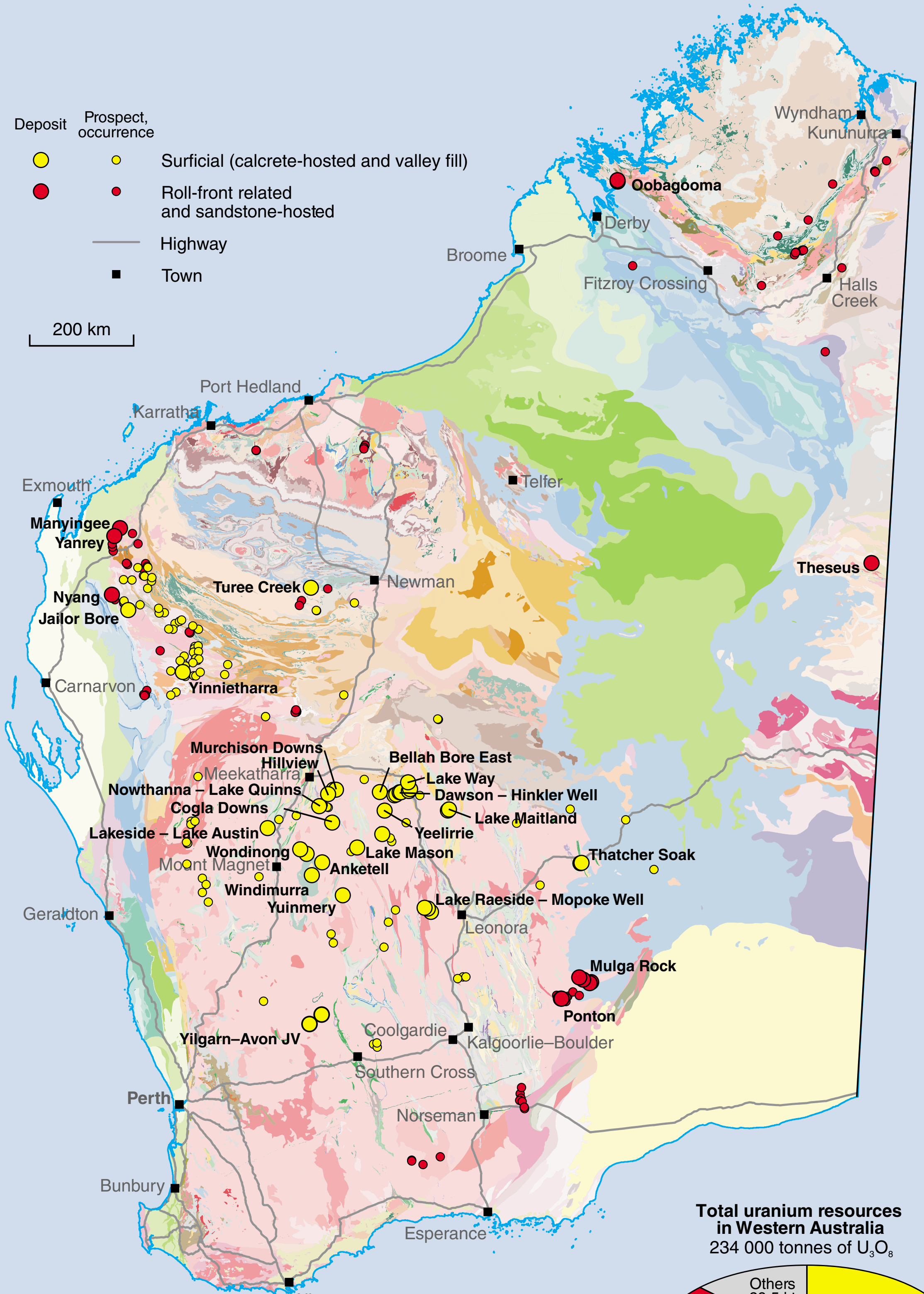
Mines, deposits, and prospects

- Pisolite/CID
- Sedimentary
- Enriched BIF
- Major road
- Railway, operating
- Town

