The birth of supercontinents

and the Proterozoic assembly of Western Australia

by

Simon P Johnson

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Cover photograph:

Complexly folded Paleoproterozoic King Leopold Sandstone outcrops along the famous Gibb River Road, Kimberley Basin

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Acknowledgements

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 new understanding of the geological evolution of Western Australia is the distillation of 30 years of geological mapping, complemented by collaborations with university and industry researchers. The emphasis has been on integration with geochronology — mainly U–Pb dating using the sensitive high-resolution ion microprobes (SHRIMPs) in the John de Laeter Centre of Mass Spectrometry at Curtin University in Perth to precisely determine the ages of igneous and metamorphic events. Combined with high-quality geochemistry and isotopic datasets, and new statewide geophysics acquisition, this has given new insights into the geological framework of Western Australia and the associated systems that produced mineral and petroleum deposits.

This volume — *The birth of supercontinents and the Proterozoic assembly of Western Australia* — is the first to be published, with three more titles to follow — *Archean: building the core of the continent*; *Gondwana: from assembly to break-up*; and *Australia goes it alone — the emerging island continent (100 Ma to the present)*. The books are aimed at geologists, particularly newcomers to the State, to enable them to quickly get a feel for the geology and economic potential of various terrains. Each book provides, from a GSWA perspective, current ideas on the geological history of the State, and a list of recommended references is provided for further reading. GSWA has amassed knowledge on the geology of Western Australia over more than 120 years. This book is a prelude to 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

June 2013

PROTEROZOIC TECTONICS

Legend

Age (Ma)

0	PHANEROZOIC
1000	NEOPROTEROZOIC
	MESOPROTEROZOIC
2000	PALAEOPROTEROZOIC
3000	ARCHEAN
4000	

- Sedimentary and volcanic rocks
- Igneous and metamorphic rocks
- Granite–greenstone rocks

CAPRICORN OROGEN — Overprint patterns are used to define the extent of each orogen

—— Seismic line (EIS and OESP)

Map labels

Kimberley and Speewah Basins
Bastion Basin
Mount House Group
Carr Boyd Basin
Lamboo Province
Louisa Basin
Wolfe Creek Basin
Birrindudu Basin
GRANITES–TANAMI OROGEN
NORTHERN TERRITORY
Phanerozoic cover
Murraba Basin
ARUNTA OROGEN
Yeneena Basin
Ashburton Basin
Bresnahan Basin
Mangarese Group
Rudall Province
PATERSON OROGEN
Officer Basin
Amadeus Basin
10GA-CP1
Gascoyne Province
Edmund Basin
Collier Basin
Scorpion Group
Salvation Group
CAPRICORN OROGEN
CAPRICORN
10GA-CP2
Phanerozoic cover
Bryah and Padbury Basins
Yerrida Basin
Earaheedy Basin
Musgrave Province
PATERSON OROGEN
10GA-CP3
Badgeradda Group
11GA-SC1
SOUTHERN CARNARVON
YLGARN–OFFICER–MUSGRAVE
11GA-YO1
Northampton Inlier
PINJARRA OROGEN
Officer Basin
SOUTH AUSTRALIA
Mullingarra Inlier
Yandanooka Group
Moora Group
12GA-T1
TROPICANA
Cardup Group
Woodline Formation
12GA-AF3
Phanerozoic cover
PINJARRA OROGEN
Stirling Range Formation
Mount Barren Group
Zone
ALBANY–FRASER
Biranup Zone
Nornalup Zone
ALBANY–FRASER OROGEN
12GA-AF2
12GA-AF1
Leeuwin Inlier
Naturaliste Plateau
Biranup Zone
Nornalup Zone
ALBANY

Tectonic map of Western Australia highlighting the Proterozoic elements. Seismic-reflection profiles are also shown. Seismic work was funded by Royalties for Regions' Exploration Incentive Scheme (EIS) and Geoscience Australia's Onshore Energy Security Project (OESP)

200 Km

The supercontinent cycle and Australia

THE TRANSITION FROM THE ARCHEAN TO THE PROTEROZOIC EON HERALDED profound changes in global-scale geological processes, culminating in the emergence of an oxygenated atmosphere on Earth. The Proterozoic Eon, by contrast, is characterized by the formation of supercontinents and the birth of the supercontinent cycle. Critical and irreversible global atmospheric and hydrospheric changes were initiated at the end of the Archean. These changes to the Earth system were driven through the Proterozoic by the constant reorganization of continents — the supercontinent cycle. Toward the end of the Proterozoic Eon unstable climatic conditions were dominated by global-scale ice ages, ultimately resulting in an atmosphere and hydrosphere able to support the evolution of complex life.

A 'supercontinent' is a term that refers to a single landmass that contained most, if not all, of the Earth's cratons at a given time in Earth history. Several supercontinents are thought to have existed throughout Earth history but only one, Pangea, which was assembled during the Phanerozoic, can confidently be reconstructed (Fig. 1). Prior to Pangea, the existence, timing of assembly, and configuration of supercontinents becomes increasingly speculative. Nevertheless, the history of multiple supercontinent assembly and dispersal events throughout the Proterozoic is preserved in the geological record. The time scales for amalgamation, stabilization, and break-up — a single supercontinent cycle — are in the order of 300 to 500 million years (m.y.); although, within that time frame, a true supercontinent — as a stable landmass containing all or most of Earth's cratons in a closely packed configuration — may only have a fleeting existence as it is progressively formed and broken apart.

The existence of three supercontinents during the Proterozoic has been proposed: Nuna, alternatively known as Columbia, formed during the Paleoproterozoic and may have been Earth's first true supercontinent; Rodinia was assembled during the Mesoproterozoic; and Gondwana formed during the latest Neoproterozoic to earliest Phanerozoic (Fig. 2).
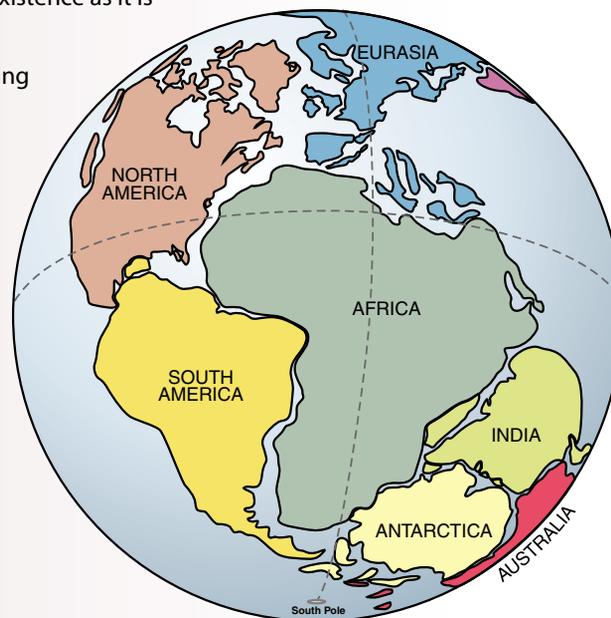
Figure 1.   Reconstruction of the Pangea supercontinent at c. 200 Ma

1

Tracking the assembly of Western Australia through the Proterozoic

Like all other present-day continents, Australia comprises several stable Archean cratonic nuclei which, mainly during the Proterozoic, were progressively sutured into successively larger cratons and, ultimately, supercontinents. Many of the Proterozoic orogenic belts formed during the collision of two cratons, and may contain slivers of oceanic or island arc crust or exotic (far-travelled) continental fragments that were caught up in the collision zone. However, some Proterozoic orogenic belts formed well away from any craton margin by the reactivation of older lithosphere, possibly as a result of far-field stresses from craton-margin processes.

Western Australia contains two of Australia's three principal cratons — the North Australian Craton (parts of which lie in the Northern Territory and Queensland) and the West Australian Craton (Figs 2, 3). Together with the South Australian Craton, all three are Proterozoic entities, having formed from smaller, older cratonic nuclei. The North Australian Craton comprises the Kimberley Craton, numerous, small and disparate Neoarchean inliers such as the Billabong, Rum Jungle, and Nanambu Complexes (all within the Northern Territory), and a large swathe of Paleoproterozoic metasedimentary and igneous material. The West Australian Craton comprises the Archean Pilbara and Yilgarn Cratons, and the Archean to Paleoproterozoic Glenburgh Terrane (Fig. 4). However, new

Figure 2. Cladogram showing the assembly history of the Australian cratonic blocks.
Abbreviations: CLP, Central Lamboo Province; ELP, Eastern Lamboo Province; GC, Gawler Craton; GT, Glenburgh Terrane; KC, Kimberley Craton; MC, Mawson Craton; MP, Musgrave Province; NAC, North Australian Craton; PC, Pilbara Craton; RP, Rudall Province; SAC, South Australian Craton; WAC, West Australian Craton; WLP, Western Lamboo Province; WP, Warumpi Province; YC, Yilgarn Craton; Zim, Zimbabwe Craton
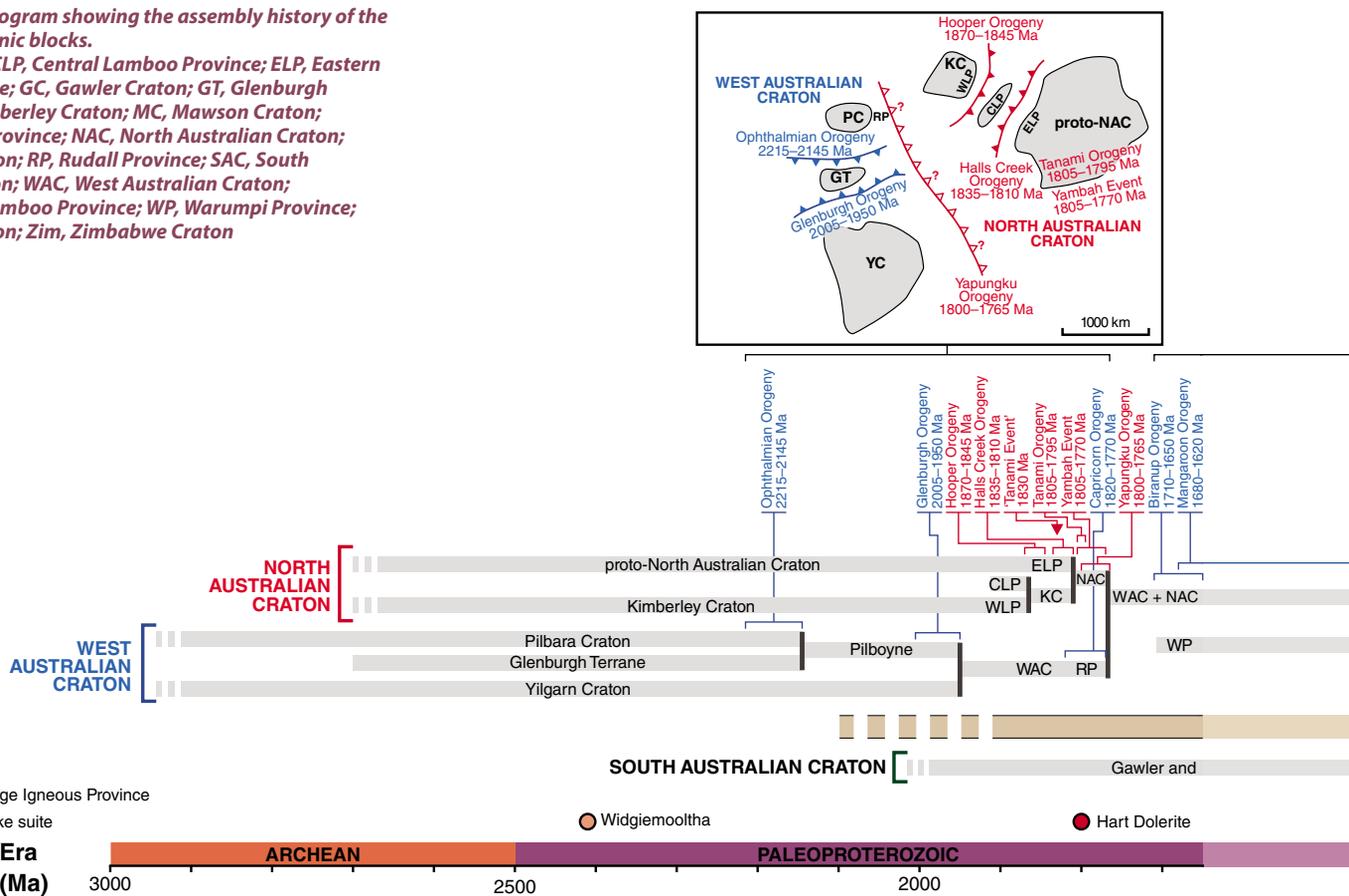
crustal material, such as in the Albany–Fraser and Pinjarra Orogens, formed major additions during structural and magmatic reworking events throughout the Proterozoic. The South Australian Craton comprises the Gawler Craton, the Musgrave Province along its northern margin, and several other Paleoproterozoic terranes. Tracking the history of these cratons, and ultimately the assembly of Western Australia, can be represented in a cladogram, which is a branching diagram that depicts successive points of craton convergence through time (Fig. 2). Points of convergence represent the timing of collisional orogenesis, craton amalgamation, and the formation of supercontinents, whereas points of divergence signify episodes of continental rifting and supercontinent break-up. The major

nodes of convergence for the Western Australian cratons coincide with the formation of Nuna, Rodinia, and Gondwana, and the nodes of divergence with the break-up episodes for each of these supercontinents (Fig. 2).

The detailed geology is depicted in a time–space plot (Fig. 3), which shows the geographic and temporal distribution of magmatic, deformation, basin formation, and mineralization events.

WEST AUSTRALIAN CRATON

Pinjarra Orogen			Capricorn Orogen				Albany–Fraser Orogen		Paterson Orogen	
LI+NP	MI	NI	SP	GP	NY	EC			RP	wMP

Ma

Leeuwin Orogeny

Paterson Orogeny *Petermann Orogeny*

Mulka Tectonic Event

Disappointment Group

600 — O'Callaghans Supersuite — Boondawari Fm. — Wahlgu Fm.

★ Cu–Au, U

Miles Orogeny *Wahlgu*

Mundine Well Dolerite Suite

Nindibillup Dyke Suite

Pirrilyungka

800 — Lamil/ Throssell Range Groups — Tarcunyah/ Sunbeam Groups — Buldya Group

Gairdner Dolerite

★ Cu

Centralian Superbasin

Thirty Three Supersuite

Kullal Dykes

Bentley Super-group

1000 — REE ★ — *Edmundian Orogeny*

Warakurna Supersuite

Giles Event ? Ni ★

Davis Dolerite — Kulkatharra Dolerite — Glenayle Dolerite

Giles Intrusions

Mn ★

Collier Group — Salvation Group

Esperance Supersuite

Gnowangerup–Fraser Dyke Suite

Musgrave Orogeny

1200 — Manganese Group

Darling Orogeny

Muggamurra Dolerites

Pb–Zn–Cu ★ Tangadee Rhyolite

Pitjantjatjara Supersuite

Recherche Supersuite

Ni ★

Ragged Basin

Gifford Creek Carbonatite Suite

REE ★

Mutherbukin Tectonic Event

Fraser Range Met.

Mount West Orogeny

Wirku Met.

Wankanki Supersuite

Arid Basin

1400 — Narimbunna Dolerite

Albany–Fraser Orogeny Stage II *Albany–Fraser Orogeny Stage I*

Papulankutja Supersuite

Mount Augustus Sandstone — Edmund Group — Scorpion Group

Krackatinny Supersuite

1600 — Bresnahan Group — Durlacher Supersuite — Pb–Zn–Cu ★

Eddy Suite

Barren Basin

Mangaroon Orogeny

Tabletop Terrane

Mount Minnie Group — Moorarie Supersuite — Pooranoo Metamorphics — Coor-de-wandy Formation

Biranup Orogeny

Kalkan Supersuite

Suspected series of oceanic arcs

Assembly of WAC and NAC

1800 — Au ★ — Mo ★ — *Capricorn Orogeny* — Miningarra Group

Yapungku Orogeny

upper Wyloo and Capricorn Groups — Leake Spring Met. — Mooloogool Group

Bertibubba Supersuite — Padbury Group — Tooloo Group

Glenburgh Orogeny

Au ★ — Dalgaringa Supersuite — Camel Hills Met. — Cu ★ Bryah Group — Narracoota Formation — iron fm. — Pb ★

Assembly of WAC

2000 — Wooly Dolomite

Cheela Springs Basalt — *Ophthalmian Orogeny* — Moogie Met. — Windplain Group

2200 — lower Wyloo and Turee Creek Groups

Meteorite Bore

Halfway Gneiss

2400 — ↓ 2555–2430 Ma

4

NORTH AUSTRALIAN CRATON

Halls Creek Orogen				
WLP+KLO	CLP	ELP	GTO	wAO

Ma

King Leopold Orogeny

Mount House Group

Louisa Downs and Albert Edward Groups

King Leopold Orogeny

Carnegie Formation

600

Walsh

⬅ **ELATINA GLACIATION**

Egan

Pertatataka

Kuniandi and Duerdin Groups

under revision

Landrigan *Fargoo*

Redcliff Pound Group

Areyonga ⬅ **STURT GLACIATION**

800

Dmd
⭐
Aries and Maude Creek Kimberlites

Bow Hill Lamprophyre Suite

Bitter Springs Fm.

Heavitree Quartzite

Western Dyke Suite

1000

Kiwirrkurra Fm.

Carr Boyd Group

Dmd
⭐
AK1 Lamproite

1200

⬅ **Assembly of WAC–NAC with SAC**

1400

Kimberley Group: plus Red Rock, Texas Downs, Moola Boola, and Revolver Creek Formations

Wulungurru Volcanics

Mount Webb Granite

Liebig Orogeny

1600

Birrindudu Group

Birrindudu, Bastion, Osmond, and Crowhurst Groups

Pollock Hills Fm.

Wotjulum Porphyry

Grimwalde–Frederick Suites

Inínti Granite

Argilke Event

Lake MacKay Quartzite

Tanami Orogeny

Ware Group

Au ⭐

Yambah Event

Hart Dolerite

Halls Creek Orogeny

1800

Speewah Gp Sally Downs Supersuite **Ni**

Carrington Suite

Hooper Orogeny

Paperbark Supersuite

Ruins Dolerite

Woodward Dolerite

Tanami Event

Tanami Group

Lander Rock Fm.

Whitewater Volcs and Marboo Fm.

Tickalara Met.

Olympio Fm.

Koongie Pk. Fm.

Biscay Fm.

Ding Dong Downs Volcanics

Sophie Downs Suite

Inspiration Peak Granite

2000

2200

2400

Figure 3.   Time–space plot of Proterozoic events in Western Australia.
Abbreviations for tectonic units: CLP, Central Lamboo Province; EC, Eastern Capricorn Orogen; ELP, Eastern Lamboo Province; GP, Gascoyne Province; GTO, Granites–Tanami Orogen; LI+NP, Leeuwin Inlier and Naturaliste Plateau; MI, Mullingarra Inlier; NAC, North Australian Craton; NI, Northampton Inlier; NY, Northern Yilgarn Craton; RP, Rudall Province and NW Officer Basin; SAC, South Australian Craton; SP, Southern Pilbara region; wAO, west Arunta Orogen and Amadeus Basin; WAC, West Australian Craton; WLP+KLO, Western Lamboo Province and King Leopold Orogen; wMP, west Musgrave Province and Officer Basin;
Other abbreviations: Dmd, Diamonds; Fm., Formation; Gp, Group; Met., Metamorphics

Legend:
- Granite magmatism
- Sedimentation
- Orogenic or tectonic event
- *Egan* Glacial deposit
- ⭐ Mineralization
- ⭐ Secondary Mineralization
- Mafic magmatism

THE CONFIGURATION OF NUNA IS POORLY constrained, due mainly to the lack of reliable paleomagnetic data, but also because many of Earth's Paleoproterozoic orogenic belts are poorly understood. However, based on the abundant during the 2215–2145 Ma Ophthalmian Orogeny and, second, this combined block — known as the 'Pilboyne craton' — collided with the Yilgarn Craton during the 2005–1950 Ma Glenburgh Orogeny.

Figure 4. Elements of the Capricorn Orogen and surrounding cratons and basins. Thick grey lines delimit the northern and southern boundaries of the Capricorn Orogen. Abbreviations: MI, Marymia Inlier; YGC, Yarlarweelor Gneiss Complex. Other abbreviations as in Figure 2
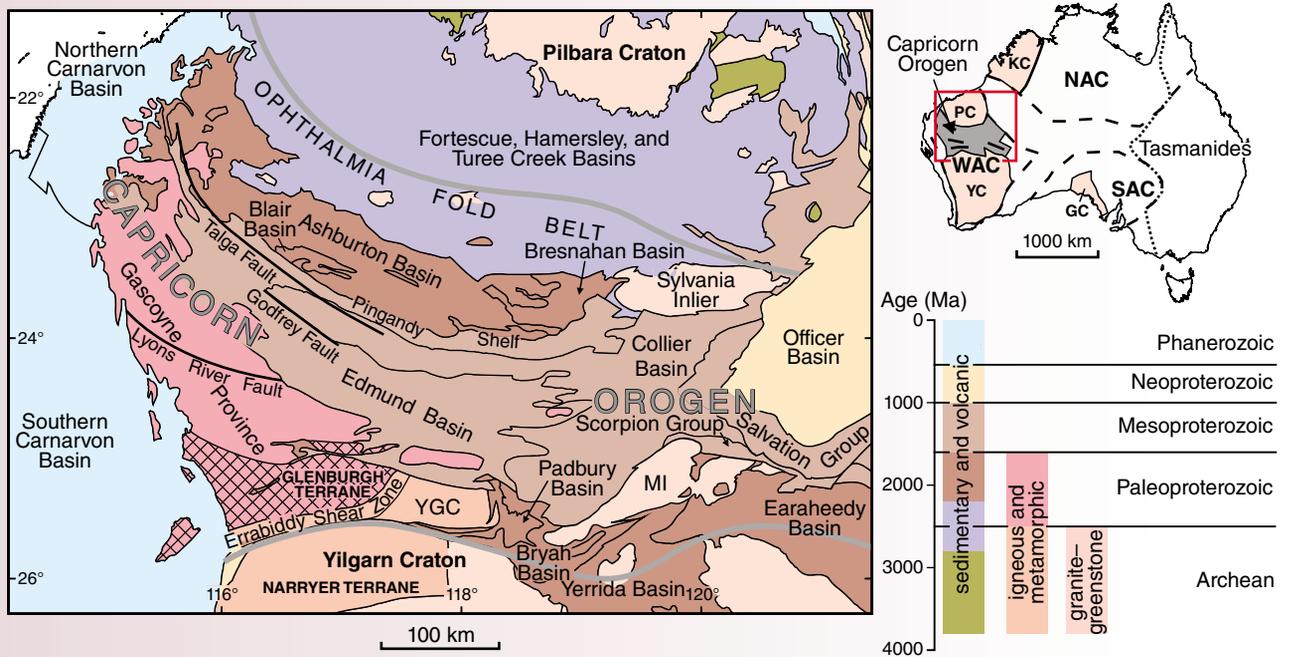
global distribution of c. 1800 Ma orogenic belts, it has been proposed that the Nuna supercontinent was amalgamated at, or about, this time, and that it may have contained most of Earth's cratons. Although Western Australia may have been a part of this supercontinent, amalgamation of the cratonic nuclei that comprise Western Australia began long before c. 1800 Ma.

Assembly of the West Australian Craton

The three principal tectonic units of the West Australian Craton, the Archean Pilbara and Yilgarn Cratons, and an exotic Archean to Paleoproterozoic terrane termed the Glenburgh Terrane, were assembled during two temporally and spatially discrete tectonic episodes (Fig. 2). First, the Glenburgh Terrane collided or accreted with the southern margin of the Pilbara Craton

The Glenburgh Terrane, an exotic crustal fragment in the Capricorn Orogen

The Glenburgh Terrane forms basement to the southern part of the Gascoyne Province in the Capricorn Orogen (Figs 2, 4). The oldest rocks in the terrane are heterogeneous granitic gneisses — the Halfway Gneiss — the protoliths to which have ages between c. 2555 and c. 2430 Ma (Figs 3, 5). The ages and Lu–Hf isotopic compositions of the inherited and magmatic zircon crystals indicate a long crustal history ranging back to c. 3700 Ma. Although crust older than c. 2555 Ma is not exposed, the evolution of Lu–Hf isotopes in zircons indicates that the crust formed in a magmatic arc between c. 2730 and c. 2600 Ma, and that these rocks were then significantly structurally and magmatically reworked at c. 2555 to c. 2430 Ma to form the exposed gneisses. The temporal and isotopic

6

Figure 5. *Pegmatite-banded tonalite gneiss of the 2555–2430 Ma Halfway Gniess, Glenburgh Terrane, Capricorn Orogen*

evolution of the Halfway Gneiss is unlike that of either the Pilbara or the Yilgarn Craton and thus this crustal block is interpreted to have developed independently as an exotic terrane until their juxtaposition during the Ophthalmian and Glenburgh Orogenies (Fig. 2).

The 2215–2145 Ma Ophthalmian Orogeny

The 2215–2145 Ma Ophthalmian Orogeny records the collision of the Glenburgh Terrane with the southern margin of the Pilbara Craton, to form the Pilboyne craton (Fig. 2). During the collision, the southern margin of the Pilbara Craton and associated supracrustal rocks of the Hamersley and Fortescue Groups were deformed, folded, and thrust northward over the Pilbara Craton to form the Ophthalmia Fold

Belt. Uplift and erosion along the axis of the Ophthalmia Fold Belt during thrusting resulted in the deposition of extensive retro-foreland basin deposits of the Turee Creek and lower Wyloo Groups, and pro-foreland basin deposits, now the Moogie Metamorphics in the Glenburgh Terrane (Fig. 6).

In the retro-foreland basin, the Turee Creek and lower Wyloo Groups have a maximum thickness of about 4 km and 3 km respectively, and are separated by a significant angular unconformity (Fig. 7). The Turee Creek Group is subdivided into the Kungarra, Koolbye, and Kazput Formations. Much of the Kungarra Formation is dominated by deep-marine mudstones and turbidite sandstones, interbedded with minor dolostone. A prominent glacigene diamictite, the Meteorite

Capricorn
Orogen

Thumbnail maps show the location of the tectonic unit under discussion

SOUTH

NORTH
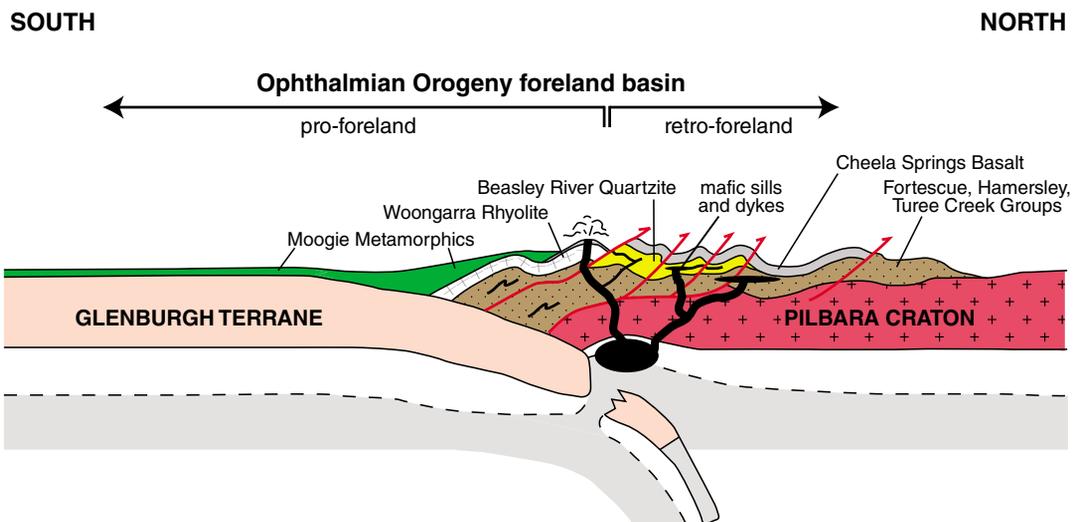
Figure 6. *Schematic cross section showing tectonic evolution during the 2215–2145 Ma Ophthalmian Orogeny, Capricorn Orogen*

Bore Member, is exposed in the upper part of the formation (Fig. 8). Fluvial to shallow-marine sandstones of the Koolbye Formation overlie the Kungarra Formation, and are themselves overlain by deltaic and shallow-marine sandstones, siltstones, and dolostones belonging to the Kazput Formation.

Fluvial to shallow-marine sandstones and conglomerates belonging to the ~300 m-thick Beasley River Quartzite (lower Wyloo Group, Ashburton Basin) unconformably overlie the Kazput Formation, and are conformably overlain by the ~2.5 km-thick Cheela Springs Basalt (Fig. 7). These continental tholeiite lavas are coeval with c. 2210 Ma dolerite sills that intrude the underlying Turee Creek Group. Throughout most of the southern Pilbara region, the Cheela Springs Basalt is unconformably overlain by the upper Wyloo Group. The Wyloo Dome is an exception. There, the basalts are conformably overlain by the c. 2030 Ma Wooly Dolomite, a 300 m-thick succession of high- and low-energy shelf carbonates laid down in the interval between lower and upper Wyloo Group deposition (Fig. 7). The unconformity between the Turee Creek and lower Wyloo Groups, together with another occurring within the upper Turee Creek Group, are interpreted to reflect the northward propagation of the Ophthalmian thrusts into the retro-foreland basin.

In the pro-foreland basin, the Halfway Gneiss is unconformably overlain by, and in tectonic contact with, metasedimentary rocks of the 2240–2125 Ma Moogie Metamorphics (Fig. 6). Although now strongly deformed and metamorphosed during younger orogenic events, the protoliths to these predominantly psammitic metasedimentary rocks were
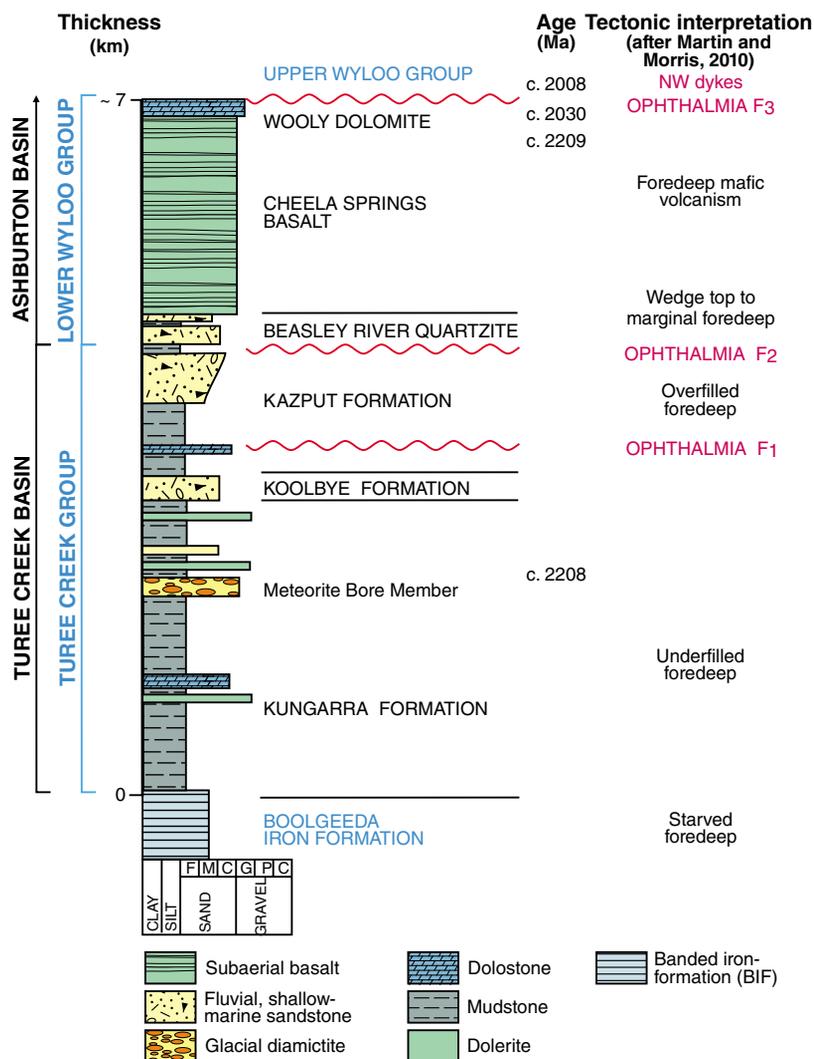
Figure 7. *Stratigraphy of the Turee Creek Group and lower Wyloo Group, Capricorn Orogen, showing the principal rock types, major deformation events, and interpreted tectonic settings*
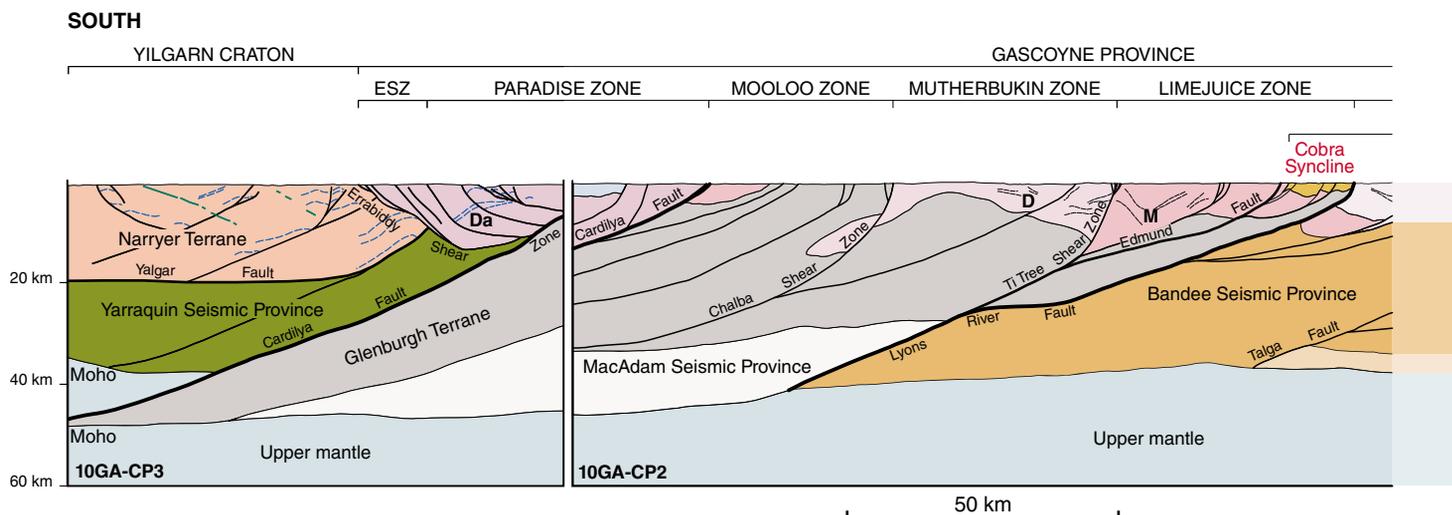
deposited in a similar time frame to the Turee Creek and lower Wyloo Groups. Provenance studies of detrital zircons indicate that they were sourced from the underlying Halfway Gneiss, and the Hamersley and Fortescue Basins along the southern margin of the Pilbara Craton.

Although the suture between the Glenburgh Terrane and the Pilbara Craton is everywhere covered by the younger Ashburton, Edmund, and Collier Basins, a recent deep-crustal seismic-reflection survey across the Capricorn Orogen indicates that the suture is coincident with the present-day Lyons River – Minnie Creek – Minga Bar Fault system (Fig. 9).
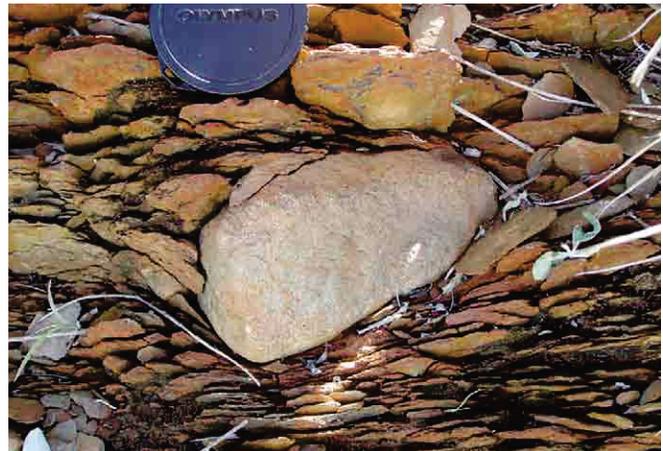
Figure 8.   Glacial rhyolitic dropstone in foliated siltstone matrix, Meteorite Bore Member of the Kungarra Formation, Turee Creek Group (Capricorn Orogen), at Meteorite Bore

The 2005–1950 Ma Glenburgh Orogeny

The younger part of the Glenburgh Terrane is dominated by felsic granitic gneisses and granites of the 2005–1970 Ma Dalgaringa Supersuite, and siliciclastic metasedimentary rocks of the 2000–1955 Ma Camel Hills Metamorphics. The gneisses and granites have whole-rock geochemical and isotopic compositions similar to those in present-day Andean-type subduction zones and are interpreted to have formed in a continental-margin arc — the Dalgaringa Arc — along the southern margin of the Glenburgh Terrane (Fig. 10), during north-directed subduction and closure of the oceanic basin between the Pilboyne craton and Yilgarn Craton (Fig. 2).

Figure 9.   Interpretation of deep-crustal seismic-reflection data across the Capricorn Orogen, combining seismic lines 10GA-CP1, 10GA-CP2, and 10GA-CP3, and showing key faults, terranes, zones, basins, and seismic provinces. Three major sutures are marked with heavy black lines.
The Baring Downs Fault separates the Pilbara Craton granite–greenstones and underlying Carlathunda Seismic Province from the Bandee Seismic Province, which underlies the northern Gascoyne Province. The age of this suture is thought to be older than c. 2775 Ma — as the Fortescue Basin (F) occurs on either side of the suture — and to represent one of the major Pilbara Craton-forming events. The Lyons River Fault is the main suture between the Pilbara Craton – Bandee Seismic Province and the Glenburgh Terrane, which formed during the 2215–2145 Ma Ophthalmian Orogeny. The Cardilya Fault represents the main suture zone between the Glenburgh Terrane and the Narryer Terrane – Yarraquin Seismic Province of the Yilgarn Craton, which formed during the 2005–1950 Ma Glenburgh Orogeny. After the suturing of the West Australian Craton this region was subject to nearly one billion years of intracontinental reactivation, resulting in the intrusion of numerous granite batholiths (pinks and purples) and deposition of sedimentary basins (tan and pale browns), all of which are imaged in the upper 20 km of crust. Location of the seismic line is shown on map of Western Australian Proterozoic elements (p. vi).
Abbreviations: D, Durlacher Supersuite; Da, Dalgaringa Supersuite; E+C, Edmund and Collier Groups; ESZ, Errabiddy Shear Zone; F, Fortescue Group; H, Hamersley Group; lWG, lower Wyloo Group; M, Moorarie Supersuite; uWG, upper Wyloo Group
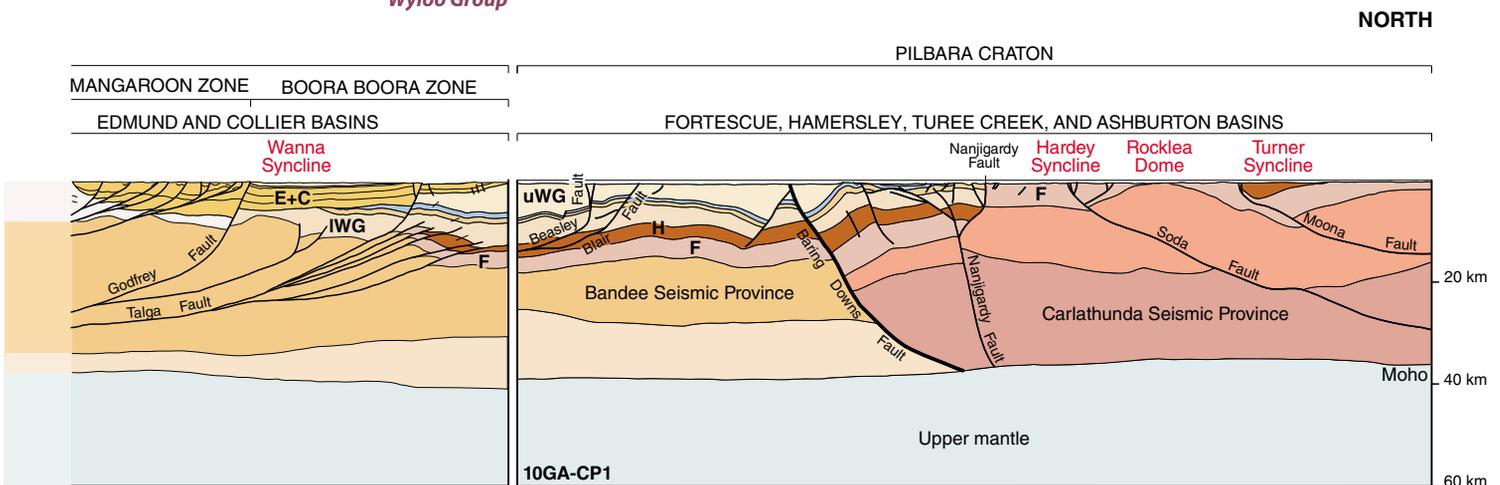
The Camel Hills Metamorphics are interpreted to be a fore-arc deposit to the Dalgaringa Arc. Detrital zircons within pelitic schists and inherited zircons within the Dalgaringa Supersuite gneisses suggest that magmatism associated with the Dalgaringa Arc extends back to as early as c. 2080 Ma. Tectonic interleaving of the Dalgaringa Arc and its fore-arc sediments, and the Yilgarn Craton and its passive margin, took place during the collision between the Pilboyne craton and the Yilgarn Craton, in the final stages of the Glenburgh Orogeny, between c. 1965 and c. 1950 Ma (Fig. 11). The geometry of the collision zone is complex. However, the Capricorn Orogen deep-crustal seismic-reflection survey (Fig. 9) shows that the suture is along the Cardilya Fault, and that the Glenburgh Terrane was underthrust beneath the Yilgarn Craton, duplicating the Moho (Figs 9, 11). During the latter stages of the collisional event, southward-directed backthrusting along the Errabiddy Shear Zone was responsible for the imbrication and interleaving of lithologies from the Glenburgh and Narryer Terranes. Following collision and final suturing, the northern margin of the Yilgarn Craton, the Errabiddy Shear Zone, and the southern margin of the Glenburgh Terrane were intruded by granite stocks and dykes of the 1965–1945 Ma Bertibubba Supersuite (Fig. 3).

Pre-, syn-, and post-tectonic basins

The Yerrida, Bryah, Earaheedy, and Padbury Basins are a series of stacked basins on the southern margin of the Capricorn Orogen (Figs 3, 4, 12). They record periods of sedimentation, volcanism, rifting, accretion, and passive-margin tectonism, and contain significant gold and base metal mineralization. All four basins are in tectonic contact with each other and with the underlying Archean rocks of the Yilgarn Craton and with its associated inliers, such as the Goodin and Marymia Inliers. Although the ages of the basins are very poorly constrained, they appear to have developed between c. 2200 and c. 1800 Ma, with the Yerrida Basin being the oldest. All four basins were deformed and metamorphosed at low metamorphic grade during the 1820–1770 Ma Capricorn Orogeny.

The Yerrida Basin contains the Windplain Group and the disconformably overlying Mooloogool Group — separated by a hiatus of 300 to 400 million years (Figs 3, 13). The Windplain
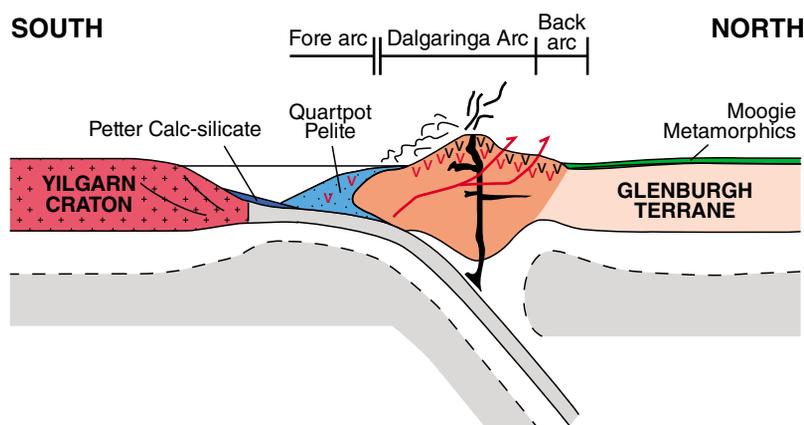

Figure 10. Schematic cross section showing the evolution of the Dalgaringa Arc leading up to the collision between the 'Pilboyne craton' (combined Pilbara Craton and Glenburgh Terrane of the Gascoyne Province) and the Narryer Terrane of the Yilgarn Craton during the 2005–1950 Ma Glenburgh Orogeny
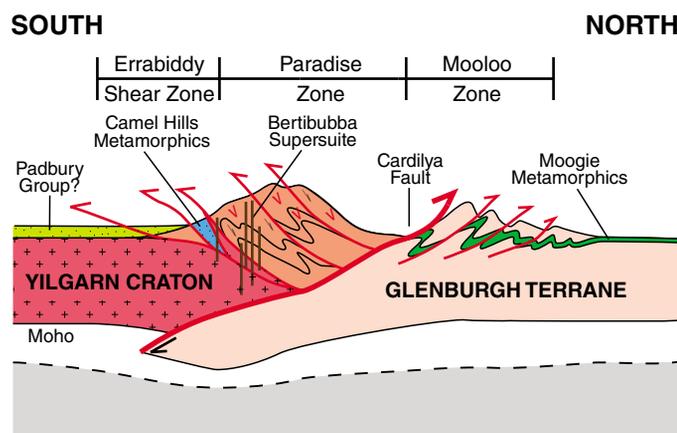

Figure 11. Schematic cross section showing the crustal architecture of the collision zone between the Yilgarn Craton and Glenburgh Terrane following the 2005–1950 Ma Glenburgh Orogeny

Group comprises siliciclastic rocks, stromatolitic carbonate rocks, evaporitic rocks (Juderina Formation), and a thick upper sequence of shales known as the Johnson Cairn Formation. The sediments were deposited in coastal and shallow-marine environments, grading to intertidal and supratidal and sabkha lagoons, and the sequence is interpreted as an intracontinental sag basin. Geochronology of detrital zircons, combined with paleocurrent analyses, indicates that the Yilgarn Craton was a major source of the detritus. A Pb–Pb age for stromatolitic carbonate rocks in the Bubble Well Member of the Juderina Formation (Fig. 14) indicates deposition close to c. 2170 Ma, prior to the terminal collision of the Yilgarn Craton and Pilboyne craton. A short-term
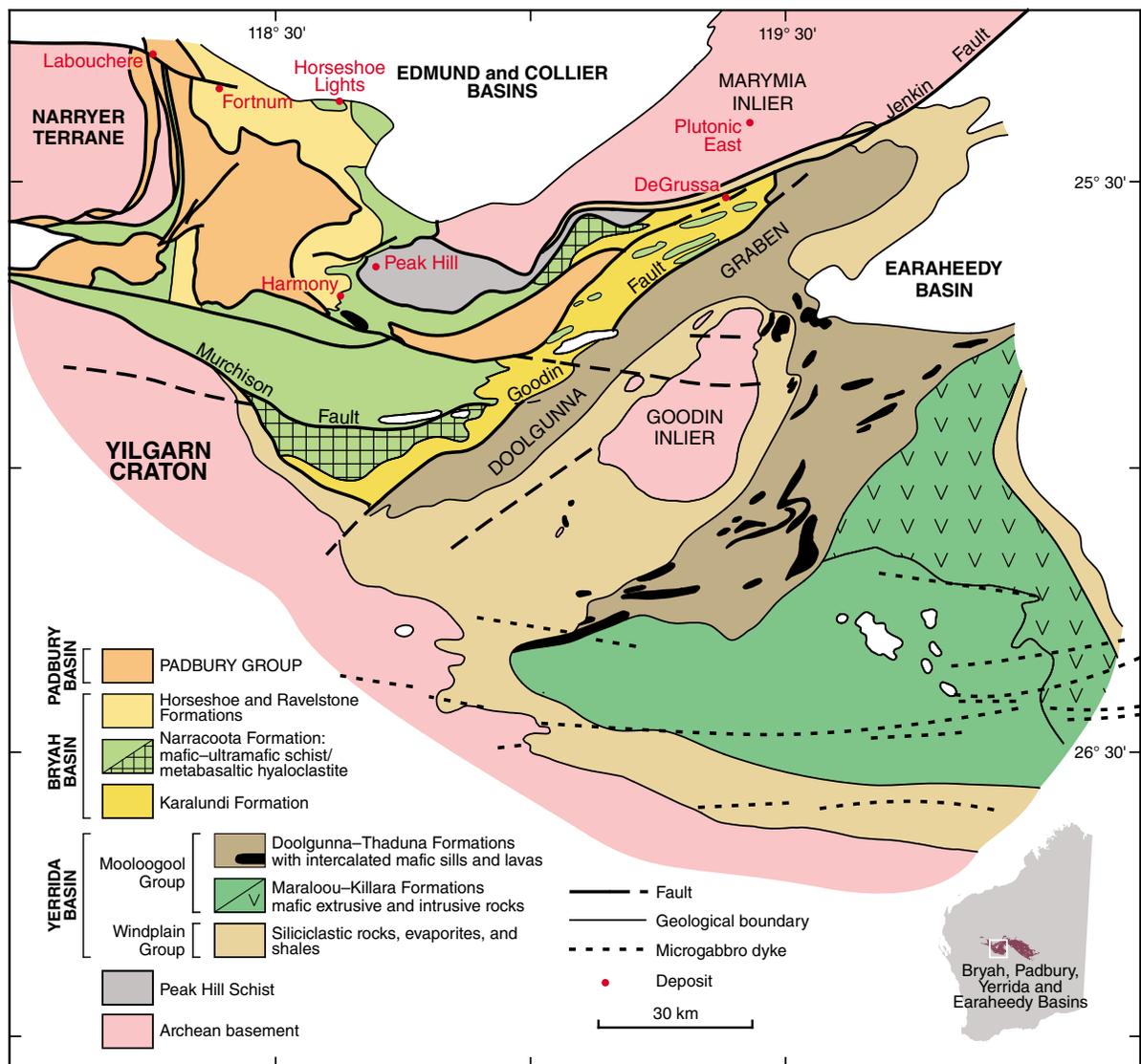
Figure 12. *Simplified geological map showing the distribution of the Yerrida, Bryah, and Padbury Basins along the southern margin of the Capricorn Orogen*

Orogenic lode-gold mineral systems in the Bryah and Padbury Basins

Orogenic, shear zone-hosted gold lodes are present within the Bryah and Padbury Basins as well as in the Peak Hill Schist, a mylonitized part of the Archean Marymia Inlier (shown on Fig. 12). Mineralization is dominated by gold and gold–copper lode deposits that are hosted in high-strain zones within metasedimentary and/or metavolcanic rocks, or along contact zones between rock units.

Deformation, shearing, hydrothermal alteration, and mineralization took place during the late stages of compressional deformation, where fluids were focused along thrust planes and shear zones that acted as conduits of high permeability in a hydrothermal regime. Mineralization is commonly associated with relatively narrow zones of hydrothermal alteration characterized by pyritization and alkali metasomatism, with albite and biotite being the most abundant hydrothermal mineral phases. Other alteration minerals include chlorite, white mica, and tourmaline. The source of the metals is unknown, but it is possible the metals were derived from either the volcanic and sedimentary rocks within the basins or the underlying Archean basement. Significant lode-gold deposits have been mined at Peak Hill, Harmony, and Fortnum (photo below shows auriferous quartz veins at Fortnum). Other economically significant lode deposits include Labouchere and Horseshoe Lights.


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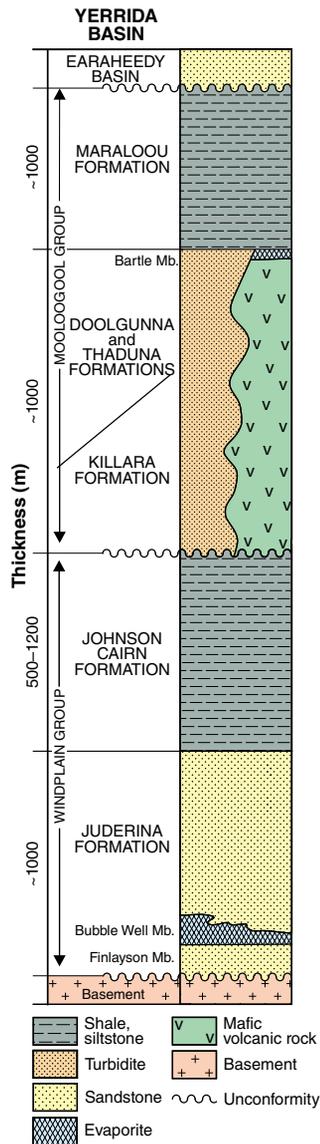
YERRIDA BASIN

Figure 13. Stratigraphy of the Windplain and Mooloogool Groups, Yerrida Basin
Abbreviation: Mb., Member

Figure 14. Photo of stromatolitic drillcore showing Bubble Well Member, Juderina Formation, Yerrida Basin. Several distinctive stromatolite taxa (particularly *Segosia finlaysoniensis*, shown here) in the Bubble Well Member have proved useful for drillhole correlation across the basin
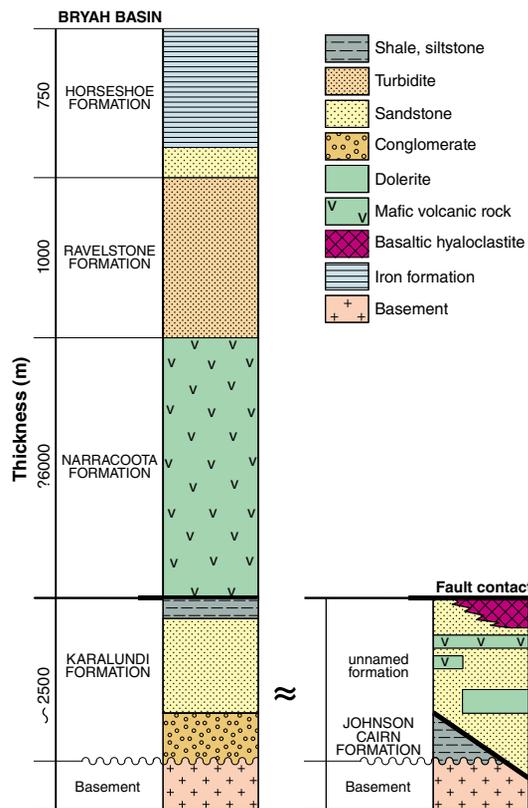

Figure 15. Stratigraphy of the Bryah Group in the Bryah Basin

but substantial positive $\delta^{13}C$ excursion, up to +9.36‰, has been recorded in stromatolitic carbonates from the Bubble Well Member. Combined with the c. 2170 Ma age for this member, the excursion correlates well with the global 2220–2060 Ma Lomagundi–Jatuli event, which has been interpreted to reflect large-scale transformations in the carbon cycle, possibly related to varying atmospheric–oceanic conditions, tectonic regimes, and biosphere evolution.