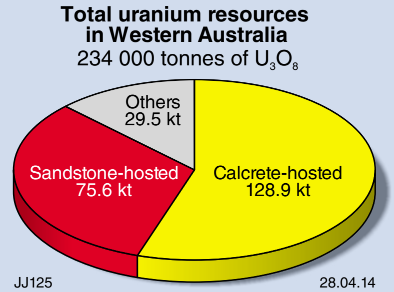
Supergene-enriched iron resources



URANIUM



Deposit
Prospect, occurrence
Surficial (calcrete-hosted and valley fill)
Roll-front related and sandstone-hosted
Highway
Town
200 km
Wyndham
Kununurra
Oobagooma
Derby
Broome
Fitzroy Crossing
Halls Creek
Port Hedland
Karratha
Telfer
Exmouth
Manyingee
Yanrey
Theseus
Turee Creek
Newman
Nyang
Jailor Bore
Carnarvon
Yinnietharra
Murchison Downs
Hillview
Meekatharra
Bellah Bore East
Lake Way
Nowthanna – Lake Quinns
Dawson – Hinkler Well
Cogla Downs
Lake Maitland
Lakeside – Lake Austin
Yeelirrie
Wondinong
Lake Mason
Mount Magnet
Anketell
Thatcher Soak
Windimurra
Yuinmery
Lake Raeside – Mopoke Well
Geraldton
Leonora
Mulga Rock
Ponton
Yilgarn–Avon JV
Coolgardie
Kalgoorlie–Boulder
Southern Cross
Perth
Norseman
Bunbury
Esperance