The lower part — the Killara, Doolgunna, and Thaduna Formations — of the disconformably overlying Mooloogool Group comprises conglomerates and turbidite-facies rocks (Fig. 13). This sequence also contains extensive mafic intrusive and extrusive rocks with whole-rock geochemical compositions consistent with
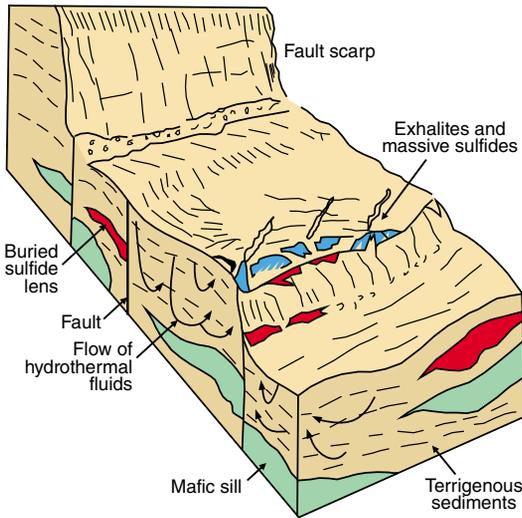
Figure 16.   Schematic diagram showing the formation of volcanogenic-hosted massive sulfide (VHMS) base metal deposits at Doolgunna in the Bryah Group

an intracontinental flood basalt origin. Peperite within finely laminated argillite and sulfidic shales of the overlying Maraloou Formation have been dated at c. 1840 Ma, suggesting that magmatism and deposition of the Mooloogool Group occurred 300 to 400 million years after deposition of the Windplain succession. This interpretation is also supported by the presence of clasts and fragments within the group coming from the Narracoota Formation of the Bryah Basin, which was deposited at c. 2000 Ma. Deposition of the Mooloogool Group must have occurred during

the initial stages of the 1820–1770 Ma Capricorn Orogeny when parts of the Bryah and Padbury Groups were thrust over the northwestern margin of the Windplain Group.

The Bryah Basin has the best resource potential of the four basins, it contains significant lode gold and VHMS-base metal mineralization (see shaded boxes). The lowermost parts of the basin — the Narracoota Formation and an unnamed sequence of terrigenous sedimentary and volcaniclastic rocks (Fig. 15) — contain extensive mafic and ultramafic rocks, but are the products of distinct, separate tectonic environments. The Narracoota Formation is interpreted to be the remnants of an accreted oceanic plateau, whereas the unnamed sequence probably formed within a narrow rift basin along the margin of the Yilgarn Craton. These sedimentary and volcaniclastic rocks carry most of the volcanic-hosted massive sulfide (VHMS-type) base metal mineralization associated with thick mafic dolerite and basalt horizons (see shaded box and Fig. 16).

The overlying Ravelstone and Horseshoe Formations (Fig. 15) comprise a conformable sequence of turbidites and fine-grained argillites and ironstones, respectively — interpreted to represent a rift-fill and post-rift-fill succession deposited on top of the Narracoota Formation. Dating of detrital zircons indicates that the Ravelstone Formation was deposited after
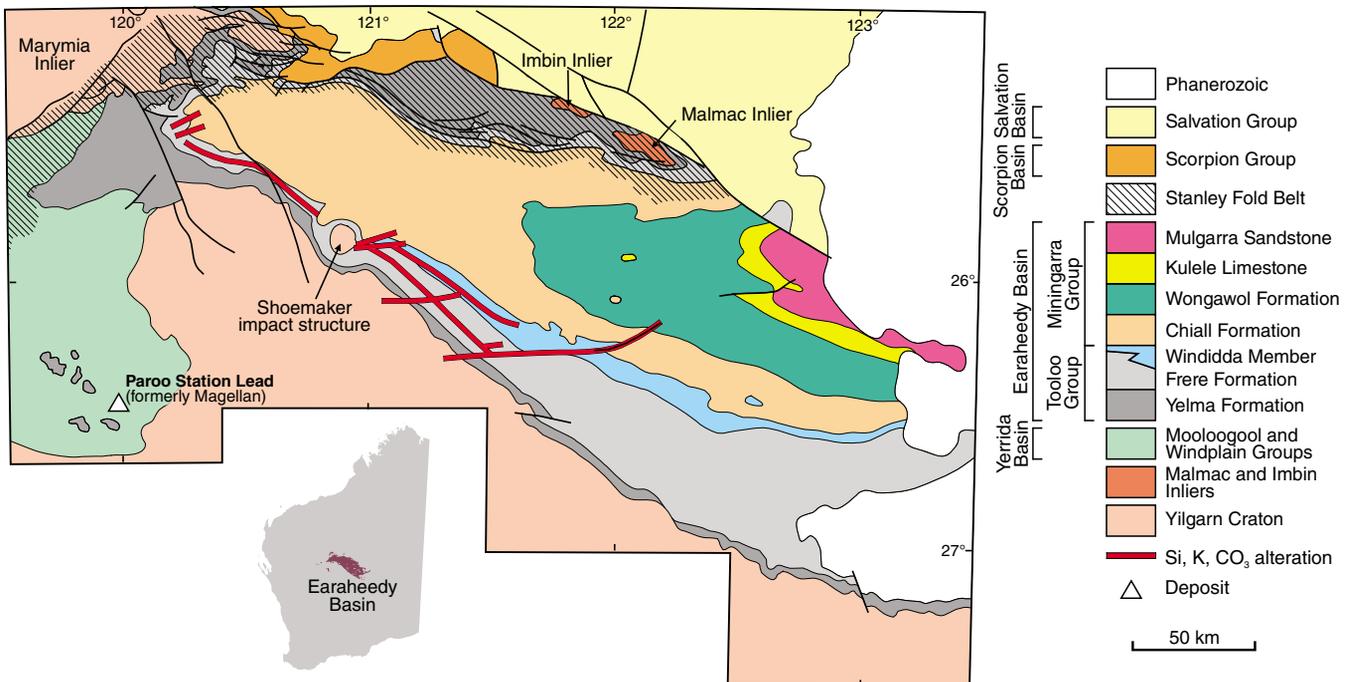

Figure 17.   Simplified geology of the Earaheedy Basin

c. 2010 Ma, and the Bryah Basin is interpreted as a pre- to syn-collisional basin. The Narracoota Formation formed as an outboard oceanic plateau accreted to the Yilgarn Craton margin immediately prior to the collision between the Yilgarn Craton and Pilboyne craton during the collisional phase of the Glenburgh Orogeny between c. 1965 and c. 1950 Ma.

The Earaheedy Basin contains a 5 km-thick succession of shallow-marine clastic and chemical sedimentary rocks (Fig. 17), interpreted as a northward-deepening, coastal to shelfal basin marginal to the northeastern Yilgarn Craton. The rocks of the Earaheedy Basin rest unconformably on Archean rocks of the Yilgarn Craton and Malmac Inlier, and on deformed Paleoproterozoic rocks of the Yerrida Group and Imbin Inlier (Fig. 17).

The basin contains two groups that may be disconformable and separated by a 50 to 100 million-year hiatus. The lower succession — the Tooloo Group — comprises shallow-marine (fluvial at the base) sandstone, siltstone, granular iron-formation, and stromatolitic carbonate rocks of the Yelma and Frere Formations. The upper succession — the Miningarra Group — comprises fine-grained, low-energy, shallow-marine siliciclastic rocks and lesser limestone of the Chiall and Wongawol Formations, Kulele Limestone, and Mulgarra Sandstone (Fig. 18).

VHMS mineral systems in the Bryah Basin

Two distinct types of volcanogenic-hosted massive sulfide (VHMS) mineralization are recognized in the Bryah Basin. The first, exemplified by the Horseshoe Lights copper–gold–silver deposit, is hosted by mylonitized chloritic schist and sericitic schist (formerly felsic volcanic rocks) of the Narracoota Formation. Primary mineralization was enriched during deformation and by supergene processes to produce a rich ore blanket dominated by chalcocite. Average grades of the supergene-enriched massive sulfides (chalcocite, native copper, and pyrite) are 10% Cu, 8 ppm Au, and 300 ppm Ag. The massive sulfide zone is enclosed by a zone of disseminated sulfides, and low-grade (0.2–0.3 ppm Au, 0.5–5 ppm Ag) stringer-sulfide mineralization.

The second type is characterized by the Doolgunna (DeGrussa) copper–gold deposit — which in 2012 was already the State's second largest producer of copper. Geological mapping by Sandfire Resources NL indicates that mineralization is hosted within terrigenous sedimentary and volcaniclastic rocks (see Figs 15 and 16), which are interpreted to have been deposited in a possible rift setting along the northern margin of the Yilgarn Craton. Within this rift structure, basaltic lavas were erupted in shallow water and emplaced as high-level sills resulting in the deposition of VHMS-type deposits. The Doolgunna VHMS mineralization is blanketed by high-grade supergene sulfide and oxide ore with total measured, indicated, and inferred resources at DeGrussa, Conductor 1, and Conductor 4 of 11.91 Mt at 5.3% Cu and 1.8 g/t Au, for 627 000 t of contained copper and 693 000 oz of contained gold.

Since the Doolgunna discovery, other companies have announced similar discoveries along strike, with drill intersections of 17 m @ 11.7% Cu and 1.73 g/t Au at Red Bore, and 9 m @ 7.2 g/t Au at Magnus.

Figure 18. Stratigraphy of the Tooloo and Miningarra Groups in the Earaheedy Basin, Capricorn Orogen. Abbreviation: Mb., Member

Figure 19. Low-energy, shallow-marine siltstone, now cleaved and folded; Wongawol Formation, Miningarra Group, Earaheedy Basin, Capricorn Orogen

The northward deepening of facies through the Miningarra Group (Fig. 19) implies that the basin continues to the north beneath younger Proterozoic strata, including the Scorpion and Salvation Groups (possible equivalents of the Edmund and Collier Basins).

Recent geochronological investigations of the Earaheedy Basin have shown that the Tooloo Group is significantly older than previously assumed. SHRIMP U–Pb dating of magmatic zircons from thin tuffaceous layers in the Yelma and Frere Formations provides depositional ages of 1970–1950 Ma and c. 1890 Ma, respectively. These new constraints indicate the Tooloo Group was deposited in a similar time interval to the Bryah and Padbury Basins. The age spectra and Lu–Hf isotopic compositions of detrital zircons in the Yelma Formation imply that this part of the basin was derived predominantly from the Gascoyne Province to the west, presumably in response to collisional orogenesis and uplift during the Glenburgh Orogeny. The Yelma Formation contains important lead deposits at Magellan (see shaded box below). The maximum depositional age of the Miningarra Group is defined by a single detrital zircon grain from the Mulgarra Sandstone, dated at c. 1808 Ma. This implies the Miningarra Group is the youngest of the Yerrida, Bryah, Earaheedy, and Padbury Basin successions.

The Magellan lead deposit: a supergene non-sulfide mineral system

The Magellan lead deposit (now called Paroo Station Lead) is located within an outlier of the Earaheedy Basin (shown on Fig. 17). It is a non-sulfide system, with cerussite ($PbCO_3$) and anglesite ($PbSO_4$) as the major ore minerals, and plattnerite, coronadite, pyromorphite, and plumbogummite as minor to negligible ore components. The lead orebodies are hosted by silcretized quartz–clay breccia (interpreted to be a silicified dolomitic collapse-breccia) and altered and weathered sandstone and siltstone of the Yelma Formation.

The composition of the ore suggests that it formed under physico-chemical conditions conducive to the stratabound precipitation of lead carbonates and sulfates derived from sulfides found in a Mississippi Valley-type (MVT) setting (b).

Recent dating of intergrown phosphate minerals indicates that mineralization took place during the early stages of the Capricorn Orogeny, at c. 1815 Ma. Subsequently, prolonged weathering caused dissolution, volume reduction, and oxidation of the galena and sphalerite, leaching away zinc to leave highly enriched lead-carbonate and sulfate mineralization. Proven and probable ore reserves as at September 2011 are 19.9 Mt grading 4.5% Pb, for 1.13 Mt of contained metal. The four panels below illustrate the formation of this unusual ore type.

a) Precursor sequence
Stromatolitic carbonate rocks, sandstone, and siltstone (Yelma Fm.); black shale

Mineralizing fluid ?(basinal brine)

+PbS
+ZnS
+SiO₂

Frere Formation

Sweetwaters Well Member

Pb / Zn sulfides

Cavities, silica alteration

Yelma Formation
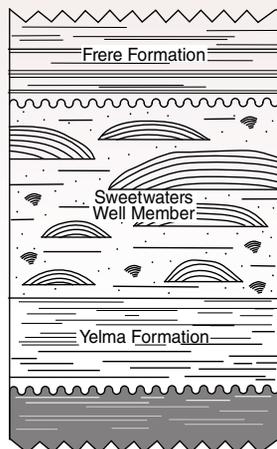
b) MVT-type mineralization
Stratabound replacement by sulfides; silica alteration
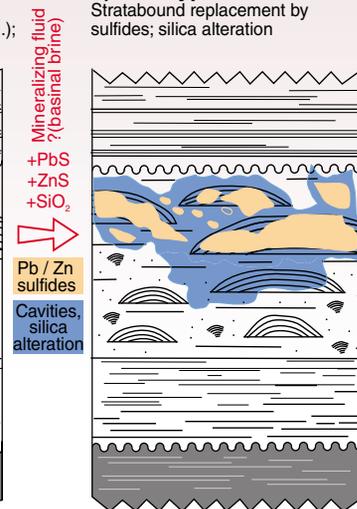
c) Volume reduction, carbonate dissolution, collapse, and cavity formation
?Hydrothermal; silica alteration, brecciation; Pb and Zn sulfide oxidation; formation of Pb sulfates
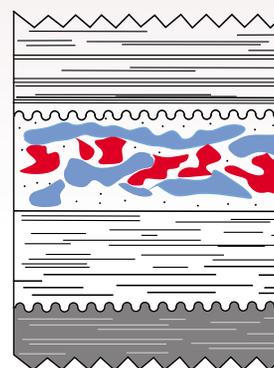
d) Weathering
Intense weathering during hot/wet climate; infiltration of rainwater and CO_2; precipitation of cerussite at expense of anglesite; formation of silcretized caprock

Meteoric H_2O + CO_2

$PbSO_4$

$PbCO_3$

15

PADBURY BASIN

MILLIDIE CREEK FORMATION

ROBINSON RANGE FORMATION

Beatty Park Mb.

WILTHORPE FORMATION

Heines Mb.

Thickness (m) 400–1300

LABOUCHERE FORMATION

3500–4000

BRYAH BASIN

Basement

Shale, siltstone

Banded iron-formation

Turbidite

Basement
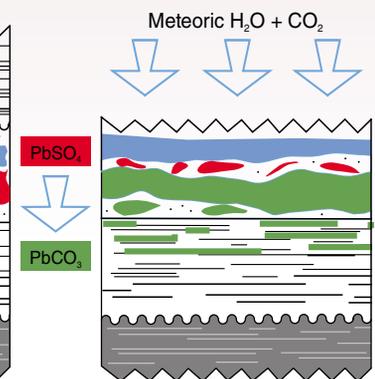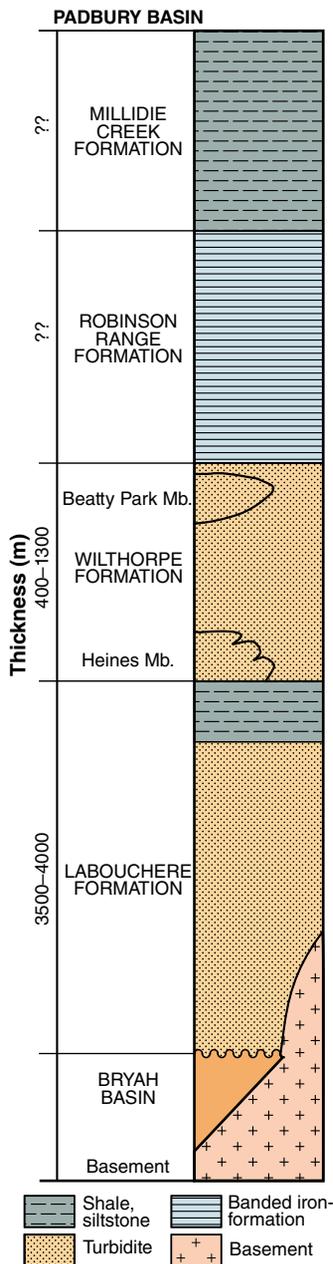
Figure 20.   Stratigraphy of the Padbury Group in the Padbury Basin, Capricorn Orogen Abbreviation: Mb., Member

The 1980–1810 Ma Padbury Basin (Fig. 20), is interpreted as a pro-foreland basin to the Yilgarn–Pilboyne collision. The lower parts of the succession — the Labouchere and Wilthorpe Formations — are an upward-coarsening succession of deep-water turbidites. Geochronology of detrital zircons reveals grains as young as c. 1980 Ma, indicating that the metasedimentary rocks contain zircons formed during the Glenburgh Orogeny, and thus must have been deposited during or after this collisional event. The upper part of the succession — the Robinson Range and Millidie Creek Formations — is a dominantly fine-grained sequence of banded iron-formation and ferruginous shales and siltstones, representing a probable continued shallowing of the depositional environment.

Assembly of Northern Australia

The North Australian Craton comprises numerous Paleo- to Mesoproterozoic units underlain by poorly exposed and isolated Neoarchean inliers. The common Neoarchean crystallization ages (c. 2670 to c. 2640 Ma) of these Archean basement inliers suggest that, at least within the Pine Creek Orogen, much of the North Australian Craton may be underlain by an extensive, contiguous Neoarchean block. Assembly of the North Australian Craton was thought to have taken place during numerous collision or accretion events throughout the Paleo- and Mesoproterozoic. However, if large portions of the North Australian Craton in the Northern Territory — hereafter termed the proto-North Australian Craton — are indeed underlain by contiguous Archean crust, then many of the Paleo- to

Granites–Tanami orogenic gold

The Granites–Tanami Orogen mostly comprises tightly folded greenschist-facies Paleoproterozoic metasedimentary and metavolcanic rocks. The Tanami Group is divided into the 1847–1840 Ma Dead Bullock and c. 1840 Ma Killi Killi Formations, which are regionally intruded by pre-tectonic dolerite sills that locally have peperitic upper and lower margins. Older (c. 1864 Ma) metasedimentary, mafic volcanic, and intrusive rocks have recently been recognized in the Bald Hill area.

The orogenic lode-gold deposits include the world-class Callie deposit in the Northern Territory, which has a resource of more than 6 million oz of gold. In Western Australia, significant mineralization

is located at Coyote and the Bald Hill deposits of Kookaburra and Sandpiper. The gold is hosted by a variety of rock types, including carbonaceous siltstone, iron formation, basalt, dolerite, and turbiditic sedimentary rocks. Geological, geochemical, and structural data suggest that gold deposition in the Granites–Tanami Orogen was structurally controlled, influenced by fluid–rock interactions in chemically reactive rocks, or controlled by fluctuations in fluid pressures due to the structural setting. The interaction of these three factors is probably the direct cause of the variety in style of the gold deposits. Many of these deposits are temporally linked to the emplacement of c. 1795 Ma granites.

Mesoproterozoic orogenic belts may represent areas of crustal reworking rather than sites of crustal accretion and growth.

During the 1865–1855 Ma time period it is not known if the Archean rocks of the Pine Creek Orogen were contiguous with those in the Kimberley Craton, or whether c. 1865 to c. 1855 Ma tectonism in both regions (known as the Hooper Orogeny) reflected orogenesis along a common margin. Alternatively, the two regions may have evolved independently until their amalgamation during the 1835–1810 Ma Halls Creek Orogeny (Figs 2, 3).

Granites–Tanami Orogen

The oldest rocks in the Granites–Tanami Orogen (Fig. 3) are high-grade Neoarchean metasedimentary rocks and leucogranites of the Billabong Complex, exposed in the Northern Territory (Fig. 21). The leucogranites have been dated at c. 2514 Ma. The oldest rocks in the Western Australian segment of the Granites–Tanami Orogen consist of turbidites, basaltic rocks, and felsic volcanic rocks of the c. 1864 Ma Stubbins Formation (Fig. 21). Siliciclastic metasedimentary rocks of the Dead Bullock Formation unconformably overlie the Billabong Complex and, together with the lower parts of the Mount Charles Formation, are considered to be a lateral equivalent of the Stubbins Formation. These siliciclastic sequences are interpreted to have been deposited in a back-arc basin or oceanic island-arc setting between the Kimberley Craton and the proto-North Australian Craton. Up to 5 km of turbiditic sandstones, siltstones, and shales assigned to the 1864–1844 Ma Killi Killi

Formation unconformably overlie the Stubbins, Mount Charles, and Dead Bullock Formations, and together form the Tanami Group. In the Northern Territory, the Killi Killi Formation is unconformably overlain by siliciclastic sedimentary and volcanic rocks of the 1825–1815 Ma Ware Group. All of these units in the Granites–Tanami Orogen are intruded by extensive granite plutons dated at c. 1795 Ma, which are broadly synchronous with regional-scale gold mineralization (see shaded box and Fig. 21).

In the western part of the Granites–Tanami Orogen, the rocks were affected by two distinct deformation events. The first event affected the older Stubbins, Mount Charles, and Dead Bullock Formations, producing a layer-parallel fabric associated with north-trending isoclinal folds. This event occurred between c. 1844 and c. 1825 Ma — the 'Tanami Event' — and can probably be correlated with the Halls Creek Orogeny. The second event — the Tanami Orogeny — produced southwest-inclined kilometre-scale disharmonic folds, broadly synchronous with granite plutonism at c. 1795 Ma, and is correlated with the Yapungku Orogeny.

Assembly of the Kimberley region and formation of the North Australian Craton

The Archean Kimberley Craton is not exposed, but is inferred from a variety of geophysical data and from the presence of abundant inherited zircons within younger metamorphic and igneous rocks exposed in the Halls Creek Orogen — the eastern margin of the craton that was reworked during the Halls Creek Orogeny. The craton is overlain by the
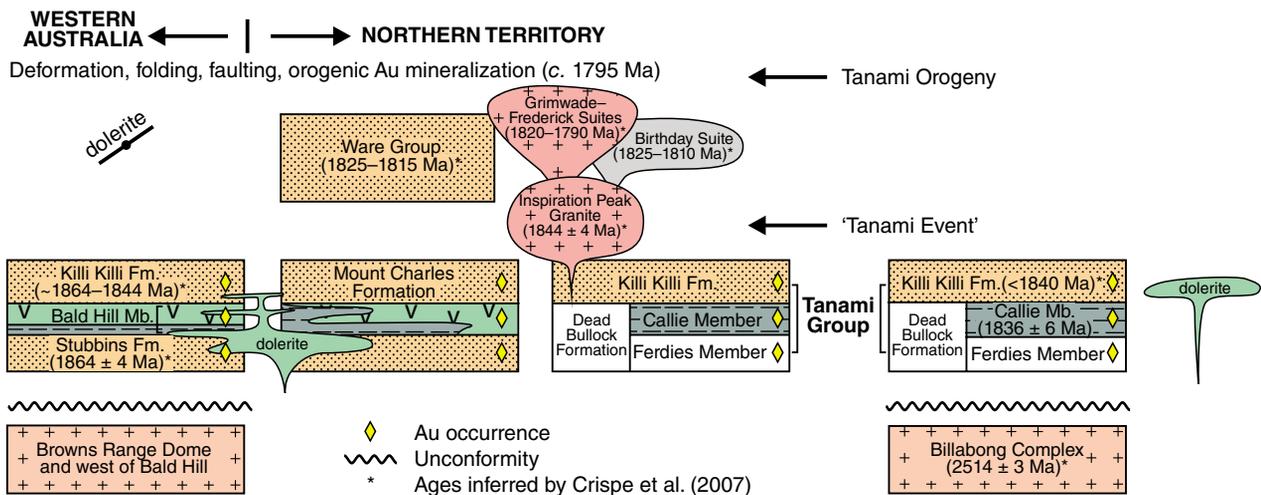

Figure 21. Summary of the stratigraphy and deformation episodes in the Granites–Tanami Orogen, as proposed by Bagas et al. (2010). Abbreviations: Fm., Formation; Mb., Member

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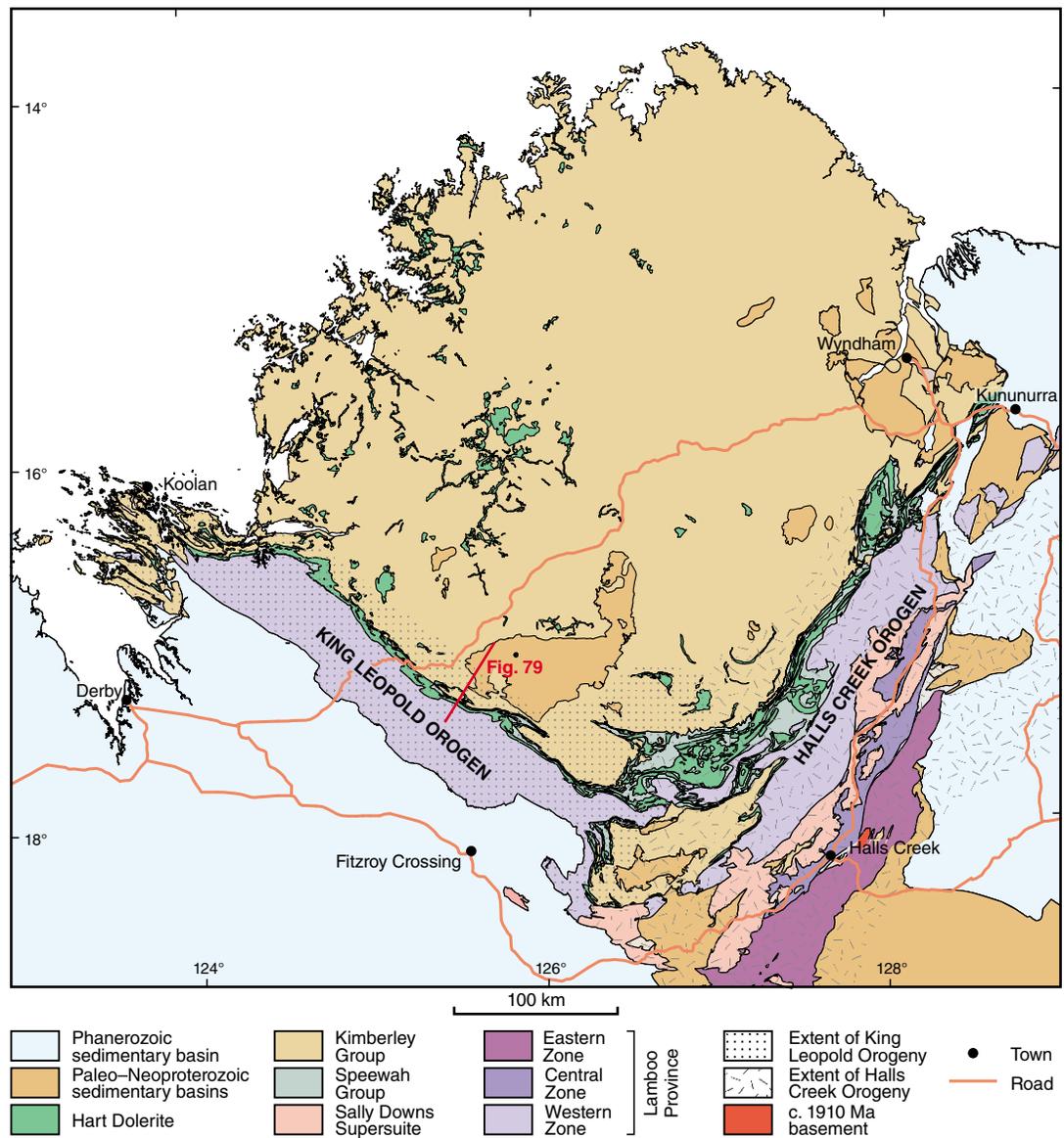
Figure 22. *Distribution of the Speewah and Kimberley Groups and the Hart Dolerite, and the subdivisions of the Lamboo Province*

Paleoproterozoic Speewah and Kimberley Basins (Fig. 22). The Paleoproterozoic crystalline rocks that define the Halls Creek Orogen are exposed in a 700 km-long, 100 km-wide belt along the southern and eastern margins of the craton, and are defined as the Lamboo Province (Figs 22, 23). In the east Kimberley, the Lamboo Province consists of three parallel north-northeast-trending zones.

The Western Zone of the Lamboo Province extends into the King Leopold Orogen in the west Kimberley and is interpreted to have formed along, and within, the Kimberley Craton margin. The oldest dated rocks — the Marboo Formation — are a series of interbedded fine- and medium-

grained turbidites with a maximum depositional age of c. 1872 Ma (Figs 3, 23). These are overlain by the c. 1855 Ma Whitewater Volcanics and intruded by granites of the 1865–1850 Ma Paperbark Supersuite (Fig. 24). Medium- to high-grade metamorphism, attributed to the Hooper Orogeny, affected the Marboo Formation at c. 1860 Ma and is interpreted to record the amalgamation of the Western and Central Zones.

In the Central Zone (Fig. 23), volcanic and associated rocks of the Tickalara Metamorphics were deposited at c. 1865 Ma and intruded by granite sheets at c. 1863 Ma, probably in an oceanic arc fringing the Kimberley Craton, or in a basin along the craton margin (Fig. 3).
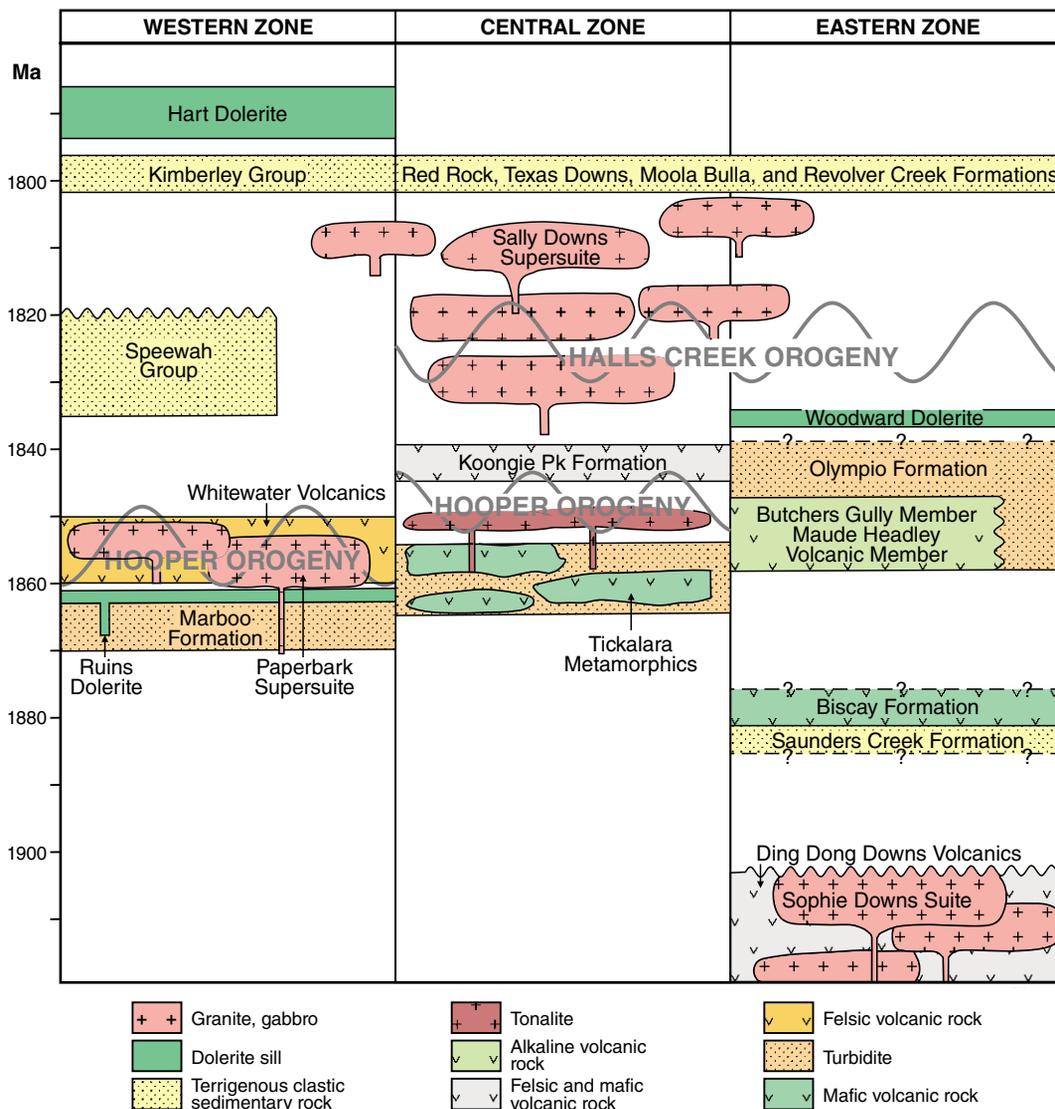
Figure 23. *Simplified time–space plot of the Paleoproterozoic rocks in the Lamboo Province of the Kimberley region*

Basement to the Central Zone is not exposed. Medium- to high-grade metamorphism during the Hooper Orogeny is recorded at c. 1850 to c. 1845 Ma, slightly younger than that in the Western Zone, and was accompanied by intrusion of tonalite and leucogranite sheets. Sedimentary and volcanic rocks of the Koongie Park Formation were deposited in the southern part of the Central Zone at c. 1845 to c. 1840 Ma, possibly in a rifted continental-arc setting above a northwest-dipping subduction zone. Layered mafic and ultramafic rocks hosting nickel–copper–cobalt–PGE–chrome were emplaced into the Lamboo Province during the Hooper Orogeny (see shaded box).

The Eastern Zone is interpreted to have developed along the western margin of the proto-North Australian Craton, although it is possible that the entire Lamboo Province formed along a contiguous Kimberley Craton – proto-North Australian Craton margin. The oldest rocks exposed in the Eastern Zone are coeval volcanic and granitic rocks of the c. 1910 Ma Ding Dong Downs Volcanics and Sophie Downs Suite (Figs 3, 23). These are overlain by sedimentary and volcanic rocks of the Halls Creek Group, including the Saunders Creek, Biscay (Fig. 25), and Olympio Formations, which were deposited between c. 1880 and c. 1845 Ma. The oldest tectonic event recorded in the Eastern Zone is the 1835–1810 Ma Halls Creek Orogeny. This orogeny, along with coeval orogenesis in the Central Zone, is interpreted to record the collision between the Western and Central Zones of the

Figure 24. Strongly foliated, coarse-grained biotite metamonzogranite of the Mussel Creek Granite, Paperbark Supersuite, Western Zone of the Lamboo Province

Figure 25. Planar parallel laminated, very fine grained recrystallized quartz arenite and graphitic siltstone of the Biscay Formation, Halls Creek Group, Eastern Zone of the Lamboo Province

Lamboo Province and the Kimberley Craton with the Eastern Zone of the Lamboo Province and the proto-North Australian Craton to form the North Australian Craton (Fig. 2).

In the Western Zone, there is no apparent record of the Halls Creek Orogeny, suggesting that this part of the orogen was passive or under extension prior to, and during, collisional orogenesis. This is reflected by the deposition of sedimentary rocks into the Speewah Basin, which unconformably overlies the Lamboo Province (Figs 22, 23, 26).

The Speewah Group comprises mainly interbedded siltstones and quartz, lithic, and feldspathic sandstones as well as minor volcanic and volcaniclastic rocks. It is interpreted to have been deposited in a retro-foreland basin. One of the volcanic rocks at the base of the Valentine Sandstone is dated at c. 1835 Ma, indicating that deposition was coeval with the onset of collision during the Halls Creek Orogeny. During this event, the Central and Eastern Zones were

intruded by voluminous granites of the 1835– 1805 Ma Sally Downs Supersuite (Figs 22, 23), as well as layered mafic–ultramafic intrusions such as the McIntosh Intrusion.

The Kimberley Basin consists of more than 3 km of siliciclastic sedimentary and mafic volcanic rocks that overlie both the Kimberley Craton and the Speewah Basin (Figs 22, 23, 26). The basin thins toward the north and is thought to have not extended much beyond the southeast margin of the Halls Creek Orogen. The Red Rock, Texas Downs, Moola Bulla, and Revolver Creek Basins on the Central and Eastern Zones of the Lamboo Province may be temporal equivalents of the Kimberley Basin. The basin was initiated immediately following tectonic activity associated with the Halls Creek Orogeny — between c. 1805 and c. 1797 Ma — and contains quartz sandstone, feldspathic sandstone, siltstone, and conglomerate, with minor volcanic and volcaniclastic rocks of the Carson Volcanics (Fig. 26). The lower part of

Red-brown shaly Paleoproterozoic Elgee Siltstone of the Kimberley Group along the bank of the Margaret River
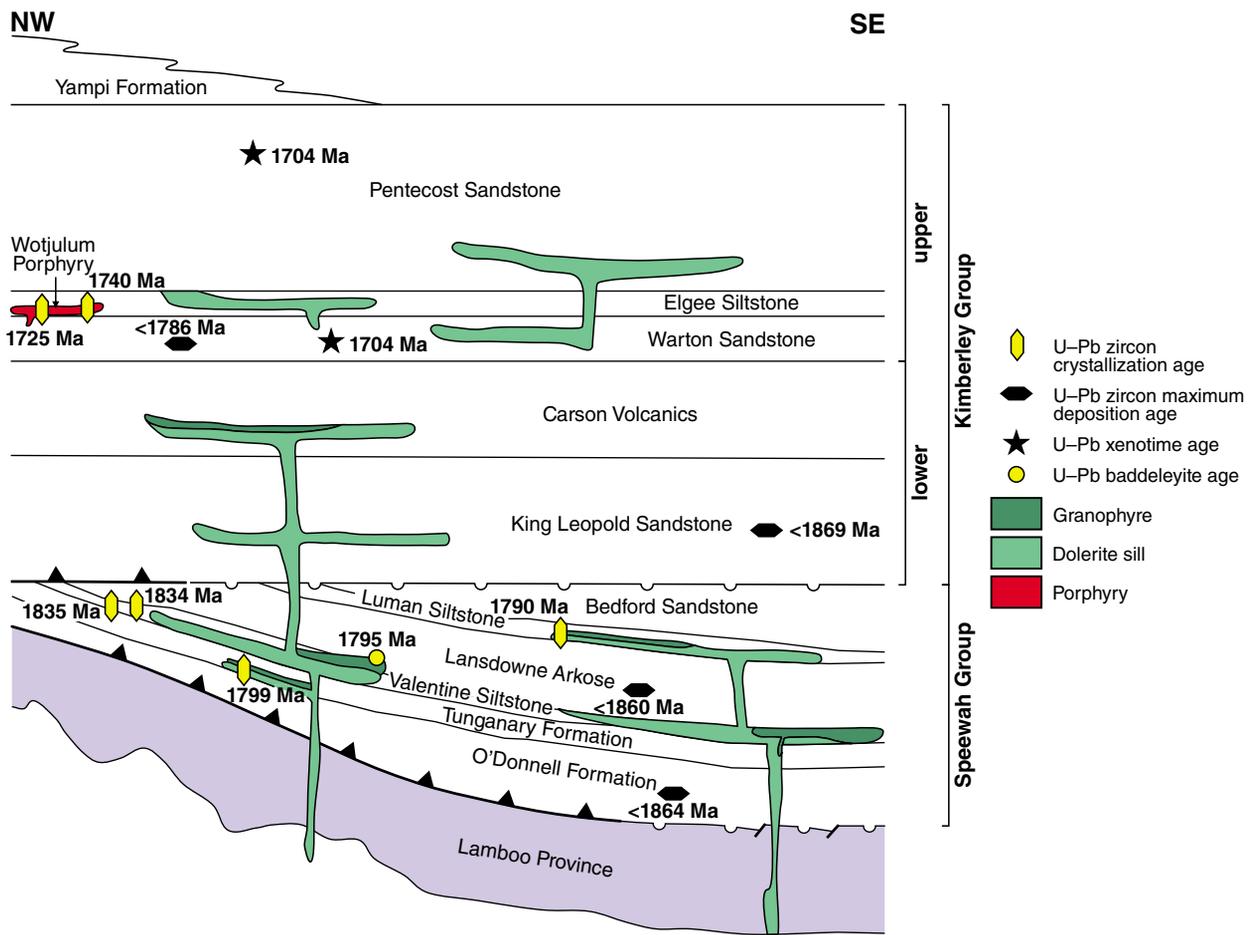
Figure 26.   Schematic stratigraphic and structural section showing the relationship between the Kimberley and Speewah Groups, the Lamboo Province, and the Hart Dolerite. The ages of various units are also shown

the basin, including the underlying Speewah Basin, is intruded by voluminous tholeiitic mafic sills and dykes of the Hart Dolerite, including subordinate granophyre. The mafic rocks have an estimated minimum volume of 250 000 km³, qualifying as a Large Igneous Province (LIP). The dolerite is dated between c. 1799 and c. 1795 Ma, coincident with the deposition of the youngest parts of the Kimberley Basin and the intrusion of the San Sou Monzogranite. Intrusion of the Hart

Dolerite and deposition of the Kimberley Group in the Kimberley Basin occurred during a period of post-collisional plate reorganization following the amalgamation of the Kimberley Craton with the proto-North Australian Craton, and is roughly coincident with the onset of collision between the West Australian and North Australian Cratons during the Yapungku Orogeny (Figs 2, 3).

Collision of the North Australian Craton with the West Australian Craton

The Yapungku Orogeny

The 1795–1760 Ma Yapungku Orogeny is the collisional event responsible for the amalgamation of the North Australian and West Australian Cratons (Fig. 2). Much of the evidence for this event is recorded in the Rudall Province of the Paterson Orogen, although deformation and granite plutonism during the 1820–1770 Ma Capricorn Orogeny is also evident in the Capricorn Orogen.

The Rudall Province consists of strongly, and multiply, deformed sedimentary and igneous rocks of the Talbot, Connaughton, and Tabletop Terranes (Fig. 27). The Talbot and Connaughton Terranes contain mostly Paleoproterozoic crust formed during the Yapungku Orogeny, whereas the Tabletop Terrane (discussed later) contains much younger Mesoproterozoic crust. The three terranes are bounded by major faults related to terrane juxtaposition, first during the Yapungku Orogeny and later during the c. 650 Ma Miles Orogeny.

The Talbot Terrane in the northern and western parts of the Rudall Province consists of multiply

Rudall
Province

Ni–Cu–Co–PGE–Cr in layered mafic–ultramafic intrusions

More than 50 Proterozoic layered mafic–ultramafic intrusions are known from the Halls Creek Orogen in the east Kimberley region. Many of these are highly prospective for nickel, copper, cobalt, platinum group elements (PGE), and chrome. These intrusions were emplaced during three main periods, generally ranging between c. 1860 and c. 1830 Ma, and have been grouped into seven types, at least three of which are coeval (I, II, and III): Group I intrusions are strongly differentiated, with the highest ratio of ultramafic to mafic cumulates, and are exemplified by the 1856 ± 2 Ma Panton intrusion, which hosts nickel, copper, and PGE in stratabound chromitite seams or layers; Group II includes moderately dipping sheet-like bodies that were intruded at the same time as the Paperbark Supersuite, and are exemplified by the 1857 ± 2 Ma Springvale intrusion that hosts minor nickel, copper, and PGE and associated chromite; Group III is represented by a single high-level mafic intrusion, the Toby intrusion, dated at 1855 ± 2 Ma; Group IV, also of predominantly mafic composition, is represented by sheet-like bodies (such as the

Wild Dog Creek intrusion) that intrude Group I bodies; a number of layered mafic–ultramafic intrusions make up Group V, including the 1844 ± 3 Ma Savannah intrusion (formerly known as Sally Malay) that hosts nickel–copper–PGE mineralization; Group VI includes layered mafic intrusions (such as the 1830 ± 3 Ma McIntosh gabbro), which are characterized by funnel-shaped and sheet-like gabbro bodies that intrude Group IV intrusions; Group VII comprises layered mafic intrusions that form plug-like or dyke-like bodies, such as the Black Hills Yard intrusion, and post-date the Group VI intrusions.

Mineralization has been classified into three associations: a sulfide association containing nickel–copper–cobalt–PGE, with lesser chrome; a chromite association containing chrome–PGE–nickel–copper, with minor gold; and an ilmenite – titaniferous magnetite association that hosts titanium–vanadium.

Savannah intrusion (Group V)

The c. 1844 Ma Savannah intrusion is economically significant. It hosts nickel, copper, and cobalt sulfides

with a (2009) resource of 6.05 Mt at 1.53% nickel, 0.81% copper, and 0.08% cobalt. The layered mafic–ultramafic body intrudes metasedimentary rocks and paragneisses of the Tickalara Metamorphics and consists of an array of ovoid-shaped chambers interconnected by feeder zones and dykes. The Savannah orebody is mostly confined to a marginal norite unit up to 40 m thick at the base of the intrusion with massive, matrix, and disseminated sulfide mineralization dominated by pyrrhotite, chalcopyrite, pentlandite, and minor pyrite.

#### Copernicus mafic–ultramafic intrusion (Group V)

The c. 1844 Ma Copernicus layered mafic–ultramafic intrusion has an overall gabbroic composition and hosts nickel, copper, and cobalt sulfides. It intrudes metasedimentary rocks and paragneisses of the Tickalara Metamorphics. It outcrops as a 600 m-long, 100 m-thick lens-shaped body that dips moderately to the west. The sulfide mineralization is confined to a cumulate-textured metapyroxenite lens-shaped unit

within the intrusion. The sulfide ores are preferentially developed at the northern end of the pyroxenite unit, with an ore mineral assemblage consisting of pyrrhotite–chalcopyrite–pentlandite and pyrite. Ore textures vary from net-textured to coarse-grained blebs and massive sulfide-rich stringer mineralization, containing between 50 and 70% sulfide.

Panton sill (Group I)

The c. 1856 Ma Panton mafic–ultramafic intrusion, about 10.5 km long and 2.5 km wide, has a total resource of 37 Mt nickel averaging 0.16% Ni, 14.3 Mt of platinum + palladium, averaging 2.19 g/t and 2.39 g/t, respectively. The mineralization is stratabound and contained within chromitite layers. The Panton intrusion is characterized by a 650 m-thick Lower Ultramafic Series and an overlying 900 m-thick Gabbroic Series. The Lower Ultramafic Series consists of cyclic units of dunite, lherzolite, and chromitite, and the Gabbroic Series comprises gabbro, gabbronorite, norite, ferrograbbro, and anorthosite. The chromitite layers occur at three levels.

Figure 27. Simplified geological map of the Rudall Province, in the northwestern Paterson Orogen (after Bagas, 2004)
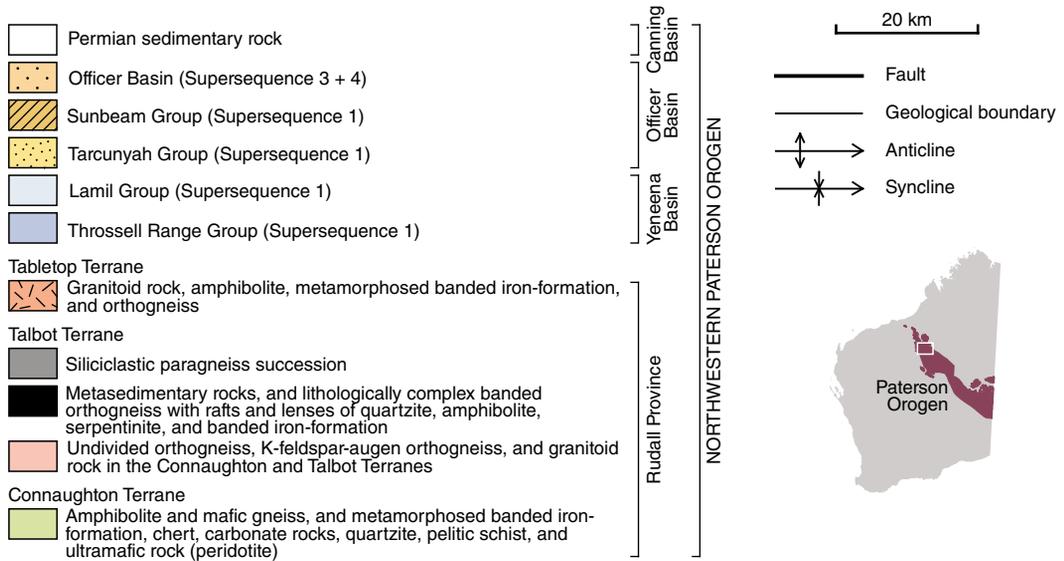
deformed and metamorphosed siliciclastic metasedimentary rocks that are up to 5 km thick in the east, and voluminous felsic intrusive rocks of the 1800–1765 Ma Kalkan Supersuite (Figs 3, 27). The siliciclastic rocks are interpreted to have been deposited in a deltaic to moderately deep marine setting on the eastern margin of the Pilbara Craton. The age of sedimentation is particularly well constrained by the age of the youngest detrital zircons in a quartzite unit — the Fingoon Quartzite — at c. 1790 Ma, and the age

of the Kalkan Supersuite granitic rocks (1800–1765 Ma) that intrude the metasedimentary package.

The Connaughton Terrane in the southeastern part of the Rudall Province comprises a series of poorly dated metamorphosed volcanic and sedimentary rocks, now schists and gneisses (Fig. 27). These rocks are also intruded by voluminous granitic rocks of the Kalkan Supersuite, the oldest of which, a K-feldspar augen gneiss, is dated at c. 1777 Ma. This

relationship indicates that the metasedimentary and metavolcanic rocks are older than c. 1777 Ma, and therefore may have been deposited at a similar time to those in the Talbot Terrane. Many of the rocks in the Connaughton Terrane have been metamorphosed to the amphibolite–granulite transition at moderate- to high-pressures of ~1200 MPa (Fig. 28).

The age spectra and Lu–Hf isotopic compositions of inherited zircons within the Kalkan Supersuite granitic rocks are similar from both the Talbot and Connaughton Terranes. The inherited zircons are also similar in age and isotopic composition to detrital zircons from siliciclastic metasedimentary rocks in the Ashburton and Blair Basins to the southwest in the Capricorn Orogen (Fig. 4). It is interpreted that the inherited zircon crystals were entrained into the Kalkan Supersuite granitic rocks from the Rudall Province sedimentary successions during granite emplacement into the upper crust. This implies that the sedimentary successions of the Rudall Province (in both the Talbot and Connaughton Terranes), which are the same age (c. 1800 Ma) as those in the Ashburton and Blair Basins, were also sourced from the southern part of the Capricorn Orogen. The Rudall and Capricorn basins were thus deposited in an autochthonous setting, in linked sedimentary basins that wrapped around the southern and eastern margins of the Pilbara Craton.

The Connaughton and Talbot Terranes have a similar structural and magmatic history during the Yapungku Orogeny, which is interpreted to record the collision between the North Australian and West Australian Cratons (Figs 2, 3). Collision was responsible for crustal thickening, producing high-pressure metamorphic rocks in the Connaughton Terrane, and the southwestward-overthrusting of the Connaughton Terrane over the Talbot Terrane. The formation of kilometre-scale, disharmonic folds and the intrusion of granite plutons during the Tanami Orogeny in the Granites–Tanami Orogen, and the Yambah Event in the west Arunta Orogen (Figs 2, 3) in the North Australian Craton, were synchronous with this collision event. The suture zone between the North Australian and West Australian Cratons lies somewhere to the northeast of the Rudall Province beneath the Canning Basin.

Figure 28. Centimetre-scale banding in garnet amphibolite showing amphibole-rich and plagioclase-rich layers; Connaughton Terrane, part of the Rudall Province that was deformed during the Yapungku Orogeny
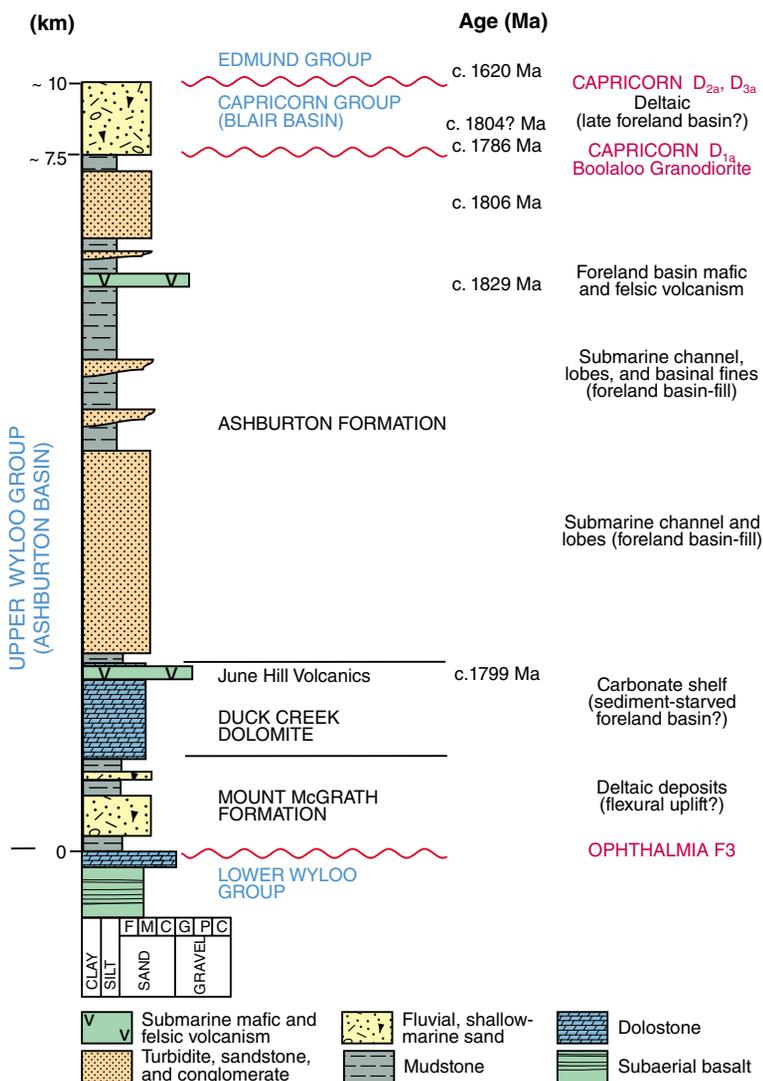

Figure 29. Stratigraphy of the upper Wyloo Group, Ashburton Basin, Capricorn Orogen

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Intracontinental reactivation during the 1820–1770 Ma Capricorn Orogeny

Deformation, granite magmatism, and deposition of the upper Wyloo and Capricorn Groups was broadly synchronous with continental collision during the Yapungku Orogeny. Previously, these events in the Capricorn Orogen were considered to relate to the lead-up and collision between the Pilbara and Yilgarn Cratons to form the West Australian Craton; however, assembly of the West Australian Craton is now recognized to have occurred much earlier, during the Ophthalmian and Glenburgh Orogenies (Fig. 2). Furthermore, the geochemical and isotopic composition of granites emplaced during the Capricorn Orogeny implies that orogenesis occurred in an intracontinental setting, possibly driven by far-field plate-margin stresses induced during the West Australian – North Australian Craton collision.

The upper Wyloo and Capricorn Groups (Figs 3, 29) contain more than 10 km of siliciclastic and volcanic rocks that are strongly deformed and metamorphosed at low grade. The ~8 km-thick upper Wyloo Group (the upper part of the Ashburton Basin) comprises a basal conglomerate and fluvial to shallow-marine sandstone succession (Mount McGrath Formation) that is overlain by a carbonate platform (Duck Creek Dolomite, see panorama below), a locally preserved sequence of felsic and mafic volcanics (June Hill Volcanics), and a thick succession of deep-marine, turbiditic sandstones and mudstones (Ashburton Formation). These rocks are unconformably overlain by ~2 km of fluvial to shallow-marine sandstones of the Capricorn Group. Both groups were deposited in a relatively short time between c. 1806 and c. 1786 Ma, although the upper Wyloo Group was deformed at least once prior to deposition of the Capricorn Group. The age modes and Lu–Hf isotopic compositions of detrital zircons within these metasedimentary successions indicate

that the sediments were sourced mostly from the southern part of the Gascoyne Province, in particular the Glenburgh Terrane. The timing of deposition and source of detritus were similar to those for metasedimentary rocks in the Rudall Province, indicating extensive uplift of the southern margin of the Gascoyne Province during the Yapungku and Capricorn Orogenies and supply of detritus northward into these linked sedimentary basins.