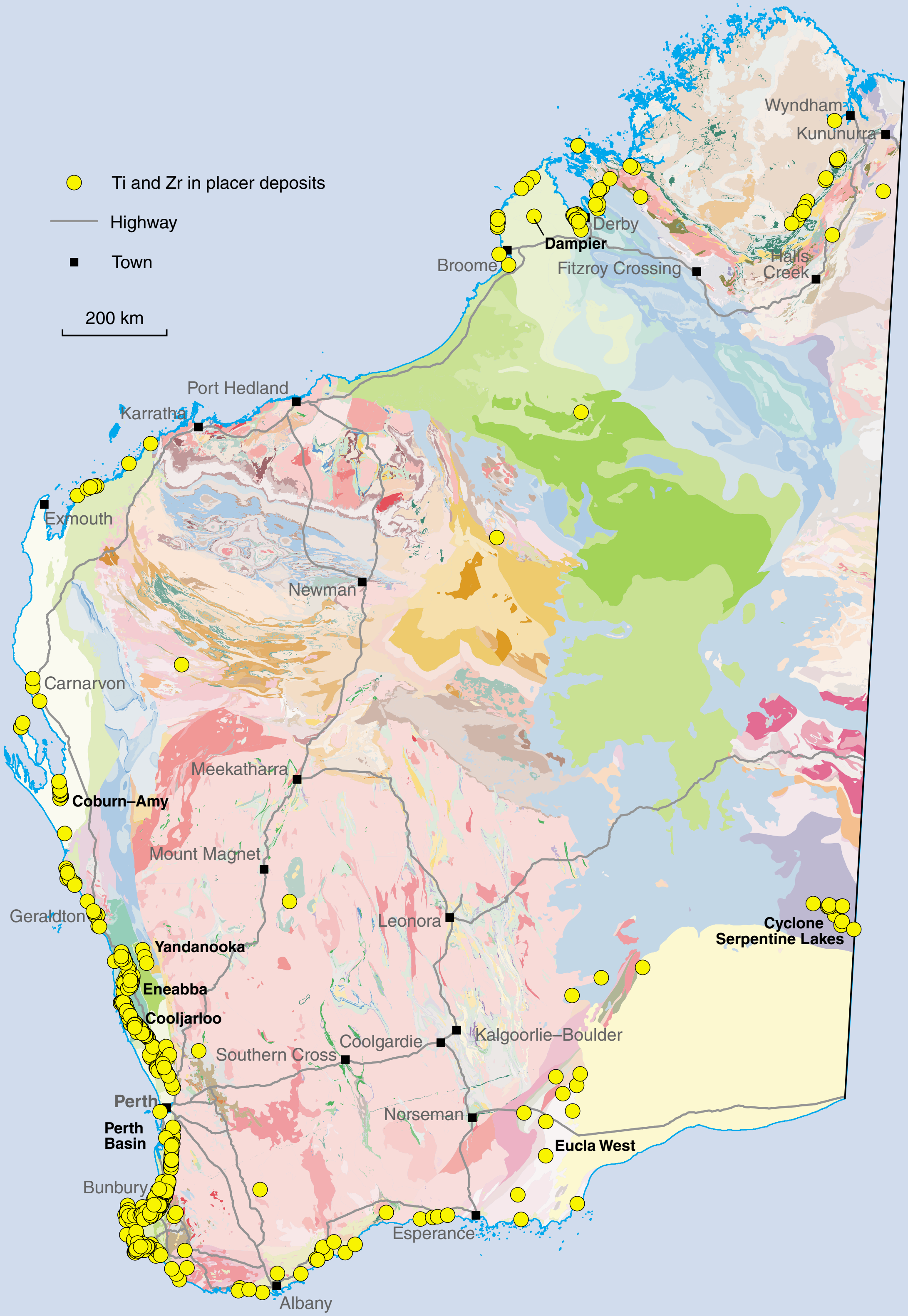


Total uranium resources in Western Australia
234 000 tonnes of U_3O_8
Others 29.5 kt
Sandstone-hosted 75.6 kt
Calcrete-hosted 128.9 kt
JJ125
28.04.14