The first deformation event, which is only evident in the upper Wyloo Group, produced a widespread foliation (or cleavage in the lowest grade metasedimentary rocks) with associated folds, the timing of which is constrained to between c. 1806 and c. 1786 Ma, the younger limit defined by the age of intrusion of the Boolaloo Granodiorite at 1786 ± 5 Ma, which cross-cuts fabrics formed during this event. The metamorphic grade of the metasedimentary rocks, especially the Ashburton Formation, increases toward the Gascoyne Province in the south — with the appearance of quartz–muscovite–biotite–cordierite–andalusite–garnet schist — where they grade into schists of the Leake Spring Metamorphics, the protoliths of which were deposited across much of the Gascoyne Province. Both groups were then deformed between c. 1786 and c. 1784 Ma and at c. 1650 Ma, at very low metamorphic grade with the production of tight to isoclinal folds, and subsequent reactivation of pre-existing faults.

Outliers of shallow-marine sandstone, pebbly sandstone, and conglomerate of the Mount Minnie Group were deposited unconformably on folded rocks of the Ashburton Formation during the initial stages of the c. 1786 to c. 1784 Ma deformation (Fig. 3). The sediments were sourced predominantly from upland areas of the upper Wyloo Group rocks and may represent the proximal part of the foreland basin to this part of the Capricorn Orogeny.

Capricorn Orogen

The eastern (stratigraphically lower) part of the section through the Duck Creek Dolomite, Duck Creek, looking north
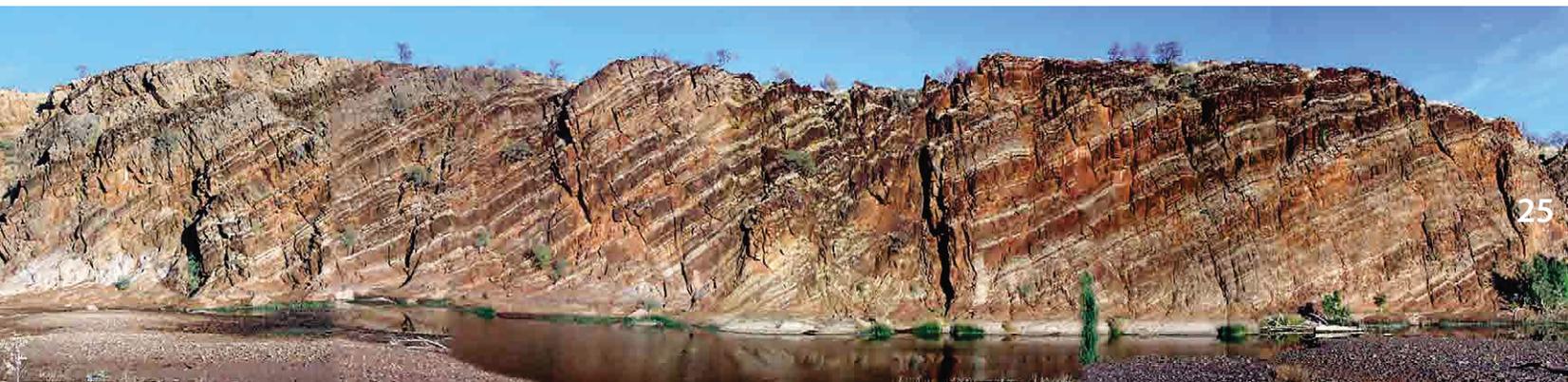
During the Capricorn Orogeny, widespread and extensive granite magmatism (the Moorarie Supersuite), deformation, and metamorphism appear to have been partitioned into distinct zones at different times across the Capricorn Orogen (Figs 3, 30). The oldest events are recorded in the southernmost parts of the Gascoyne Province — the Yarlarweelor Gneiss Complex (Fig. 4) — where magmatic activity, dated between c. 1820 and c. 1810 Ma, was accompanied by low- to mid-amphibolite facies metamorphism, extensive deformation, and reworking of the northern part of the Yilgarn Craton. Compressional deformation at this time is also recorded to the south and east of the orogen, where parts of the Padbury and Bryah Basins were thrust over the Yerrida Basin, with the deposition of the Mooloogool Group and intrusion of c. 1840 Ma mafic sills into the base of the Maraloou Formation.

Magmatism dated at c. 1820 to c. 1810 Ma is rare in the central and northern parts of the Gascoyne Province. Instead, voluminous magmatic activity — including the intrusion of the Minnie Creek batholith — occurred between c. 1795 and c. 1770 Ma, synchronous with the peak of deformation, and greenschist facies metamorphism in both the Gascoyne Province and upper Wyloo Group. The geochemical and isotopic compositions of all the Moorarie Supersuite granites throughout the orogen indicate that they formed by the reworking of older crust rather than by the substantial input of new, juvenile, mantle-derived material. Magmatism may have occupied a position analogous to the present-day Cordilleran Interior batholiths of North America, which are located 600 km or more away from the convergent plate boundary.

Irrespective of the intraplate setting for the Capricorn Orogeny, the interplay between regional deformation, metamorphism, and magmatism appears to have been extremely complex. The earliest events (between c. 1840 and c. 1810 Ma) in the southernmost part of the orogen record compressional or transpressional regimes. After c. 1810 Ma, orogenesis is dominated by voluminous magmatic activity and large-scale crustal extension accompanied by short-lived, punctuated, compressional events responsible for deformation within the upper Wyloo and Capricorn Groups. The peak of magmatic activity at c. 1795 Ma is roughly coincident with the peak of collision-
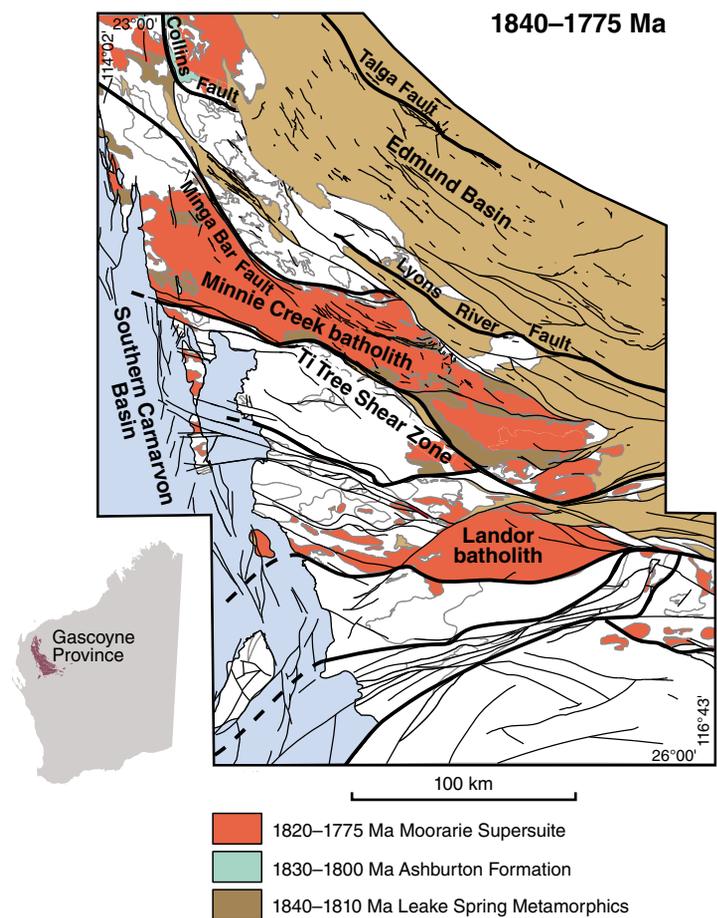

Figure 30. Distribution of the 1840–1775 Ma granitic and metasedimentary units in the Gascoyne Province, Capricorn Orogen
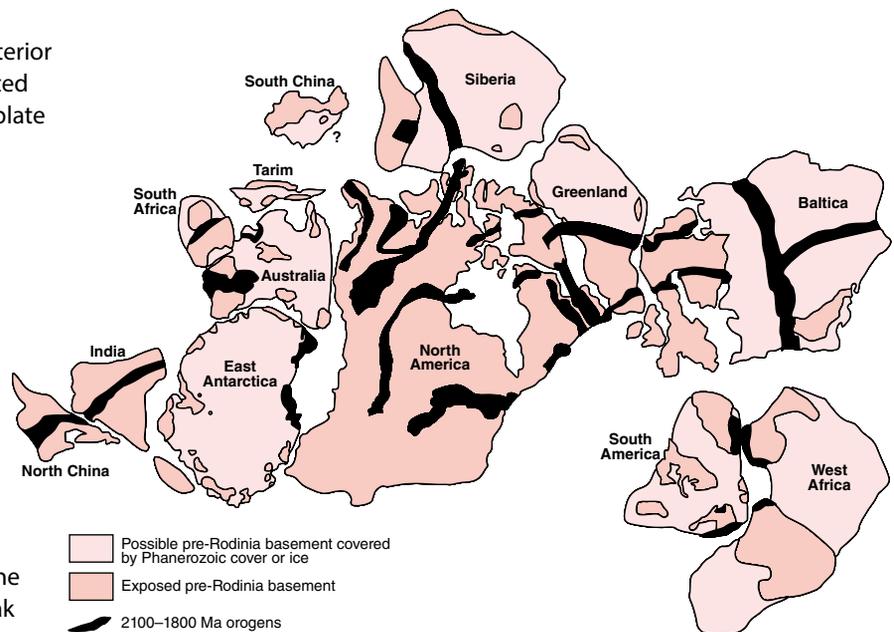

Figure 31. Reconstruction of the Nuna Supercontinent (after Zhao et al., 2002)

related orogenesis in the Rudall Province during the Yapungku Orogeny (Fig. 2). Minor mafic magmatic underplating and intraplating during subduction–collision along the West Australian Craton margin, may have thermally weakened the crust enough to allow far-field (collision-related) stresses to drive intraplate deformation.

Western Australia's place in Nuna

Because of the lack of precise global geological (including geochronological and paleomagnetic) constraints from the Earth's Paleoproterozoic cratons and orogenic belts, the make-up and configuration of Nuna is poorly known. However, detailed geological constraints on the Western Australian components do provide critical information on the timing and style of Nuna assembly.

The Paleoproterozoic history of the West Australian and North Australian Cratons indicate growth by the progressive assembly of independent crustal blocks until the amalgamation of the two cratons during the 1795–1760 Ma Yapungku Orogeny (Fig. 2). The protracted assembly of these blocks implies that if the West Australian and North Australian Cratons were part of the Nuna supercontinent, then this part of Nuna must also have been progressively assembled over a 600 million-year

period. These geological constraints also provide critical information on the configuration of Nuna by identifying potential neighbouring cratonic blocks. For example, the stratigraphic similarities between the 2780–2660 Ma Ventersdorp Supergroup on the Kaapvaal Craton and the 2775–2630 Ma Fortescue Group on the Pilbara Craton suggest that these two cratons were part of a much larger cratonic entity — a supercraton known as Vaalbara — before the construction of the West Australian Craton. Recent high-quality paleomagnetic data demonstrate that this connection is possible at c. 2780 Ma, but that Vaalbara had, most likely, broken apart prior to, or during, Nuna assembly at c. 2000 to c. 1800 Ma. Equally, the similarity in age between the large dyke swarms of the c. 2410 Ma Widgiemooltha Dyke Suite in the Yilgarn Craton and the c. 2408 Ma Sebangwa Poort dykes in the Zimbabwe Craton, suggests that these two cratons may have been close neighbours within the Nuna supercontinent.

The most common Nuna configuration is based around the core components of the Mesoproterozoic Rodinia supercontinent (Fig. 31), but this reconstruction does not satisfy the known geological constraints from Western Australia. An alternative model reconstructs the positions of individual, or groups of cratons based entirely on the age, location, and form of giant radial and linear dyke swarms (Fig. 32). Although this reconstruction does not attempt to be as detailed or as comprehensive as the 'proto-Rodinia' model, it does allow both the West and North Australian Cratons to be placed close to their identified potential cratonic neighbours, and within a geologically reasonable position within Nuna along its peripheral margin.
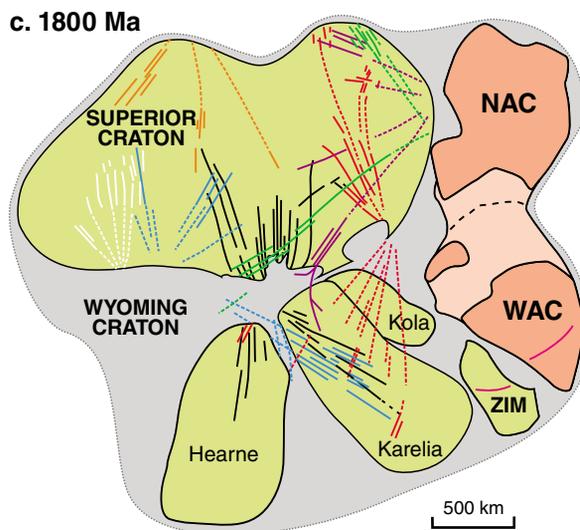

Figure 32. Reconstruction of the Nuna Supercontinent (modified from Söderlund et al., 2010). Craton abbreviations: NAC, North Australian Craton; WAC, West Australian Craton; ZIM, Zimbabwe Craton. Dyke swarms are coloured from oldest to youngest: red, black, pink, purple, green, blue, white, and orange

A stable supercontinent? (1700–1400 Ma)

FOLLOWING THE PROGRESSIVE ASSEMBLY of the Western Australian part of the Nuna supercontinent, the locus of tectonic activity shifted to the current southern and eastern margins of the West Australian Craton and the southern margin of the North Australian Craton.

This activity, including subduction-related magmatism, deformation, and sedimentation, indicates that this extensive continental margin faced an open-oceanic tract, possibly forming a peripheral margin of the Nuna supercontinent (Fig. 32).
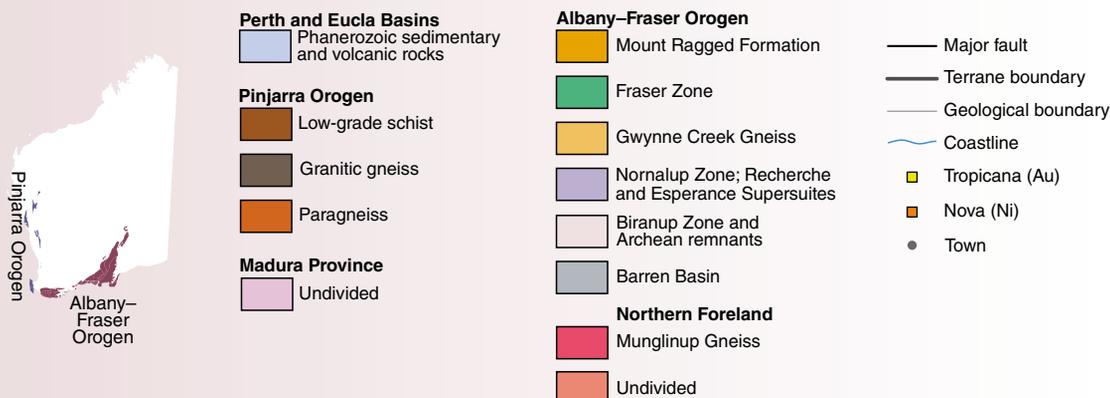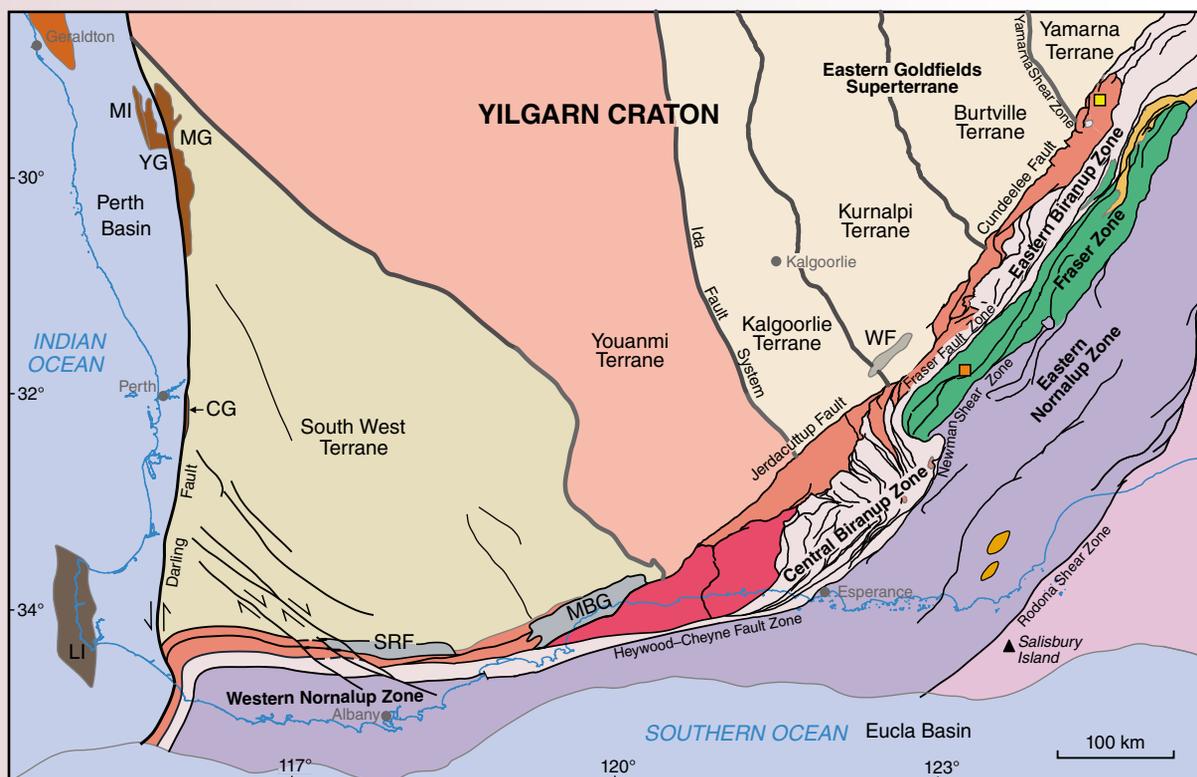

Figure 33. *Simplified geological map of the Albany–Fraser Orogen and southern Archean Yilgarn Craton, showing the division into tectonic zones, terranes, and provinces. Abbreviations: CG, Cardup Group; LI, Leeuwin Inlier; MBG, Mount Barren Group; MG, Moora Group; MI, Mullingarra Inlier; SRF, Stirling Range Formation; WF, Woodline Formation; YG, Yandanooka Group*

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Subduction magmatism and growth of the West Australian Craton

Albany–
Fraser
Orogen

The Albany–Fraser Orogen is an arcuate orogenic belt of predominantly amphibolite to granulite facies paragneiss and orthogneiss that lies along the southern and southeastern margin of the Yilgarn Craton (Fig. 33). Previously, the orogen was thought to have formed as a response to the Mesoproterozoic collision between a combined North Australian and West Australian Craton with the South Australian and Mawson Craton of Antarctica. However, recent geochronological, geochemical, and isotopic investigations demonstrate that much of the orogen was formed initially during the Paleoproterozoic, and marks the in-situ growth and reworking of the southern West Australian Craton margin. The Paleoproterozoic activity is marked by voluminous magmatism from c. 1800 to c. 1650 Ma, and includes Na-poor, calc-alkaline granitic gneisses intruded during the 1710–1650 Ma Biranup Orogeny that are suggestive of a back-arc setting (Fig. 3). The presence of fragments of Archean crust with Yilgarn-like ages, extensive formation of related

sedimentary basins (the Barren Basin), Hf and Nd isotopic signatures that indicate Yilgarn-like sources for the Paleoproterozoic magmas, and a progressive increase of juvenile material into Archean unradiogenic crust, are all indicative of a rift-style tectonic setting (Fig. 34). This setting could have been part of a back-arc system, but the distance to any former subduction zone is not clear (present-day easterly direction), nor is the extent of attenuated Yilgarn Craton crust.

Based on a model of a back-arc system, modification of the craton margin and formation of the Biranup Zone (Fig. 33) may have formed initially by the northwestward-directed subduction of oceanic crust under the Yilgarn Craton (Fig. 34). With continued convergence, subduction, and slab roll-back, fragments of the Yilgarn Craton may have rifted away as the back-arc basin evolved. The associated basins were filled by cycle one sediments of the Barren Basin. Compression, high-grade metamorphism, and migmatization of lithologies in the back-arc region during the c. 1680 Ma Zanthus Event indicate tectonic switching and a change in plate dynamics, possibly caused by the arrival of a seamount. This event produced a series of northwesterly trending structures under high-
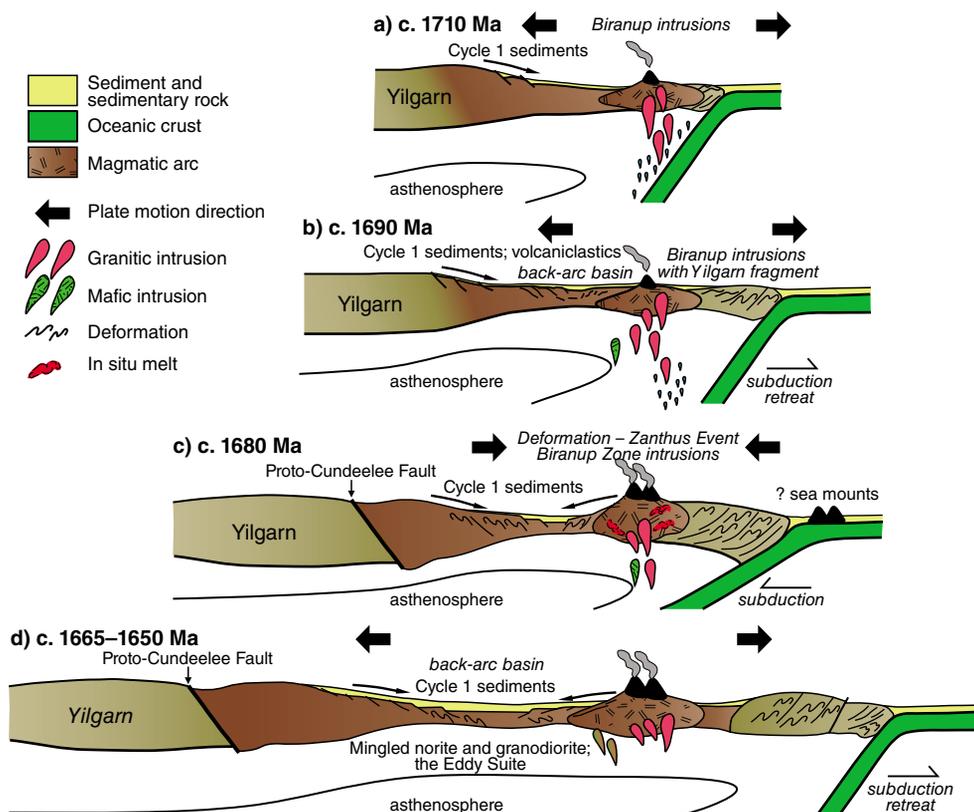

Figure 34. Tectonic evolution of the Albany–Fraser Orogen and southern Yilgarn Craton margin during the 1710–1650 Ma Biranup Orogeny

temperature conditions. The youngest suite of intrusive rocks — Eddy Suite — at c. 1665 Ma shows an increase in Mg#, ƐHf, and ƐNd, reflecting a progressively more juvenile influence that might signify renewed back-arc extension. The interpreted effect of back-arc extension and slab roll-back was to rift Archean fragments from their original location on the Yilgarn Craton margin and isolate them within Paleoproterozoic Biranup Zone intrusive rocks.

After c. 1800 Ma, siliciclastic sediments including the Woodline and Stirling Range Formations and the Mount Barren Group — cycle one sediments of the Barren Basin — were deposited on the southern Yilgarn Craton, and are interpreted to be the inboard remnants of a much larger basinal system that developed along the southern margin of the West Australian Craton (Fig. 33). All three successions are dominated by similar lithologies, including shallow-marine to fluvial, mature, quartz-rich sandstones with interbedded siltstones and minor conglomerate.

U–Pb geochronology of diagenetic xenotime within the Mount Barren Group and Stirling Range Formation and U–Pb dating of detrital zircons from all three successions have shown that they were deposited at slightly different times and were derived from different source
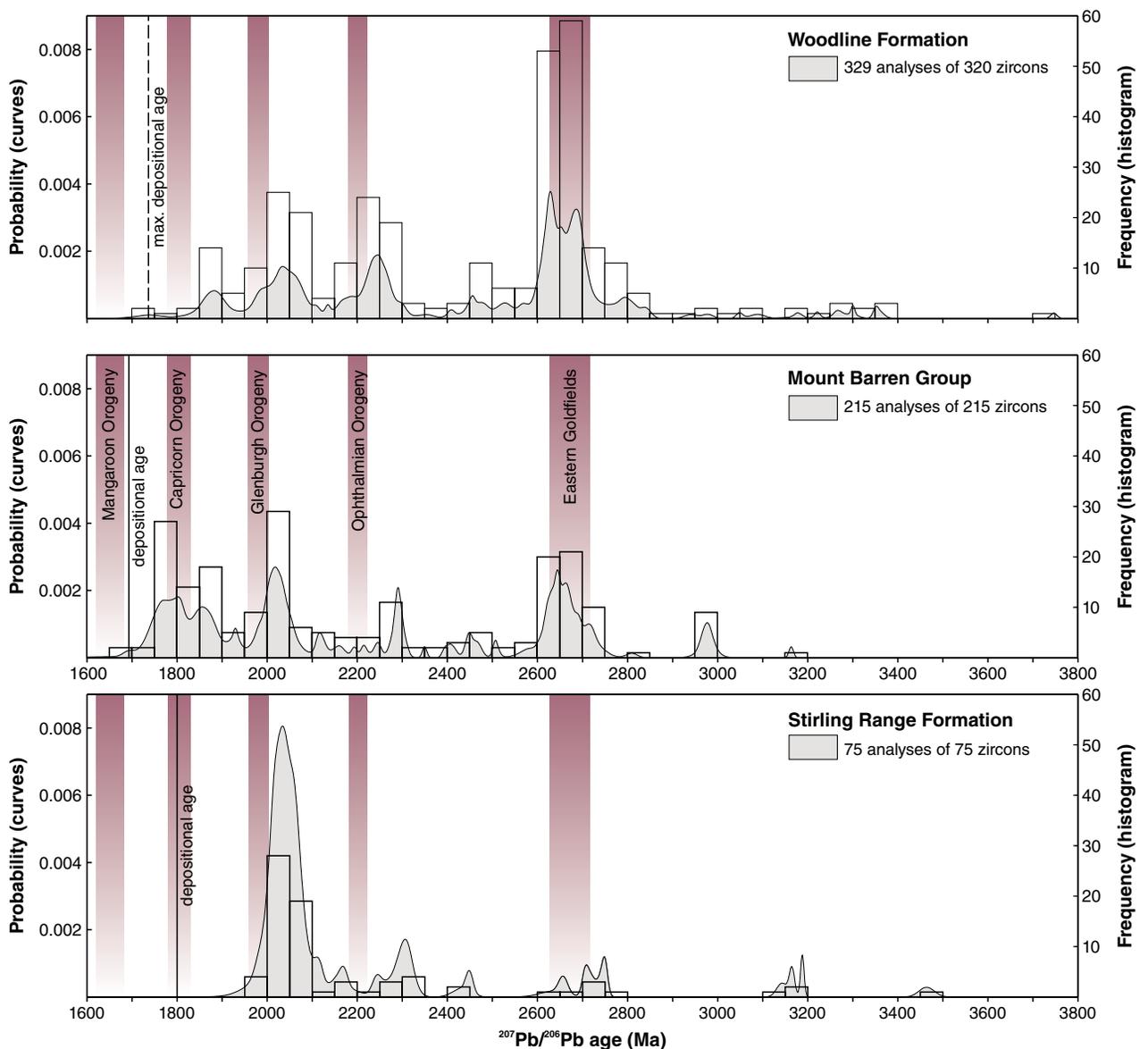

Figure 35. Comparison of detrital zircon age components within cycle 1 metasedimentary rocks of the Barren Basin (after Hall et al., 2008)

regions (Fig. 35). At c. 1800 Ma, the Stirling Range Formation is about 100 million years older than the c. 1693 Ma Mount Barren Group (Fig. 36 and shaded box). The Woodline Formation has a maximum depositional age of c. 1737 Ma. The age spectra of detrital zircon indicate that both the Mount Barren Group and the Woodline Formation contain a significant proportion of Paleoproterozoic material that initially appears to have been sourced from the Capricorn Orogen on the northern side of the Yilgarn Craton, some 1000 km away. However, ongoing geochronological studies on the Albany–Fraser Orogen and on basement rocks within the Eucla Basin, confirm that many of these formerly 'unique' Paleoproterozoic age modes could have been sourced locally from within the orogen. Deposition of the cycle one sediments of the Barren Basin are interpreted to be a response to extensional activity associated with back-arc formation along the Yilgarn Craton margin prior to, and during, the Biranup Orogeny (Fig. 34).

Associated arc magmatism in the North Australian Craton?

Arc-related magmatism along the southern margin of the North Australian Craton in the Arunta Orogen took place between c. 1690 and c. 1660 Ma. High-K, calc-alkaline arc magmatism

— the Argilke Igneous Event — occurred within the Warumpi Province, which is interpreted as an approximately 500 km-long exotic terrane and magmatic arc that accreted to the southern margin of the North Australian Craton — the Aileron Province (Fig. 37). These provinces extend westward into Western Australia, to form the west Arunta Orogen. In the west Arunta Orogen the oldest known rocks of the Aileron Province are polydeformed metasedimentary rocks of the 1840–1835 Ma Lander Rock Formation (Fig. 3). This formation is intruded by metagranitic rocks of the 1805–1770 Ma Carrington Suite, which coincides with the Yambah Event. Carrington Suite metagranites are overlain by deformed and strongly recrystallized quartzite — the Lake MacKay Quartzite — which has a maximum depositional age of 1750 ± 19 Ma. This quartzite may correlate with the Reynolds Range Group in the Northern Territory, which has a maximum depositional age of 1798 ± 10 Ma.

The Warumpi Province in the west Arunta Orogen is dominated by variably deformed greenschist facies rocks of the Kintore Domain. The oldest known lithology is a strongly foliated metasyenogranite containing metasedimentary xenoliths — the Ininti Granite, part of the Argilke Event — dated at 1691 ± 5 Ma. The granitic rocks are intruded by felsic igneous rocks, including

West
Arunta
Orogen

The birth of multicellular organisms

Quartz sandstones of the Stirling Range Formation, metamorphosed in the sub-greenschist to lower greenschist facies, contain rare megascopic discoid fossils that have been interpreted as motile multicellular (or possibly syncytial) organisms (image below is of a medusoid impression showing possible stalked structure). The presence of such fossils initially suggested that the sandstones were Neoproterozoic (Ediacaran) in age. However, U–Pb geochronological dating of diagenetic xenotime in the sandstones shows them to be considerably older, at 1800 ± 14 Ma, indicating that motile multicellular organisms developed during the Paleoproterozoic. These biota, together with the emergence of the first large algal-like multicellular eukaryotes, indicate that an evolutionary threshold was crossed in the Paleoproterozoic, following a long period of environmental change across the Archean–Paleoproterozoic boundary.

20 mm
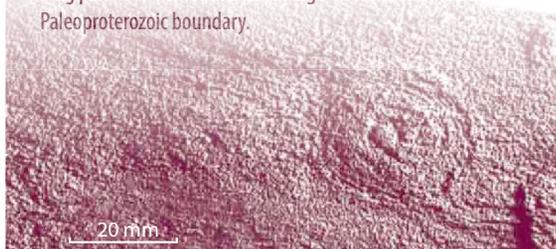
Figure 36. Moderately south-dipping recrystallized quartzites of the Stirling Range Formation, Barren Basin, Albany–Fraser Orogen. View from top of Bluff Knoll, looking east
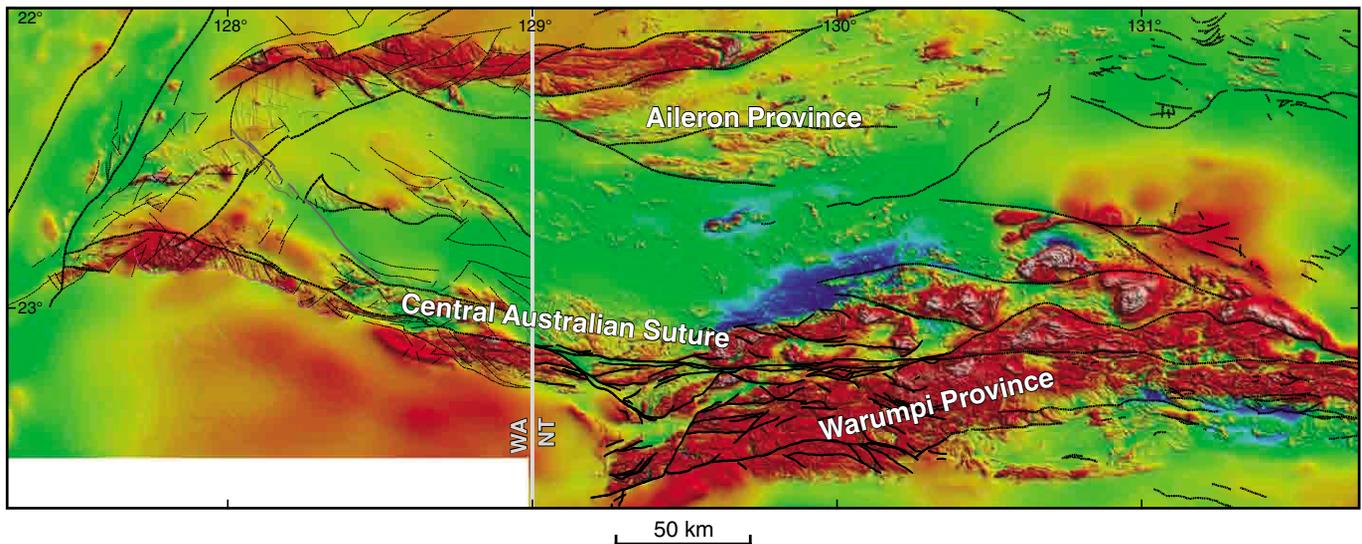
Figure 37.   Reduced to Pole (RTP) aeromagnetic image of the Arunta Orogen in Western Australia and the Northern Territory, showing the distribution of the Aileron and Warumpi Provinces as well as the Central Australian Suture

the c. 1640 Ma Mount Webb Granite, and overlain by volcaniclastic rocks including the c. 1670 Ma Pollock Hills Formation and c. 1650 Ma Walungurru Volcanics. In the Northern Territory the Walungurru Volcanics have a wide range of felsic, intermediate, and mafic compositions that have an overall calc-alkaline affinity. Granitic and volcanic rocks of the Warumpi Province in the west Arunta Orogen have been intruded by the northwesterly trending Western Desert Dyke Suite, dated at 976 ± 3 Ma.

Closure of the ocean basin and the oblique accretion of the Warumpi Province to the Aileron Province occurred during the c. 1640

to c. 1635 Ma Liebig Orogeny (Fig. 2), which produced the Central Australian Suture and both intrusion and extrusion of felsic magmatic rocks in the Warumpi Province (e.g. Mount Webb Granite). However, the Lu–Hf isotopic compositions of magmatic zircons from the Ininti Granite in the Warumpi Province suggest that the magma was derived from, or interacted with, felsic crust with a composition similar to that of the Aileron Province, providing a possible connection to the North Australian Craton during the Argilke Event. This would imply that either i) a juvenile arc (the Warumpi Province) formed along the southern margin of the North
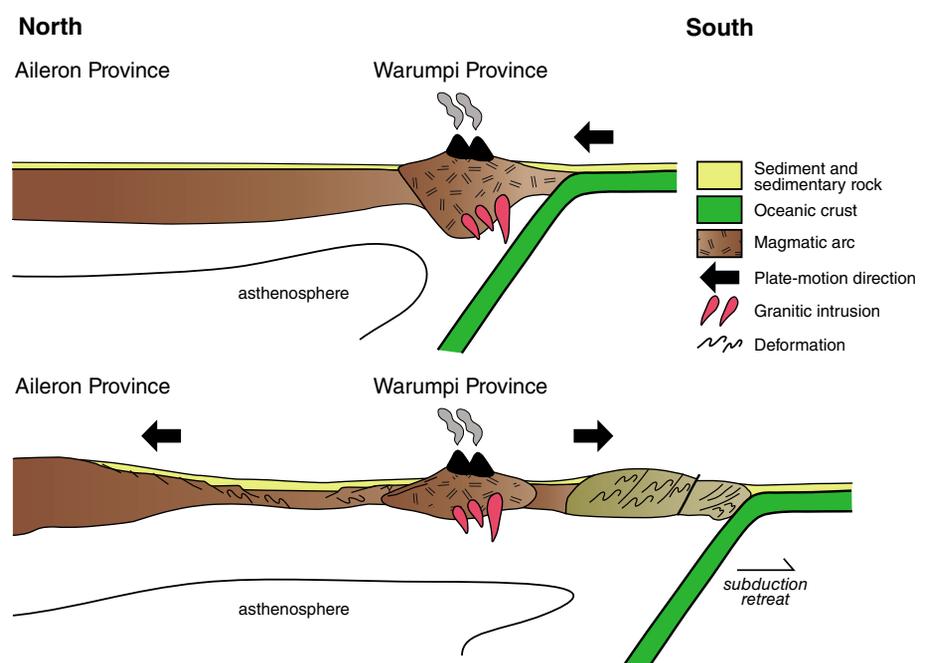
Figure 38.   Possible tectonic settings for the evolution of the Aileron and Warumpi Provinces in the Arunta Orogen
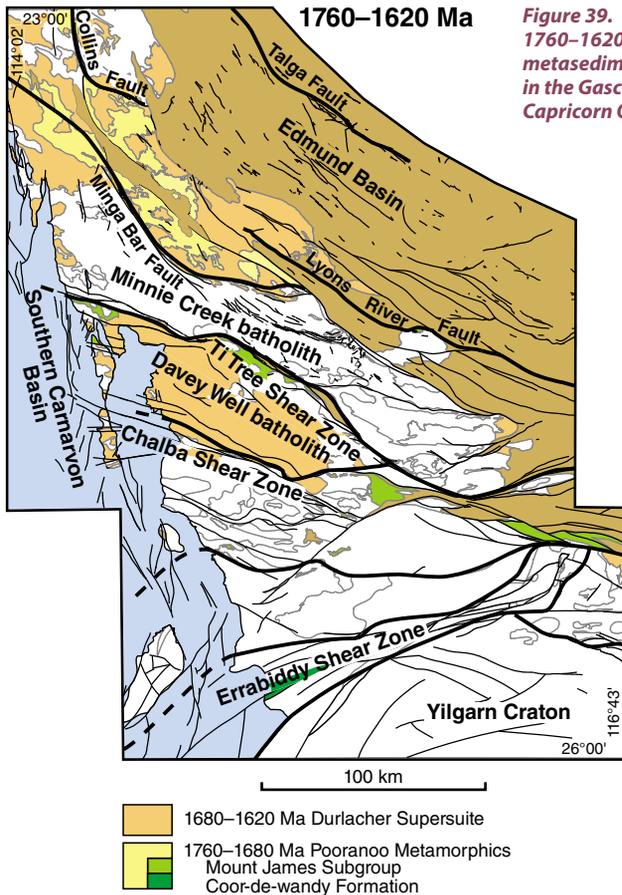
1760–1620 Ma

Figure 39. Distribution of 1760–1620 Ma granitic and metasedimentary units in the Gascoyne Province, Capricorn Orogen

1680–1620 Ma Durlacher Supersuite

1760–1680 Ma Pooranoo Metamorphics
  Mount James Subgroup
  Coor-de-wandy Formation

Australian Craton (the Aileron Province); or ii) during the initiation of subduction, the formation of a ribbon continent — a proto-Warumpi Province — was rifted away from the southern margin (Fig. 38). Both of these scenarios imply northward subduction of oceanic crust beneath the North Australian Craton, a subduction architecture similar to that envisaged during the contemporaneous Biranup Orogeny in the Albany–Fraser Orogen (Fig. 34). Alternatively, the Warumpi Province may have formed outboard of the North Australian Craton within an exotic sliver of crust with similar isotopic compositions to the Aileron Province.

Intra-supercontinental basins and extensional orogeny

In the central-western part of the West Australian Craton, siliciclastic sedimentary rocks of the 1760–1680 Ma Pooranoo Metamorphics (Fig. 3) were deposited across the Gascoyne Province and northern margin of the Yilgarn Craton, where they are correlated with the Coor-de-wandy Formation (Fig. 39). Throughout the southern part of the province, the base of the succession is marked by the Mount James Subgroup, a series of poorly sorted, immature, fluvial sandstones, pebbly sandstones, and conglomerates that are overlain by locally mature, well-sorted, shallow-marine quartz sandstones. The sequence is up to 700 m thick. The basin deepens and youngs toward the north, where it is dominated by turbiditic sandstones. Seismic reflection images across the northern part of the Gascoyne Province suggest that, in the Mangaroon Zone, the basin is up to 6 km

Figure 40. (below) Interpreted migrated seismic-reflection profile (part of 10GA-CP2) through the Mangaroon Zone. Extensional movement on the Geegin Fault, a moderately southwest-dipping fault, has allowed the deposition of over 6 km of siliciclastic sedimentary rocks — the Pooranoo Metamorphics — into the Mangaroon Zone. Subsequent high-grade metamorphism and deformation during the 1680–1620 Ma Mangaroon Orogeny, and intrusion of voluminous granites of the Durlacher Supersuite have deformed and disrupted the basin architecture, except for a few sub-parallel seismic reflections (form lines) that may represent remnant coherent packages of metasedimentary material. Location of seismic line is shown on map of Western Australian Proterozoic elements (p. vi).
Abbreviations: CDP, Common Depth Point; D, Durlacher Supersuite; E, Edmund Group; M, Moorarie Supersuite; P, Pooranoo Metamorphics; TWT, two-way travel time
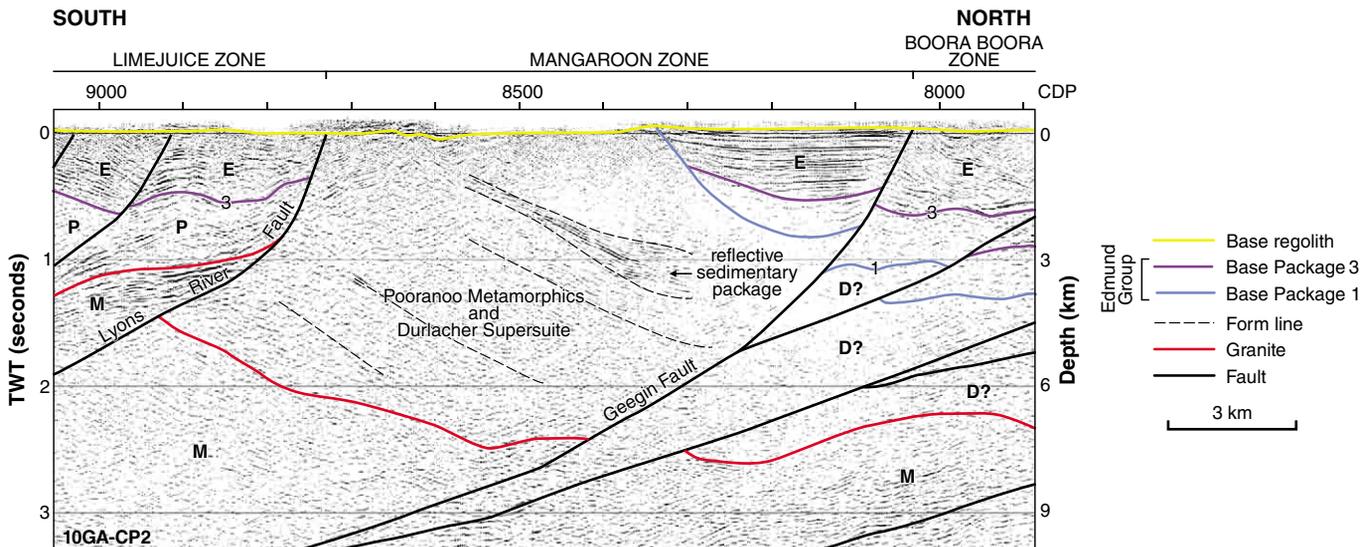
thick (Fig. 40). However, some of the basin thickness may be due to structural repetition during deformation and metamorphism. In the Mangaroon Zone, the turbiditic sandstones were deformed and metamorphosed in the upper amphibolite to granulite facies, and intruded by voluminous granites of the Durlacher Supersuite during the 1680–1620 Ma Mangaroon Orogeny. Although granite magmatism peaked between c. 1680 and c. 1675 Ma, granite plutons were emplaced throughout the Gascoyne Province until c. 1620 Ma. High-temperature (~650° C), low-pressure (~330 MPa) metamorphism took place entirely within the Mangaroon Zone, in a short time interval between c. 1680 and c. 1677 Ma, and resulted in localized in situ melting of turbiditic rocks of the Pooranoo Metamorphics. Metamorphism was accompanied by the intrusion of voluminous granitic rocks that show extensive mixing and assimilation with the metasedimentary and meta-igneous country rocks. The equivocal nature of associated deformation structures,

including shear sense indicators, makes it difficult to resolve the tectonic setting for orogenesis from field relations alone. However, the extremely high geotherm (70° C/km) required for metamorphism, short time duration of orogenesis, and the lack of syntectonic sedimentation implies that the Mangaroon Orogeny may have occurred within an extensional tectonic setting.

Deformation of Mangaroon Orogeny age is also recorded on the margins of the Capricorn Orogen. Along the southern part of the orogen, sericite from strongly cleaved pelites from the Stanley Fold Belt (Fig. 17) — the northern margin of the Earaheedy Basin — yielded ^{40}Ar/^{39}Ar ages of c. 1650 Ma. These results suggest that open to tight, regional-scale folding of sedimentary rocks within the Earaheedy Basin took place during the Mangaroon Orogeny.

Similar ^{40}Ar/^{39}Ar muscovite ages of c. 1653 Ma were obtained from regional-scale extensional shear zones within the Archean Sylvania Inlier
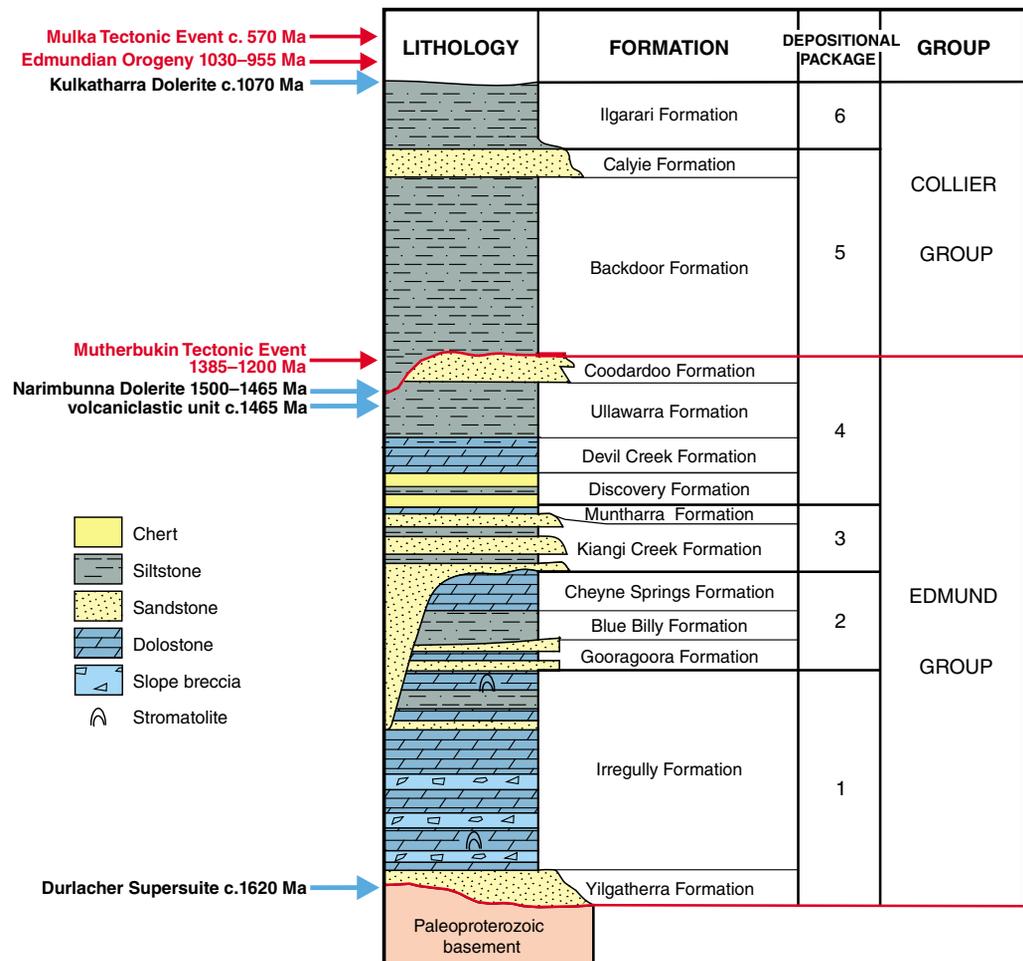

Figure 41. Stratigraphy of the Edmund and Collier Groups, Capricorn Orogen

(Fig. 4), along the northern margin of the orogen. These shear zones appear to have controlled the deposition of the Bresnahan Group, a succession of coarse-grained continental to fine-grained lacustrine siliciclastic sedimentary rocks that unconformably overlie older, more deformed, rocks of the upper and lower Wyloo Groups (Fig. 3).

Mesoproterozoic rifting

During the Mesoproterozoic, the Capricorn Orogen was again subject to intraplate rifting and extension. Up to 5 km of fine-grained siliciclastic and carbonate sedimentary rocks — the Edmund Group — accumulated within the Edmund Basin in the western and central Capricorn Orogen (Fig. 3). The precise age for the initiation of rifting and basin deposition is poorly constrained. However, abundant mafic intrusive rocks — the Narimbunna Dolerite — and felsic volcaniclastic rocks in the uppermost part of the Edmund Basin have been dated to between c. 1500 and c. 1465 Ma, providing a younger age limit for deposition. The Edmund Group consists of four main packages of carbonate and siliciclastic shelf to basinal deposits, each of which is separated by basal unconformities or major marine flooding surfaces (Fig. 41), suggesting that deposition occurred during multiple, punctuated extensional events. The locally preserved Mount Augustus Sandstone may correlate with the basal fluvial facies of

Depositional Package 1, or be an older succession of fluvial rocks, unrelated to the Edmund Group.

Sedimentation and the distribution of lithofacies were controlled principally by the extensional reactivation of major basement faults such as the Talga, Godfrey, and Lyons River Faults (Fig. 4). Downthrow on these predominately northwest-trending faults was to the southwest, forming a series of half grabens. The most northerly growth fault — the Talga Fault — formed the southwestern edge of a paleogeographic high known as the Pingandy Shelf, across which there are major lithofacies and thickness variations.

In the Edmund Basin, the oldest package — Depositional Package 1 — consists of fluvial to shallow-marine siliciclastic and carbonate rocks that were deposited unconformably on older Paleoproterozoic basement including granitic rocks of the 1680–1620 Ma Durlacher Supersuite (Fig. 41). Deposition was controlled by extension on the major faults and deepening of the half-graben basins. Continued extension and marine incursion resulted in the deposition of deltaic to deep-marine siliciclastic and carbonate rocks of Depositional Package 2.

A significant angular unconformity between Depositional Packages 2 and 3 indicates a period of uplift, tilting, and erosion (Fig. 41). Renewed extension and marine influx resulted in the deposition of shallow- to deep-marine siliciclastic and carbonate deposits of Depositional Package 3. Depositional Package 4, comprising deep-marine siliciclastic and carbonate rocks, lies unconformably on all the underlying packages. In the upper part of Depositional Package 4, the Ullawarra Formation contains significant horizons of felsic volcaniclastic material, recently dated at c. 1460 Ma. These volcaniclastic rocks were essentially coeval with the intrusion of voluminous mafic sills — Narimbunna Dolerite — that mark the end of this period of sedimentation and extension. The tectonic significance of these bimodal mantle-derived intrusive and volcaniclastic rocks is not yet fully understood.

Facies and thickness changes across the Pingandy Shelf demonstrate that deposition was controlled by episodic reactivation of the Talga, Godfrey, and Lyons River Faults. Paleocurrent directions throughout the succession in the central and northern parts of the basin indicate that sediment was derived predominantly from a source region to the north and northeast. Ongoing research on the Lu–Hf isotopic compositions of detrital zircon grains implies

Edmund Basin
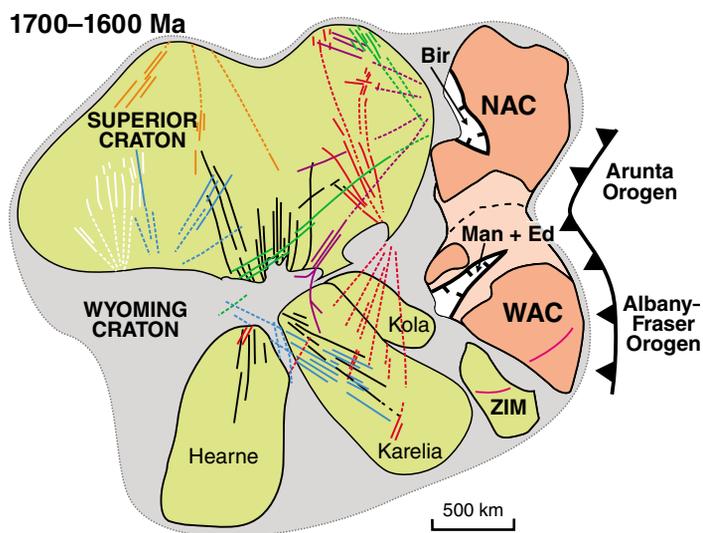
1700–1600 Ma

*Figure 42. Reconstruction of Nuna (1700–1600 Ma) showing the possible tectonic setting of the West Australian Craton during the Mangaroon Orogeny and formation of the Birrindudu, Bastion, Osmond, Crowhurst, and Edmund Basins (modified from Söderlund et al., 2010).*
Abbreviations: Bir, Birrindudu, Bastion, Osmond, Crowhurst Basins; Ed, Edmund Basin; Man, Mangaroon Orogeny; craton abbreviations as for Figure 32

that the lower parts of the Edmund Group were derived from the erosion of the Capricorn, Mount Minnie, and Bresnahan Groups in the Ashburton and Blair Basins. Continued uplift and unroofing in this source region resulted in the eventual exposure and erosion of the underlying Hamersley and Fortescue Groups, which provided detritus for the upper part of the Edmund Group. The U–Pb dating and Lu–Hf isotopic work demonstrate that, during crustal extension and basin formation in the central part of the Capricorn Orogen, significant uplift and unroofing took place along the southern Pilbara Craton margin. These opposing stress regimes were tectonically separated by the Talga Fault, underlining the importance of this major, long-lived structure in the deposition and evolution of the Edmund Basin.