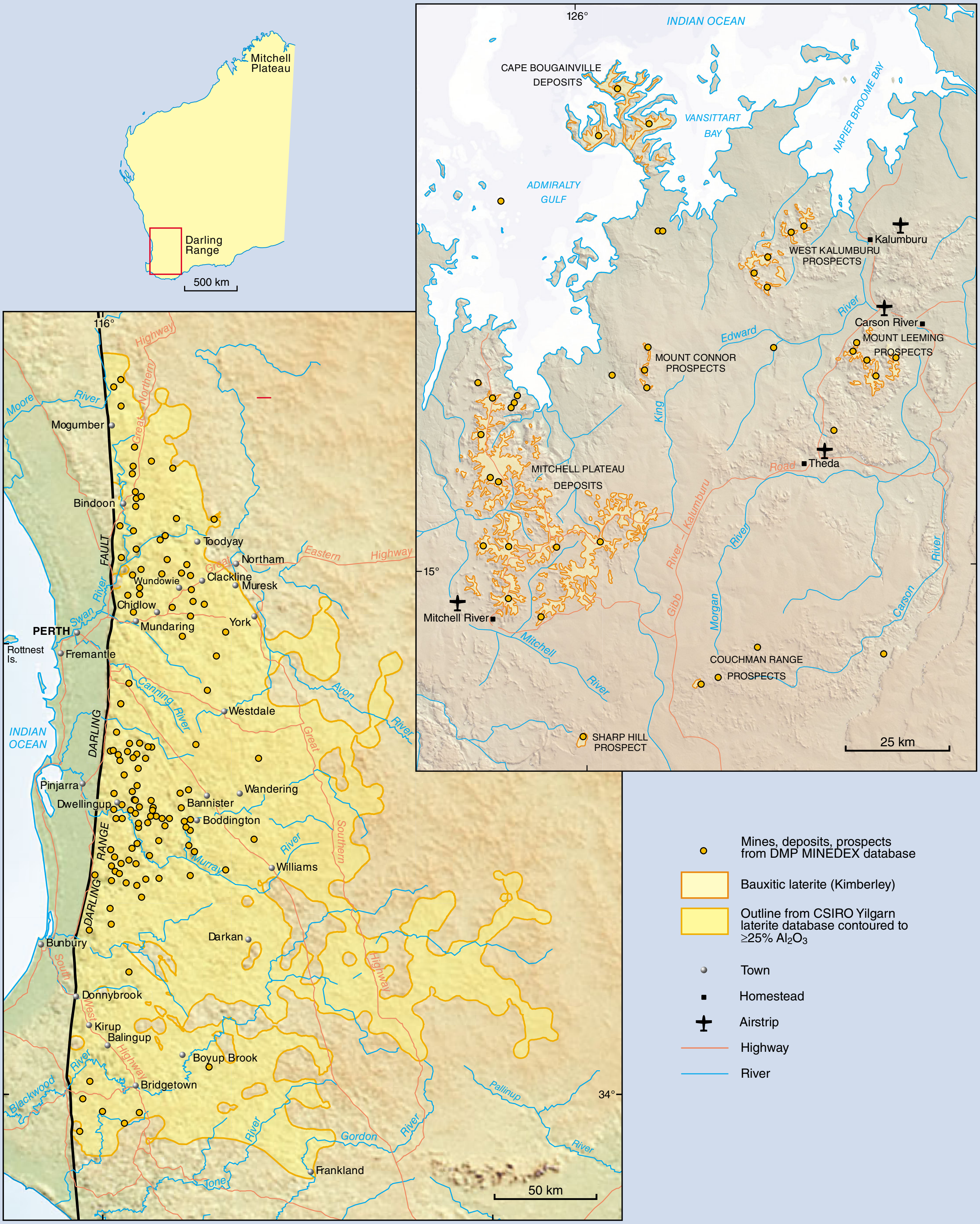
LATERITIC NICKEL

Mineralization style	Historic production (kt)	Current resources (kt)	Total (kt)
Lateritic nickel	416	25 618	26 034
Nickel sulfide	3693	12 013	15 706
Total	**4109**	**37 631**	**41 740**

Note: Data on a 'contained nickel' basis


Ti and Zr in placer deposits
Highway
Town
200 km
Wyndham
Kununurra
Derby
Dampier
Broome
Fitzroy Crossing
Halls Creek
Port Hedland
Karratha
Exmouth
Newman
Carnarvon
Meekatharra
Coburn–Amy
Mount Magnet
Geraldton
Leonora
Yandanooka
Eneabba
Cooljarloo
Cyclone
Serpentine Lakes
Coolgardie
Kalgoorlie–Boulder
Southern Cross
Perth
Perth Basin
Norseman
Eucla West
Bunbury
Esperance
Albany