The Scorpion Group (Figs 3,17), a succession of sandstone, carbonate rocks, and evaporites possibly 10 km thick, was deposited in the eastern Capricorn Orogen after c. 1650 Ma, the age of deformation of sedimentary rocks in the Earaheedy Basin from which clasts are reworked into the Scorpion Group. This is probably at the same time as deposition of the lower Edmund Group, based on broad similarities in stromatolites within the two basins. Deposition was in much shallower (commonly coastal) settings than all but Depositional Package 1 of the Edmund Group. Evaporites are not preserved in outcrop, but a cauliflower-like outcrop pattern about 8 km across is very suggestive of an evacuated diapir, and halite pseudomorphs (salt hoppers) can be seen in sandstones. Sandstones commonly display giant cross-bedding, with transport generally to the west (see panorama below).

Within the North Australian Craton, extensional deformation and basin formation is recorded between c. 1790 and c. 1640 Ma, with the deposition of siliciclastic sediments into the Birrindudu, Bastion, Osmond, and Crowhurst Basins (Fig. 3). These basins unconformably overlie Paleoproterozoic rocks of the Pine Creek and Halls Creek Orogens.

Giant cross-beds in the basal Wonyulgunna Sandstone, Mesoproterozoic Scorpion Group, Ingebong Hills, Capricorn Orogen, looking southwest

A view from Nuna's peripheral margin

The synchronicity in timing and duration of magmatism, and the comparable subduction architecture between the Albany–Fraser and Arunta Orogens, suggest these two orogens may have been part of the same subduction margin, which would have extended some 1500 km along the periphery of the Nuna supercontinent (Fig. 42). The length of this active margin is comparable to the present-day South American Andean margin. Although the central parts of the supercontinent appear to have remained relatively geologically inactive from c. 1800 Ma, implying stabilization of the supercontinent, the history of the West Australian and North Australian Cratons was dominated by punctuated tectonic reactivation, including deformation and metamorphism associated with the Mangaroon Orogeny and the formation of numerous sedimentary basins, such as the Birrindudu, Bastion, Osmond, Crowhurst, and Edmund Basins (Fig. 3). These episodic reworking events in an otherwise 'stable' supercontinent most likely reflect the transfer of plate-margin stresses from subduction-related processes along Nuna's peripheral margin. The transfer of strain appears to have been localized within sites of pre-weakened orogenic crust (i.e. the sites of older collision or accretion zones), by the reactivation of older crustal-scale structures, such as the Lyons River Fault in the Gascoyne Province (Fig. 4).

FOLLOWING THE AMALGAMATION AND stabilization of the Nuna supercontinent, numerous magmatic, metamorphic, and deformation events in both the Musgrave Province and Albany–Fraser Orogen record tectonic activity that may represent the lead-up to collision of the combined South Australian – Mawson Craton to Nuna's periphery. Also at this time several intraplate events affected the West Australian Craton, and although the significance of this is poorly understood, similar-aged tectonism and magmatism in other crustal segments of Nuna have been interpreted to relate to the break-up of this supercontinent.

Mid-Mesoproterozoic tectonic activity

Plate-margin magmatism

The oldest rocks in the west Musgrave Province (Fig. 43) — that part of the Musgrave Province in Western Australia — are felsic gneisses of
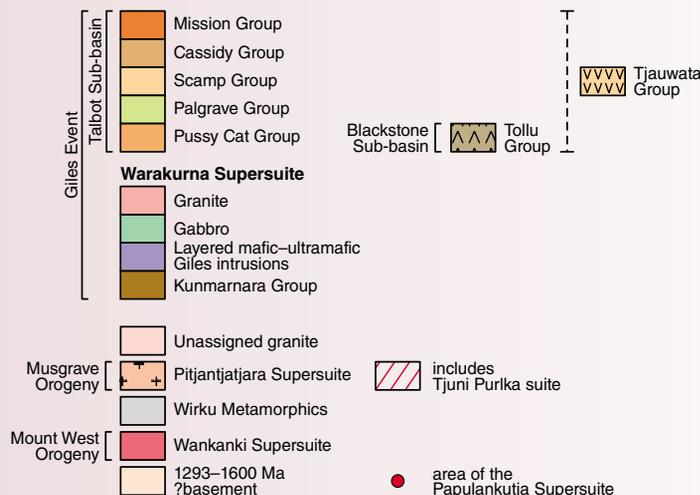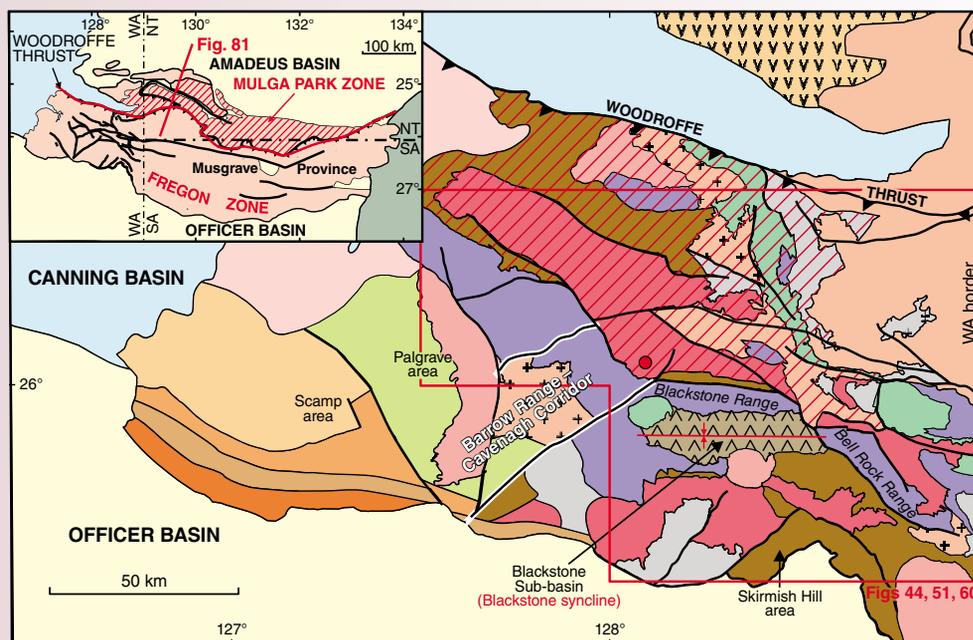

Figure 43. Regional geological sketch of the west Musgrave Province — that part of the Musgrave Province that lies in Western Australia
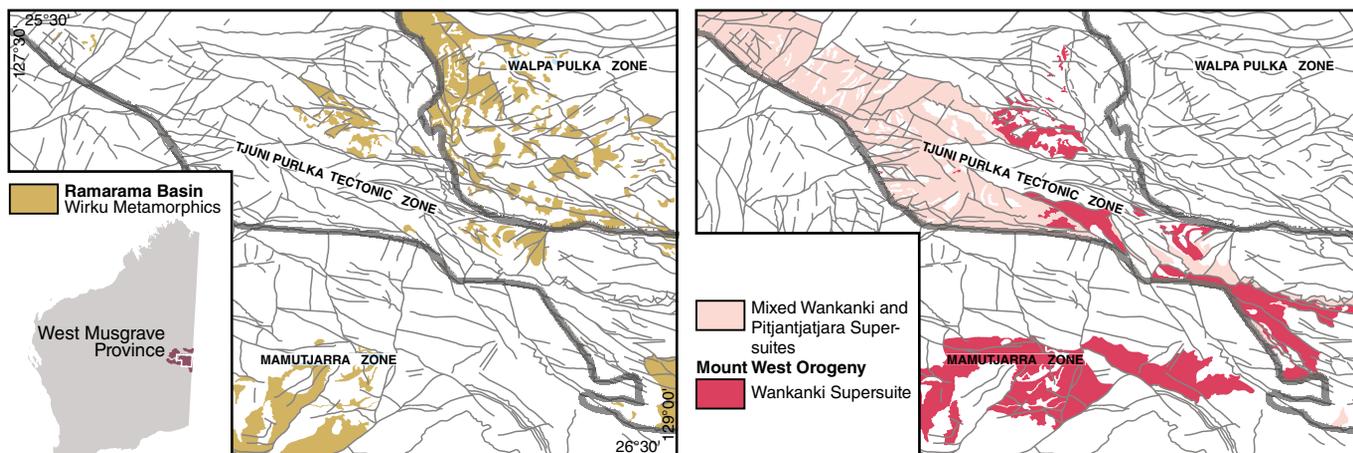
Figure 44.   Interpreted bedrock geology maps showing the distribution of 1345–1270 Ma metasedimentary and meta-igneous rocks within the eastern portion of the west Musgrave Province. Location of map shown on Figure 43

Figure 45.   Reconstruction of Nuna (c. 1400 Ma) showing the possible tectonic setting of the Western Australian cratons during the Mount West Orogeny in the west Musgrave Province and Stage I of the Albany–Fraser Orogeny in the Albany–Fraser Orogen (modified from Söderlund et al., 2010).
Abbreviations: SAC, South Australian Craton; MC, Mawson Craton; MP, Musgrave Province; other abbreviations as for Figure 32

the c. 1400 Ma Papulankutja Supersuite (Fig. 3). Although rocks of this age are rare, c. 1400 Ma detrital zircons form significant age components within younger metasedimentary rocks of the 1340–1270 Ma Wirku Metamorphics (Fig. 44). These metasedimentary rocks also contain detrital zircons with a significant age component at 1650–1530 Ma, indicating the presence of older (i.e. c. 1650 to c. 1400 Ma) felsic basement in the province, some of which is exposed in the Fregon Zone in South Australia (Fig. 43). However, the Lu–Hf isotopic compositions of c. 1650 to c. 1270 Ma magmatic and detrital zircons indicate that the felsic basement rocks were themselves derived from, or interacted with, significant mafic to intermediate material that was emplaced into the lower crust at c. 1950 to c. 1900 Ma.

In the west Musgrave Province, the 1345–1293 Ma Mount West Orogeny records voluminous felsic magmatism, including both plutonic and volcano-sedimentary rocks — the 1345–1293 Ma Wankanki Supersuite — that have geochemical and isotopic compositions consistent with their formation in a continental-margin arc. Psammitic and minor pelitic metasedimentary rocks of the 1340–1270 Ma Wirku Metamorphics were deposited in the Ramarama Basin across all three major tectonic zones in the province — the Walpa Pulka Tectonic, Tjuni Purlka, and Mamutjarra Zones (Fig. 44). The sediments were deposited immediately prior to, and during arc magmatism. They are locally interlayered with volcanic rocks, and contain detrital components derived from them. Age spectra of detrital zircons demonstrate that metasedimentary rocks within the Walpa Pulka Tectonic Zone contain a significant proportion of older detritus (c. 1650 to c. 1530 Ma). The age spectra and isotopic compositions of detrital zircon grains from the Wirku Metamorphics closely resemble those of the Gawler Craton and associated Proterozoic rocks of the South Australian Craton, and so it is interpreted that arc magmatism was initiated by the southward subduction of oceanic crust under the northern margin of the South Australian Craton (Fig. 45).

Deformation, metamorphism, and magmatism during Stage I (1345–1260 Ma) of the Albany–Fraser Orogeny were synchronous with the 1345–1293 Ma Mount West Orogeny in the west Musgrave Province (Figs 3, 46). Similar to the Mount West Orogeny, Stage I is dominated by the intrusion
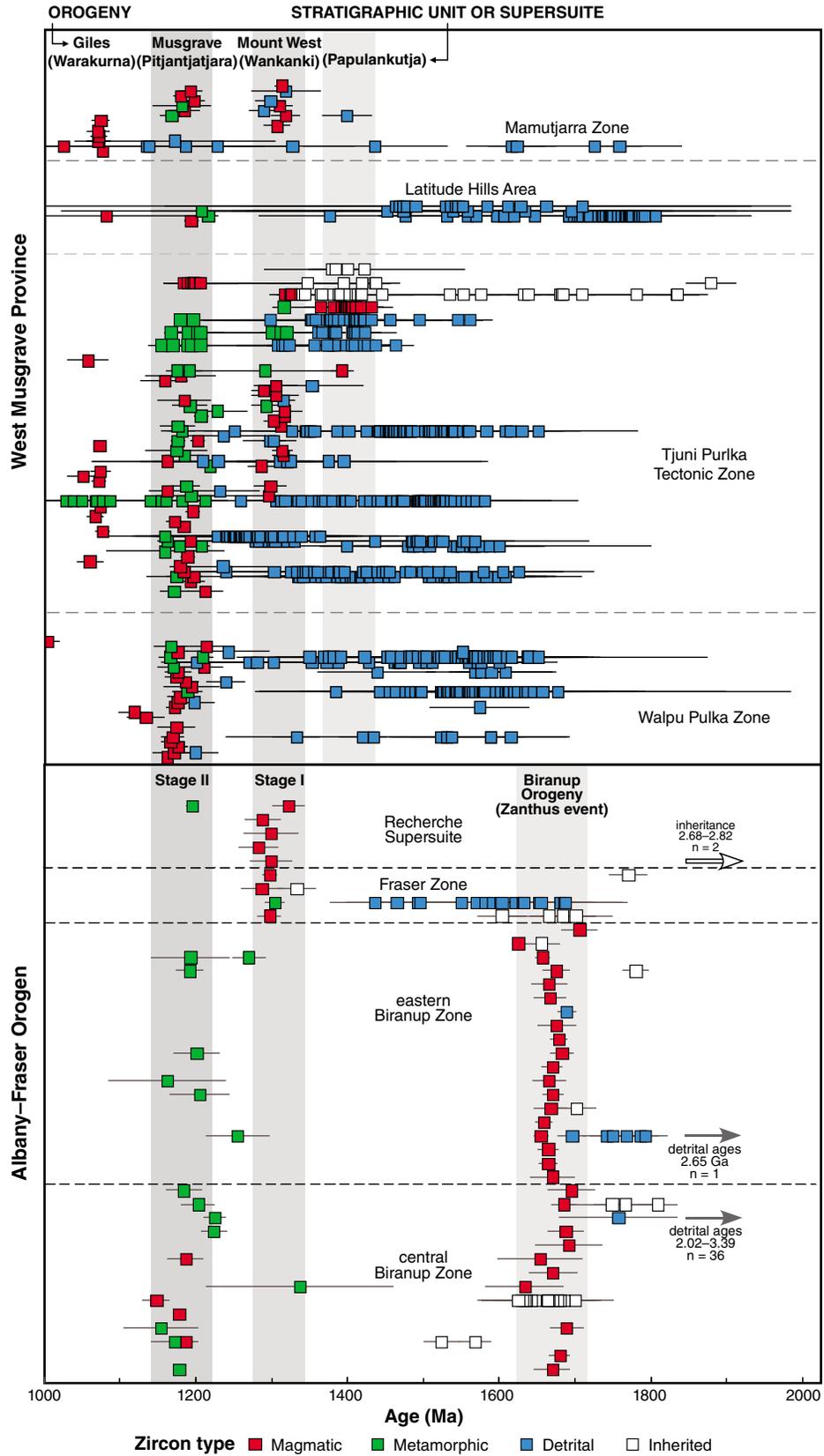
Figure 46.   Time–space diagram for the Albany–Fraser Orogen and the west Musgrave Province, showing the distribution of U–Pb zircon dates that define the orogenic events (light-grey bars)

of felsic magmatic rocks — the 1330–1280 Ma Recherche Supersuite — although there was also voluminous mafic magmatism in the Fraser Zone. Prior to and during Stage I, sedimentary rocks of the Arid Basin were deposited across a broad region spanning the Fraser and Nornalup Zones, most likely in restricted basin centres (Fig. 33).

The Recherche Supersuite (Fig. 33) comprises strongly deformed and metamorphosed felsic plutonic rocks, with minor gabbroic rocks. Although these intrusions appear to be most abundant in the Nornalup Zone, they also intrude the southeastern part of the Biranup Zone, and there is one occurrence in the Northern Foreland.

The Fraser Zone (Fig. 33) contains the 1305–1290 Ma Fraser Range Metamorphics, dominated by sheets of metagabbroic rocks, interlayered with sheets of granitic rocks and layers or slivers of pelitic, semipelitic, and calcic metasedimentary rocks of the Arid Basin (Fig. 47). Protoliths to the metasedimentary rocks were deposited just prior to intrusion of the mafic and felsic magmatic rocks, and all have been metamorphosed at generally moderate to high pressures and at high temperatures (granulite facies), with some locally retrogressed to amphibolite facies. Several inherited zircons within the Fraser Zone magmatic rocks have Paleoproterozoic ages similar to those in the Biranup Zone, suggesting intrusion of Fraser Zone magmas into Biranup Zone crust. This interpretation is supported by the Lu–Hf compositions of the magmatic zircons, and suggests that the Fraser Zone does not represent an oceanic arc or exotic crust. Whole-rock geochemistry as well as field relationships indicate that the Fraser Range Metamorphics represent a structurally modified, mid- to deep-crustal 'hot zone', formed by the repeated intrusion of gabbroic magma into quartzofeldspathic country rock. Newly discovered nickel–copper mineralization at Nova has opened up the Fraser Range Metamorphics as a new nickel province. Although the tectonic origin of the Fraser Zone is somewhat enigmatic, plausible options are a continental magmatic arc, back-arc, or rift setting, rather than an oceanic magmatic arc, or exotic crust.

Stage I (1345–1260 Ma) of the Albany–Fraser Orogeny marks the time when the Northern Foreland, Biranup, Fraser, and Nornalup Zones underwent synchronous tectono-thermal or magmatic activity. Isotopic and other geological evidence now demonstrates the autochthonous nature of at least the Northern Foreland, Biranup,

and Fraser Zones to the Yilgarn Craton, implying that the Stage I events may have occurred in a back-arc or extensional setting. These events were also synchronous with magmatic activity in the west Musgrave Province during the 1345–1293 Ma Mount West Orogeny. The synchronicity of tectono-magmatic activity between these two regions, and the similar geological evolution of the Albany–Fraser Orogen and west Musgrave Province during subsequent deformation, metamorphism, and magmatism, imply that this

Figure 47.   Folded calc-silicate rocks (green) interlayered with mafic amphibolite (black) of the Malcolm Metamorphics, Arid Basin, Albany–Fraser Orogen

tectono-magmatic activity may record the lead-up to collision between the combined West and North Australian Craton with the South Australian – Mawson Craton during the latter stages of the Mount West Orogeny and Stage I of the Albany–Fraser Orogeny (Fig. 2). The location of the suture zone to this collisional orogen is currently not known but must be located farther outboard of the exposed part of the Albany–Fraser Orogen, in the poorly understood Eucla basement.

Intraplate deformation

The Tabletop Terrane of the Rudall Province in the Paterson Orogen comprises Mesoproterozoic igneous and metasedimentary rocks and is distinct from the much older, more-deformed Talbot and Connaughton Terranes with which it is juxtaposed along the Camel–Tabletop Fault Zone (Fig. 27). The terrane is dominated by weakly deformed and metamorphosed felsic and mafic igneous rocks of the 1590–1550 Ma Krackatinny Supersuite (Fig. 3), minor felsic intrusions dated at c. 1476 and c. 1310 Ma, as well as minor quartzite, mafic and ultramafic schists, amphibolite, and banded iron-formation. The isotopic composition of the felsic intrusive rocks is similar to that of the 1800–1765 Ma Kalkan Supersuite in the Talbot and Connaughton Terranes, implying that
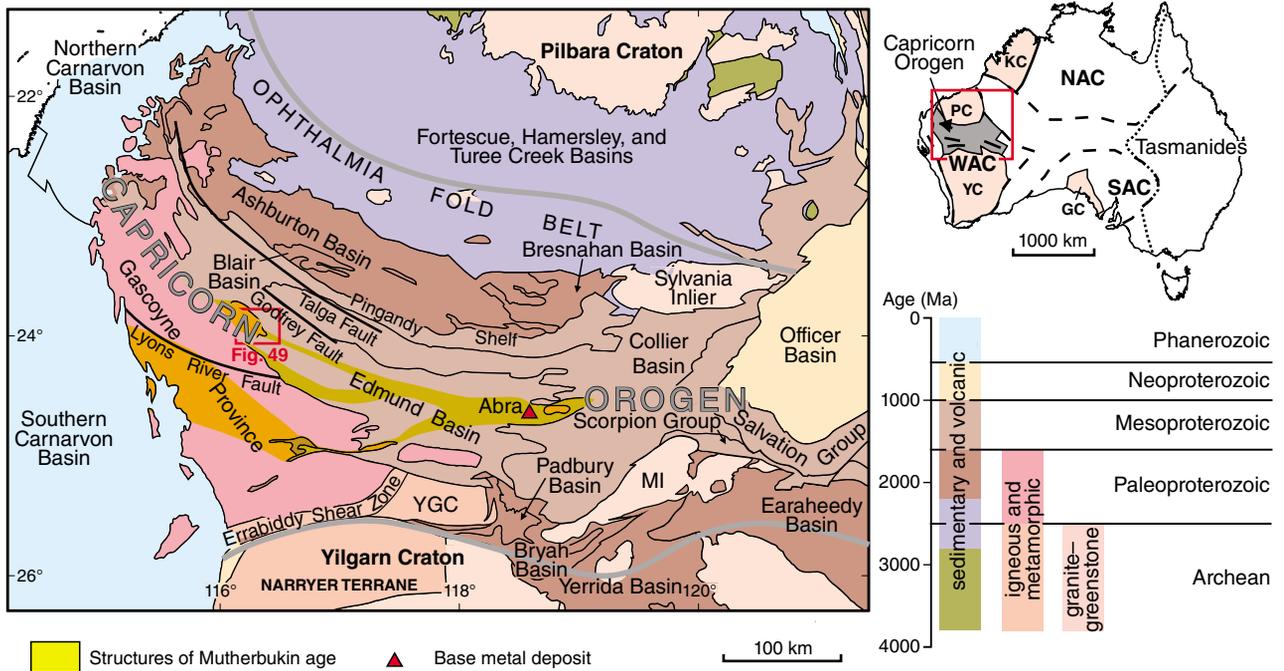
Rudall Province

Figure 48. *Regional distribution of the Mutherbukin-age structures within the Gascoyne Province and Edmund Basin of the Capricorn Orogen. Legend and abbreviations as for Figure 4*

all three terranes in the Rudall Province share a common heritage and that the Tabletop Terrane is not exotic to the Rudall Province.

In the Capricorn Orogen discrete corridors of dominantly oblique strike-slip deformation, low- to medium-grade metamorphism, and hydrothermal alteration during the 1385–1200 Ma Mutherbukin Tectonic Event (Fig. 3), affected both basement gneisses and granites of the Gascoyne Province as well as sedimentary rocks of the overlying Edmund Basin (Fig. 48). In the Gascoyne Province basement, deformation peaked between c. 1280 and c. 1200 Ma, producing widely developed foliations and gneissic fabrics along with regional-scale sheath folds. Deformation was dominated by sinistral strike-slip mechanisms with a large component of extension. Low-grade metasedimentary rocks of the 1840–1810 Ma Leake Spring Metamorphics were metamorphosed in the amphibolite facies with the production of andalusite, garnet, and staurolite porphyroblasts. In the overlying Edmund Group sedimentary rocks, brittle sinistral strike-slip faulting was accompanied by extensive hydrothermal alteration and low-grade metamorphism, and may have also been responsible for the upgrading of ore minerals at the Abra polymetallic deposit (see shaded box). Hydrothermal monazite from these low-grade

cover rocks is dated to between c. 1385 and c. 1200 Ma, indicating that hydrothermal activity in the upper crust accompanied, but also preceded, medium-grade metamorphism and deformation in the basement.

In the northern part of the Gascoyne Province, intrusion of c. 1300 to c. 1280 Ma sills, dykes, and veins of ferroan carbonatite — the Gifford Creek Carbonatite Suite — occurred during the Mutherbukin Tectonic Event (Fig. 49 and shaded box). During emplacement, the country rocks were extensively fenitized, forming abundant sodic amphibole and a variety of other alkaline minerals. Although the suite has a relatively restricted occurrence, the intrusions parallel the Lyons River Fault, which is the main crustal suture zone between the Glenburgh Terrane of the Gascoyne Province and the Pilbara Craton (Fig. 9). This alkaline magmatic activity occurred in an extensional tectonic setting, where mantle-derived melts interacted with thinned, metasomatized, subcontinental lithospheric mantle. These melts were subsequently channelled into the upper crust by the Lyons River Fault. During the subsequent 1030–955 Ma Edmundian Orogeny (see below), remobilization and hydrothermal alteration of the carbonatites led to extensive upgrading of rare earth elements into a series of mineralized ironstone veins and dykes.

Kimberley

The Lamboo Province and sedimentary rocks of the Revolver Creek Formation and the Carr Boyd Group are host to the diamondiferous Argyle lamproite intrusion in the northern part of the Halls Creek Orogen (Fig. 50 and shaded box). The Argyle lamproite is one of many diamondiferous and non-diamondiferous alkaline (lamproite, kimberlite, and carbonatite) intrusions within the Kimberley region, although radiometric dating indicates they are of various ages, ranging from Mesoproterozoic to Miocene (Fig. 3). The Argyle lamproite and associated pyroclastic rocks form an outcrop 2 km long and up to 500 m wide, and probably consisted of at least two volcanic edifices that coalesced during subsequent faulting and tilting. The lamproite is dated at c. 1178 Ma, and intruded into wet sediments of the Carr Boyd Group. However, the diamonds themselves are much older, having been dated at c. 1580 Ma. Other intrusions, such as the Bow Hill lamprophyre are Neoproterozoic in age (c. 815 Ma), whereas lamproites in the west Kimberley are as young as c. 20 Ma. All of these intrusions represent small volume melts extracted from metasomatized subcontinental lithospheric mantle at depths >120 km beneath the Kimberley Craton, and the Halls Creek and King Leopold Orogens. The tectonic driver for prolonged and punctuated melting in this region is currently unknown.

Ultra-high-temperature magmatism and metamorphism

At the same time as tectonic activity associated with the Mutherbukin Tectonic Event, the west Musgrave Province was subject to ultra-high-temperature metamorphism and magmatism. This tectonic event is recorded by the intrusion of voluminous, anhydrous, orthopyroxene-bearing felsic magmatic rocks of the 1220–1150 Ma Pitjantjatjara Supersuite during the 1220–1150 Ma Musgrave Orogeny (Figs 3, 51). Magmatism took place mainly within the Walpa Pulka Zone and the Tjuni Purlka Tectonic Zone and has an antithetic spatial relationship with the older Wankanki Supersuite intrusions. Pitjantjatjara Supersuite intrusions mainly form composite plutonic bodies that range from monzodiorite through to alkali-feldspar granite

Abra: a giant polymetallic breccia-pipe

Abra is a buried, strata-bound, sedimentary rock-hosted, iron–lead–zinc–barium–copper(–gold–silver–bismuth–tungsten) deposit within the Jillawarra Sub-basin, of the Edmund Group. It is a giant deposit, and remains the most significant mineral discovery in the Capricorn Orogen.

Mineralization is hosted by siltstones, dolostones, sandstones, and conglomerates of the lowermost Edmund Group — the Irregully and Kiangi Creek Formations — and lies entirely beneath an erosion surface that marks a change from fluvial to marine facies. Although buried at a depth of 250 m below the present-day land surface, mineralization is at least 400-m thick in the core of the intense alteration system, and is open in all directions. The mineralization is vertically zoned: with an upper stratabound domain, in which the original character of the sedimentary host rock is totally obscured; and a lower domain of a complex hydrothermal breccia and laminated vein stockwork.

The stratabound domain is 200 to 250 m thick, and is further divided into three zones: an upper Red Banded Zone, characterized by silica-banded iron oxide (hematite and subordinate magnetite), barite (massive in places), siderite, pyrite, and galena; an intermediate, variably developed Dolomite Banded Zone, comprising dolomite, silica, magnetite, galena, and sphalerite; and a lower Black Banded Zone, typified by silica, banded iron oxide (grey hematite or magnetite), Fe-rich carbonate, chlorite, barite, and rhythmically banded galena, sphalerite, and pyrite, with minor tetrahedrite, chalcopyrite, and scheelite.