BAUXITE

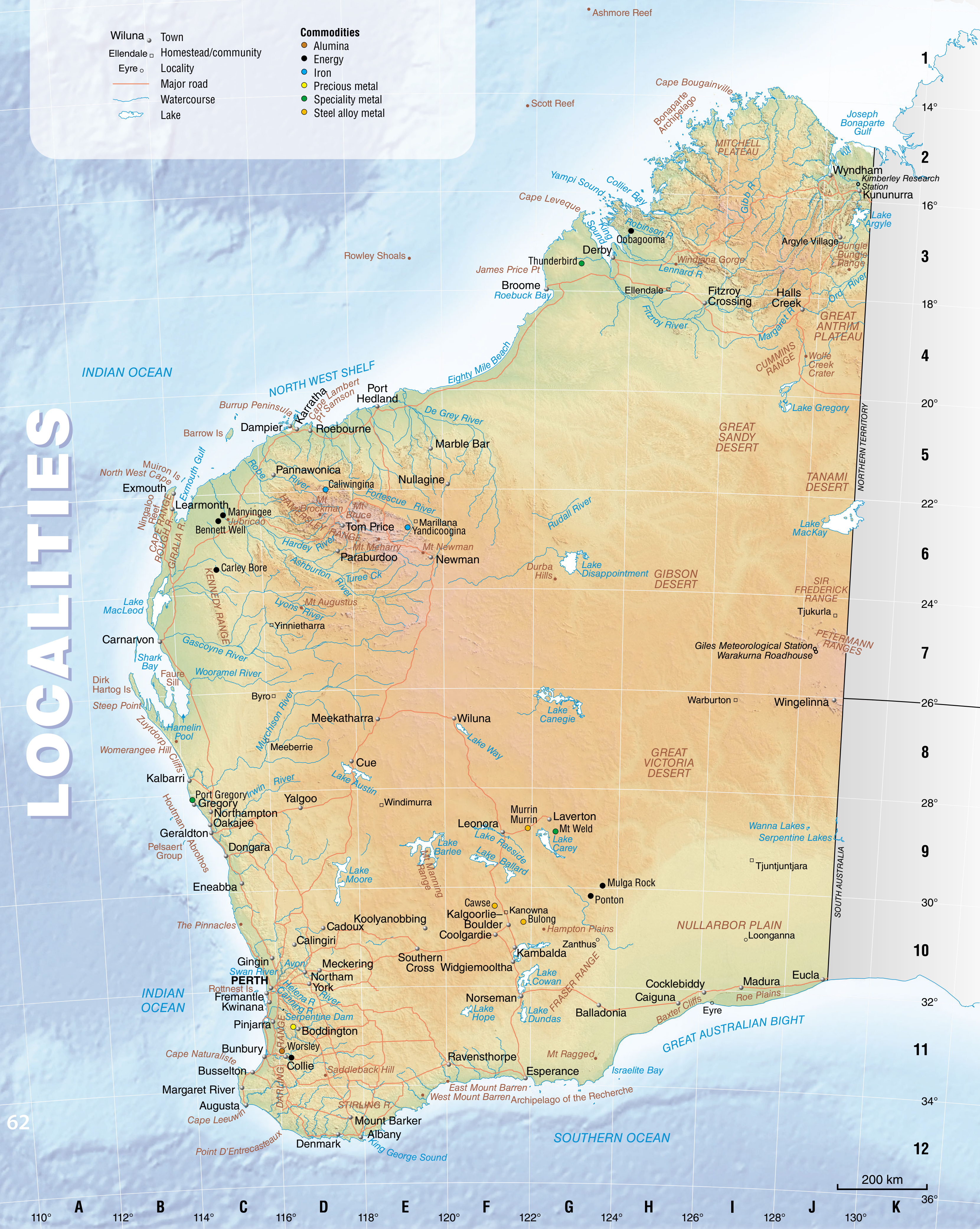

Mitchell Plateau
Darling Range
500 km
126°
INDIAN OCEAN
CAPE BOUGAINVILLE DEPOSITS
VANSITTART BAY
NAPIER BROOME BAY
ADMIRALTY GULF
Kalumburu
WEST KALUMBURU PROSPECTS
Carson River
MOUNT LEEMING PROSPECTS
MOUNT CONNOR PROSPECTS
Edward
River
King
Theda
Road
MITCHELL PLATEAU DEPOSITS
River – Kalumburu
Gibb
River
Morgan
15°
Mitchell River
Mitchell
River
Carson
River
COUCHMAN RANGE PROSPECTS
SHARP HILL PROSPECT
25 km
116°
Highway
Northern
Great
Moore
River
Mogumber
Bindoon
Toodyay
FAULT
Northam
Eastern
Highway
Great
Clackline
Wundowie
Muresk
Swan
River
Chidlow
PERTH
Mundaring
York
Rottnest Is.
Fremantle
Canning
River
Avon
River
Westdale
INDIAN OCEAN
DARLING
Great
Pinjarra
Wandering
Dwellingup
Bannister
Boddington
RANGE
River
Southern
Murray
Williams
DARLING
Bunbury
Darkan
Highway
South
Donnybrook
West
Kirup
Balingup
Highway
Boyup Brook
River
Blackwood
Bridgetown
Palinup
34°
River
Gordon
River
River
Frankland
Tone
50 km
Mines, deposits, prospects from DMP MINEDEX database
Bauxitic laterite (Kimberley)
Outline from CSIRO Yilgarn laterite database contoured to ≥25% Al_2O_3
Town
Homestead
Airstrip
Highway
River

Index to Localities map

Name	Category	Ref
Albany	Town	D12
Archipelago of the Recherche		G12
Argyle Village	Town	J3
Ashburton River		D6
Ashmore Reef		G1
Augusta	Town	C12
Avon River		D11
Balladonia	Locality	G11
Barrow Island		C5
Baxter Cliffs		H11
Bennett Well	U	C6
Boddington	Au Cu	D11
Boddington	Town	D11
Bonaparte Archipelago		H2
Broome	Town	G3
Bulong	Ni Co	F10
Bunbury	Town	C11
Bungle Bungle Range		J3
Burrup Peninsula		D5
Busselton	Town	C11
Byro	Homestead	D8
Cadoux	Town	D10
Caiguna	Town	H11
Calingiri	Town	D10
Caliwingina	Fe	D5
Canning River		D11
Cape Bougainville		I1
Cape Lambert		D5
Cape Leeuwin		C12
Cape Leveque		G3
Cape Naturaliste		C11
Cape Range		B6
Carley Bore	U	C6
Carnarvon	Town	B7
Cawse	Ni Co	F10
Cocklebiddy	Town	I11
Collie	Coal	D11
Collie	Town	D11
Collier Bay		H3
Coolgardie	Town	F10
Cue	Town	D8
Cummins Range	REE	I4
Dampier	Town	D5
Darling Range		D11
De Grey River		E5
Denmark	Town	D12
Derby	Town	G3
Dirk Hartog Island		B7
Dongara	Town	C9
Durba Hills		G6
East Mount Barren		F11
Eighty Mile Beach		F4
Ellendale	Homestead	H3
Eneabba	Town	C9

Name	Category	Ref
Esperance	Town	F11
Eucla	Town	J10
Exmouth	Town	C5
Exmouth Gulf		C6
Eyre	Locality	I11
Faure Sill	Seagrass bank	C7
Fitzroy Crossing	Town	H4
Fitzroy River		H4
Fortescue River		E6
Fraser Range		G11
Fremantle	Town	C11
Gascoyne River		C7
Geraldton	Town	C9
Gibb River		I3
Gibson Desert		H7
Giles Meteorological Station		J7
Gingin	Town	C10
Giralia Range		C6
Great Antrim Plateau		J4
Great Australian Bight		I11
Great Sandy Desert		I5
Great Victoria Desert		H8
Gregory	Town	C9
Halls Creek	Town	I4
Hamelin Pool		C8
Hamersley Range		D6
Hampton Plains		G10
Hardey River		D6
Helena River		D11
Houtman Abrolhos	Island group	B9
Indian Ocean		B4
Irwin River		C9
Israelite Bay		G11
James Price Point		G3
Joseph Bonaparte Gulf		J2
Jubricoo	Hill	C6
Kalbarri	Town	C8
Kalgoorlie–Boulder	Town	F10
Kambalda	Town	F10
Kanowna	Homestead	F10
Karratha	Town	D5
Kennedy Range		C7
Kimberley Research Station		J2
King George Sound		E12
King Sound		G3
Koolyanobbing	Town	E10
Kununurra	Town	J2
Kwinana	Town	C11
Lake Argyle		J3
Lake Austin		E8
Lake Ballard		F9
Lake Barlee		E9
Lake Carey		G9
Lake Carnegie		G8

LOCALITIES



Wiluna Town
Ellendale Homestead/community
Eyre Locality
Major road
Watercourse
Lake
Commodities
Alumina
Energy
Iron
Precious metal
Speciality metal
Steel alloy metal
Ashmore Reef
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Windjana Gorge
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Fitzroy River
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Burrup Peninsula
Dampier
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Hampton Plains
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Israelite Bay
East Mount Barren
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Archipelago of the Recherche
Margaret River
STIRLING R.
Augusta
Cape Leeuwin
Mount Barker
Albany
Point D'Entrecasteaux
Denmark
King George Sound
SOUTHERN OCEAN
200 km
110° 112° 114° 116° 118° 120° 122° 124° 126° 128° 130°
14° 16° 18° 20° 22° 24° 26° 28° 30° 32° 34° 36°
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About this book

Western Australia covers a third of the continent of Australia with rocks ranging in age from the most ancient (close to 3.75 billion years old) to those that are forming along the coastline at present. In this book Tony Cockbain has drawn together the various strands of geology covering the period from 100 Ma to the present — these include Australia's split from Antarctica, four sedimentary depositional cycles between the Paleocene and the Holocene, the formation of giant iron ore deposits by regolith processes, Western Australia's seismic and earthquake history, and the precious water resources of a dry and thirsty State. Geologists and enquiring readers will enjoy dipping into this book to learn about the recent geological events that have shaped and are still shaping Western Australia.

Australia goes it alone — the emerging island continent 100 Ma to present is the second volume to be published under the banner of 'Western Australia unearthed', a series that will progressively chronicle the geological evolution of Western Australia.





Further details of geological publications and maps produced by the Geological Survey of Western Australia can be obtained by contacting:

Information Centre
Department of Mines and Petroleum
100 Plain Street
EAST PERTH WESTERN AUSTRALIA 6004

Telephone: +61 8 9222 3459 Facsimile: +61 8 9222 3444
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