The stockwork domain is broadly funnel-shaped and up to 100 m thick, with zones of quartz–hematite–chalcopyrite(gold)–pyrite–magnetite–dolomite, and breccias that exhibit abundant fluidized and/or jigsaw textures indicating several overprinting phases of hydrothermal activity (photo at left is of jigsaw breccia in core). The stockwork domain is interpreted to be the feeder zone to the overlying stratabound domain, and research suggests that this highly dynamic hydrothermal system may have been the result of pulses of high-pressure fluids propagating from aftershocks of large earthquakes.

Latest mineral resource estimates published in May 2008 indicate that the upper, stratabound, lead-rich domain contains an indicated and inferred resource of 93 Mt at 4.0% Pb and 10 g/t Ag (2.5% Pb cutoff), and the lower, copper–gold-enriched stockwork domain contains an indicated and inferred resource of 14 Mt grading 0.62% Cu and 0.49 g/t Au (0.4% Cu cutoff).

1cm

and include significant rapakivi granite (Fig. 52). Mafic rocks are extremely rare. The granites were emplaced at temperatures ≥1000° C, and were variably deformed under extensional regimes, both during and after emplacement. Their geochemical, Nd and Hf isotopic homogeneity reflects a similarly homogeneous source, including older enriched felsic crust and intermediate to mafic crust. Granite intrusion was accompanied by, but not the cause of, ultra-high-temperature crustal conditions, with a geotherm of >40° C/km that prevailed during the approximately 100 million-year long Musgrave Orogeny. Such conditions reflect a very unusual tectonic setting. Mafic magmatic intraplating and underplating caused the assimilation of lower crust into MASH (melting, assimilation, storage, homogenization) zones, that were periodically remobilized during subsequent intraplating and underplating events (Fig. 53).

During the period of ultra-high-temperature magmatism in the west Musgrave Province, the Albany–Fraser Orogen was also subject to magmatism, deformation, metamorphism, and localized basin formation. During the period between Stages I and II (c. 1260 to c. 1225 Ma), uplift and associated brittle deformation is recorded in the Gwynne Creek Gneiss of the Arid Basin, the Fraser Range Metamorphics (to less than ~400 MPa), and Recherche Supersuite. The uplift events coincided with the deposition of the sedimentary protolith to the Mount Ragged Formation — as part of the Ragged Basin, cycle three sediments (Fig. 3) — which contains zircon detritus from Stage I, interpreted as being derived from the Recherche Supersuite. Sedimentary protoliths to the Salisbury Gneiss were also probably deposited at this time, although there is no geochronology on detrital zircons in this unit.

The 1225–1140 Ma Stage II event is characterized by a widespread, prolonged period of high-temperature metamorphism and deformation, including the formation of the fold and thrust systems that characterize the main architecture of the orogen (Fig. 33). Reactivation or formation of major shear zones, particularly those bounding different tectonic units, took place
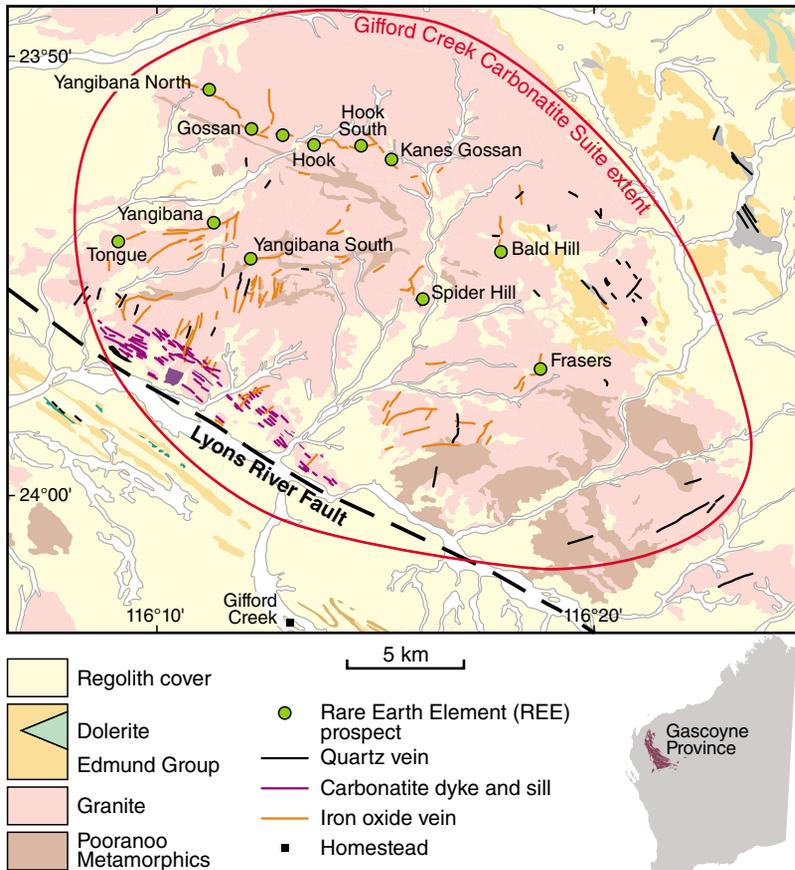
Figure 49. Gifford Creek Carbonatite Suite in the Gascoyne Province, showing rare earth element (REE) prospects. See Figure 48 for location

Gifford Creek Carbonatite Suite has REE

The Gifford Creek Carbonatite Suite, intruded at 1300–1280 Ma, shares the characteristics of igneous systems related to alkaline magmatism in extensional settings. The suite comprises sills, dykes, and veins of ferroan carbonatite, ironstone, and hydrothermally altered rocks (fenites) that intrude granitic rocks of the 1680–1620 Ma Durlacher Supersuite in the northern part of the Gascoyne Province (see Figs 48, 49).

The ferroan carbonatites are distributed within a northwest-trending belt parallel to the Lyons River Fault and are associated with complex and irregularly distributed zones of fenitic alteration. Recent field and petrographic work shows that these rocks range from ankeritic carbonatites (usually >50% ankerite–dolomite matrix) to arfvedsonite-rich silico-carbonatites, and also contain pyrochlore, apatite, barite, monazite, lamprophyllite, and phlogopite. The northeastern part of the suite is dominated by iron oxide-rich (magnetite, hematite, and goethite) veins, locally associated with quartz veins, and related fenitic alteration haloes. The ironstone veins are believed to have formed by post-magmatic replacement of iron carbonate minerals in a second phase of ferroan hydrothermal alteration. These rocks, especially the ironstones, contain significant REE oxides with an estimated total resource of about 2.77 Mt, averaging 1.52% REE oxides.

in the late stages of Stage II. The Esperance Supersuite represents voluminous granitic magmatism predominantly in the Nornalup Zone, with intrusion of strongly magnetic plutons. Magmatism was originally defined as having occurred during the latter stages of the Stage II event, at c. 1140 Ma, but has now been dated as spanning nearly the entire event, c. 1200 to c. 1140 Ma. These granites are variably deformed, with many preserving relatively undeformed interiors compared to their deformed margins. The widespread effects of the Stage II event across the orogen, and in the Salisbury Gneiss within the adjacent Madura Province to the east, are indicative of an intraplate setting.

The oldest metamorphic event is recorded in the southeastern Biranup Zone at c. 1225 Ma. This was followed by the intrusion of voluminous mafic dykes of the c. 1210 Ma Gnowangerup–
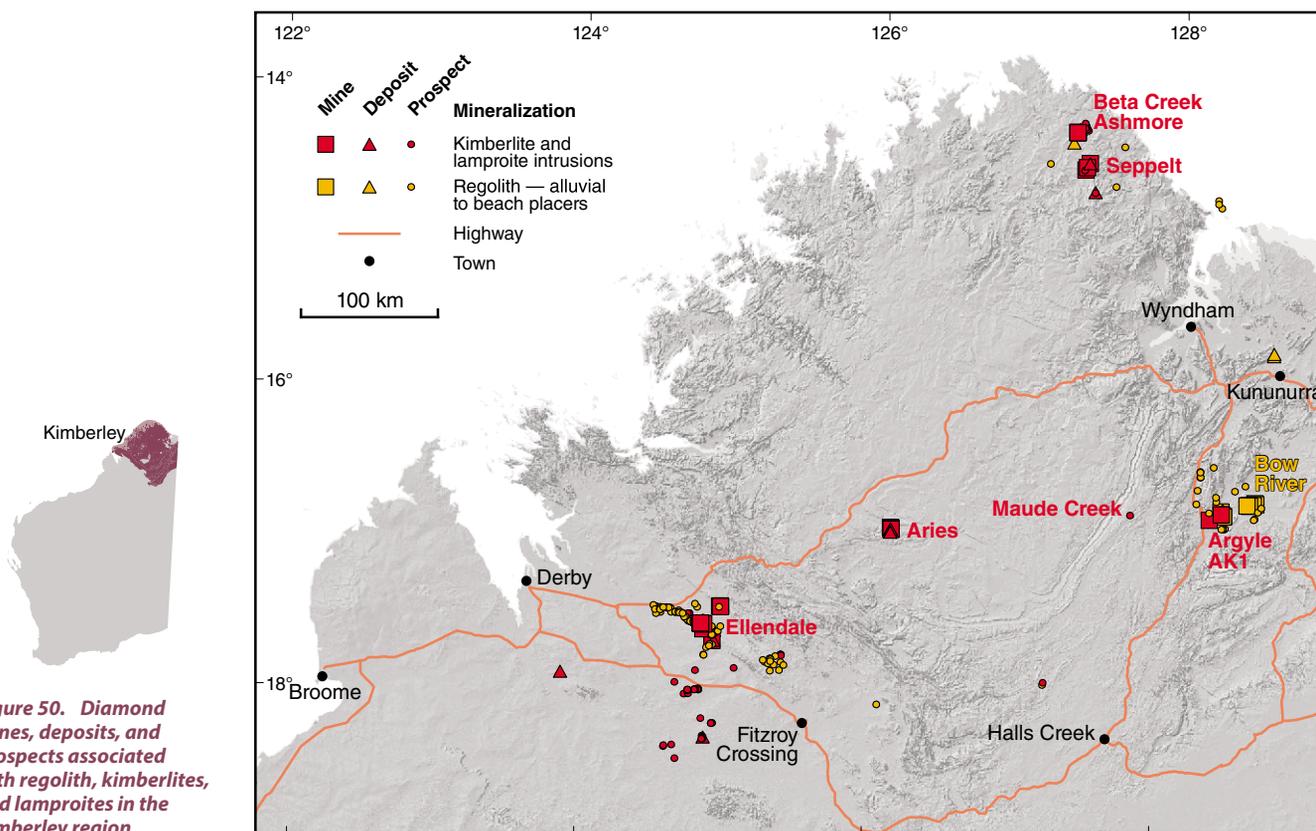
Figure 50. Diamond mines, deposits, and prospects associated with regolith, kimberlites, and lamproites in the Kimberley region

Fancy pink, red, champagne, and yellow diamonds

The Argyle mine is famous worldwide for its gem-quality pink diamonds, which come from the AK1 lamproite pipe, 110 km south of Kununurra in the eastern Kimberley region (Fig. 50). It is the largest diamond mine in the world. The Argyle pipe was discovered in 1979, by following alluvial diamonds upstream for 35 km to their source.

The lamproite at Argyle has been dated, using the Rb–Sr isotopic system, at c. 1178 Ma, whereas the diamonds are c. 1580 Ma. The lamproite was intruded into wet, nearly flat-lying sedimentary rocks of the c. 1200 Ma Carr Boyd Group. The wet country rocks caused the resulting eruption to be very violent, forming tuffaceous lamproite.

Mining commenced in 1985, and the mine now accounts for about 25% of world production. Argyle has produced some 500 million carats (Mct) since 1985, comprising about 5% (by weight) of gem quality, 40% cheap gems, and the remainder (55%) industrial diamonds. The high-quality gems comprise brown (80%), yellow (15%), white (4%), and about 1% of the fancy pink, red, green, and blue hues. Colour variations are caused by impurities (often nitrogen) as well as plastic deformation structures, and by structural vacancies within the carbon lattice.

Resources remaining in 2012 totalled 108 million tonnes averaging 2.68 carats/tonne for 290 million carats of contained diamond, almost half of which are categorized as 'reserves'. After 27 years of open-cut mining, Argyle transitioned to underground mining in April 2013.

Ellendale (southwest Kimberley region) consists of a cluster of small lamproite pipes, intruded at only c. 20 Ma with related explosive tuffs. About 60% of the diamonds are gem quality with colours of 'fancy yellow', brown, colourless, and grey.

Photo courtesy Kimberley Diamond Company

West Musgrave Province

Albany– Fraser Orogen

Fraser Dyke Suite, part of the Marnda Moorn LIP that also intruded the southern Yilgarn Craton (Figs 3, 54). Following the intrusion of these dykes, between c. 1210 and c. 1170 Ma, the effects of Stage II deformation and metamorphism were widespread, affecting rocks of the Northern Foreland, the Biranup Zone, and the Nornalup Zone. Metamorphic dates from the Biranup Zone span a long period from c. 1225 Ma to c. 1150 Ma, reflecting prolonged, high-temperature conditions. In the central Biranup Zone at Bremer Bay, high-temperature metamorphism and medium- and large-scale boudinage relating to two phases of extension occurred at c. 1180 Ma, and bracket large-scale northwest-vergent folding.

Figure 51. Interpreted bedrock geology showing the distribution of meta-igneous rocks of the 1220–1150 Ma Pitjantjatjara Supersuite in the eastern portion of the west Musgrave Province

25°30'
127°30'
WALPA PULKA ZONE
TJUNI PURLKA TECTONIC ZONE

Musgrave Orogeny
Pitjantjatjara Supersuite

- Unassigned granite
- Younger Pitjantjatjara Supersuite
- Older Pitjantjatjara Supersuite
- Mixed Wankanki and Pitjantjatjara Super-suites

MAMUTJARRA ZONE
129°00'
26°30'

Intraplate mafic magmatism

The Marnda Moorn LIP extends over at least 500 000 km^2 and includes extensive swarms of mafic dykes concentrated around the margins of the Yilgarn Craton (Figs 3, 54). U–Pb dating of zircon or baddeleyite from these dykes indicates that they were intruded between c. 1218 and c. 1202 Ma, synchronous with the earliest stages of ultra-high-temperature magmatism, and high-temperature metamorphism in the west Musgrave Province and Albany–Fraser Orogen, respectively. The intrusions consist mainly of dolerite or gabbro with minor quartz diorite. The short duration of magmatism is consistent with emplacement above a mantle plume, although the apparent concentration of dykes around the Yilgarn Craton margin suggests that plate-boundary stresses were a major influence on dyke emplacement. The location and orientation of the Gnowangerup–Fraser dykes, within, adjacent to, and parallel to the Albany–Fraser Orogen, is consistent with emplacement into lines of weakness that originated during Stage I orogenesis. The prevalence of dykes along the western and northwestern margins of the Yilgarn Craton implies that the Pinjarra Orogen was active during this time.

Break-up of the Nuna supercontinent?

During the period 1400–1150 Ma, widespread deformation, metamorphism, magmatism, and basin formation took place within and along the boundaries of the West Australian Craton. In both the Albany–Fraser Orogen and west Musgrave Province, tectono-magmatic activity during Stage I of the Albany–Fraser Orogeny and the Mount West Orogeny record subduction magmatism along the cratonic margins of the West and South Australian Cratons. The younger, late Mesoproterozoic events of Stage II and the Musgrave Orogeny record a period of high-temperature intracratonic magmatism (ultra-high-temperature in the west Musgrave Province). The intracratonic nature of these later events implies that collision of the South Australian – Mawson Craton, with the combined West Australian and North Australian Cratons occurred during Stage I of the Albany–Fraser Orogeny and the Mount West Orogeny, i.e. sometime between c. 1345 and c. 1260 Ma

Figure 52. Rapakivi granite of the Pitjantjatjara Supersuite, west Musgrave Province
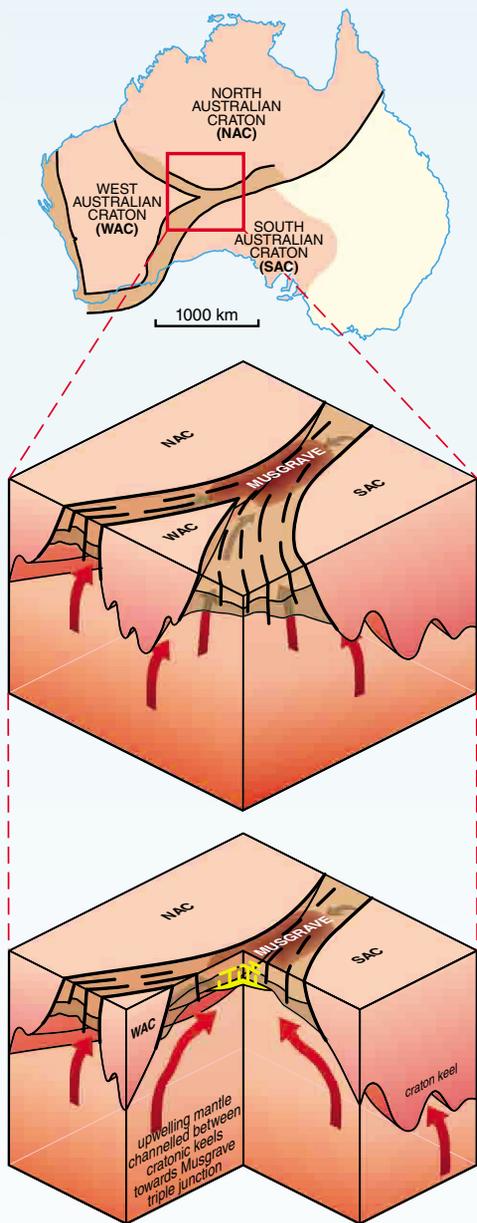
Figure 53. Block diagram showing the influence of crustal blocks on tectono-thermal evolution during the Musgrave Orogeny

Vista from Heather's Hill, west Musgrave Province, looking northward

(Figs 2, 45, 55). During this time interval, parts of the Albany–Fraser Orogen record substantial uplift, exhumation, and basin formation.

Younger, late Mesoproterozoic events including the Stage II event of the Albany–Fraser Orogeny, the Musgrave Orogeny, and the Mutherbukin Tectonic Event, as well as the intrusion of the Marnda Moorn LIP, may record the break-up of the Nuna supercontinent (Fig. 56). The impingement of a mantle plume under the Nuna margin may have initiated extensional deformation; however, the extended duration of high- and ultra-high-temperature metamorphism and magmatism in the Albany–Fraser Orogen and Musgrave Province, negate plume activity as the sole driver for tectono-magmatic activity. The position of the Musgrave Province at the triple junction between the West Australian, North Australian, and South Australian Cratons, and the presence of an extensive, hot, previously overthickened collisional margin along these craton margins may have played a significant role in focusing mantle-derived magmas into the Musgrave Province and along this tectonic corridor (Fig. 53).

The late Mesoproterozoic intraplate extensional events mark the break-out and birth of Proterozoic Australia (the combined West Australian – North Australian and South Australian – Mawson Craton) from the Nuna supercontinent (Fig. 2). Similar-age break-up events are also recorded in other parts of Nuna, including the North China Craton, indicating the widespread dismemberment of the supercontinent. Additional evidence for the break-out of Proterozoic Australia from Nuna is illustrated by the Apparent polar wander path (APWP) for Australia (Fig. 57 and shaded box). Between c. 1600 and c. 1300 Ma paleomagnetic poles from the North Australian, South Australian, and West Australian Cratons show a relatively straight APWP, but at, or just before, c. 1210 Ma, a significant bend in the path implies a major period of plate reorganization.

Did Nuna really exist?

Based on the geological evolution of the Australian crustal blocks, the Nuna supercontinent does not appear to have conformed to the rigorous timing constraints of the supercontinent cycle because it
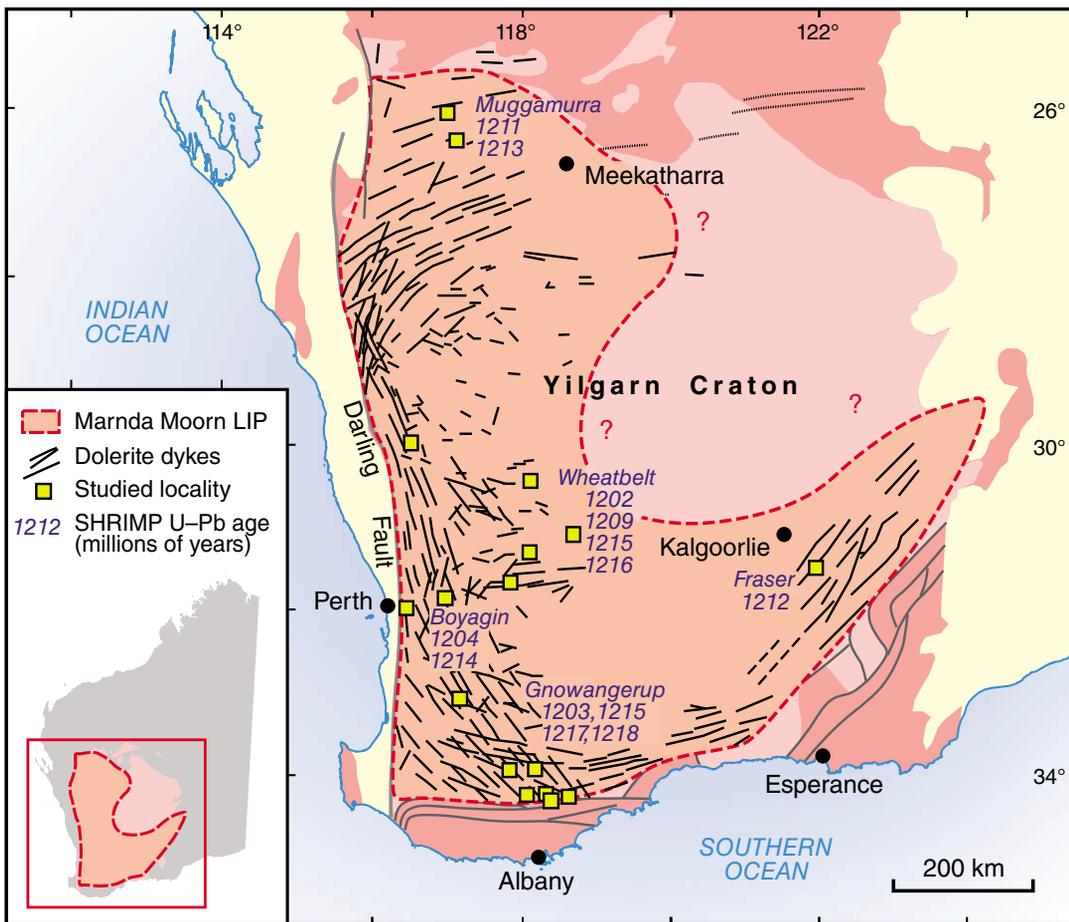
Figure 54. Location of mafic dykes associated with the Marnda Moorn Large Igneous Province (LIP)
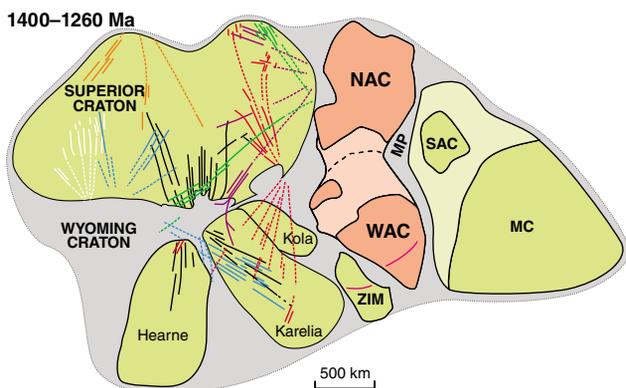
Figure 55. Reconstruction of Nuna between c. 1400 and c. 1260 Ma (modified from Söderlund et al., 2010), following the Mount West Orogeny and Stage I of the Albany–Fraser Orogeny, showing a fully amalgamated Proterozoic Australia. Abbreviations as for Figures 32 and 45
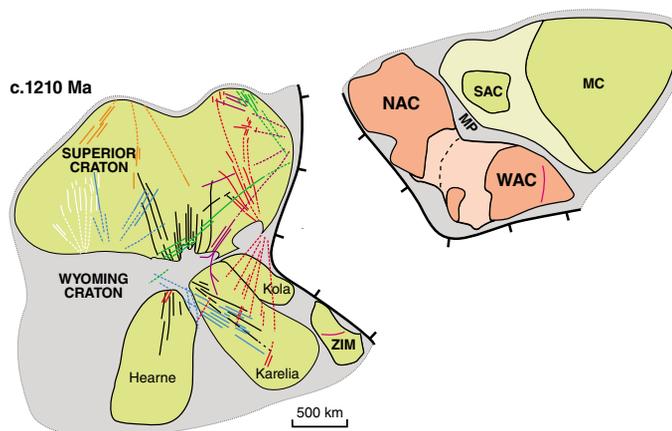
Figure 56. Reconstruction of Nuna at c. 1210 Ma (modified from Söderlund et al., 2010), showing the possible tectonic setting of the cratons in Western Australia during the Musgrave Orogeny and Stage II of the Albany–Fraser Orogeny. These events may be due to the break-up of Proterozoic Australia from the Nuna supercontinent. Abbreviations as for Figures 32 and 45

Paleomagnetic data for the Australian crustal blocks during the Proterozoic can be assembled into an Apparent polar wander path (APWP) shown on Figure 57. This trace defines the apparent movement of the Earth's magnetic pole relative to a stationary Proterozoic Australia. Major kinks define changes in plate motion and periods of plate reorganization and the timing of these kinks has been shown to coincide with the generation of new juvenile crust, commonly associated with mineralization. From the beginning of the APWP at c. 1800 Ma, the coincidence of paleomagnetic data from both the North Australian

and West Australian Cratons imply that these blocks were contiguous by this time. However, the amalgamation of the South Australian Craton with a combined West Australian – North Australian Craton to form Proterozoic Australia appears to have occurred much earlier (at c. 1600 Ma) than has been inferred from the geological evidence (which places it between c. 1345 and c. 1260 Ma). This difference may, in part, be due to poor age constraints on the critical paleopoles themselves, but may also highlight inadequacies or alternative interpretations of the geological record.

took much longer than any of the younger supercontinents (Rodinia, Gondwana, and Pangea) to assemble. Also, it is not apparent whether the supercontinent contained all of Earth's cratons in a close-packed configuration at any single point in time. Although this may have been due to Australia's peripheral setting in the supercontinent, it is more likely a reflection of the initiation and establishment of the supercontinent cycle itself. The early Proterozoic history of Australia, and presumably Nuna, is characterized by the protracted assembly of numerous, small and disparate cratonic blocks into larger, more stable crustal blocks through time. This is in contrast to the assembly histories of the younger supercontinents, which were constructed from fewer, much larger crustal entities, over a much shorter time period. The continual and protracted assembly history of Nuna meant that different parts of the supercontinent were subject to plate-margin activity (including subduction magmatism, terrane accretion, and continental collision) throughout its history, and thus while some parts of Nuna were being assembled, other parts were breaking up. At present, Nuna appears to be a more transitional supercontinent defined by the assembly of individual cratonic blocks into Phanerozoic-sized stable continental blocks over an 800 million-year period.

Figure 57. Apparent polar wander path (APWP) for the Australian cratons through the Proterozoic.
Abbreviations: BBS, Bangemall Basin sills (Kulkatharra Dolerite); BDu, Upper Balbarini Dolomite; FDS, Fraser dyke; GA, GA Dykes (Eyre Peninsula); GB, GB Dykes (Eyre Peninsula); GC, Giles Complex; GR, Gawler Range Volcanics; HD, Hart Dolerite; IAR, Lakeview Dolerite; JO, Mount Jope Volcanics; KDS, Kulgera dyke swarm; LG, Elgee Formation; MDS, Mundine Well Dolerite Suite; ML, Morawa lavas; RG, Roper Group sills; SDS, Stuart Pass Dolerite; WTC, Walsh Tillite.
Lighter symbols signify poles based on overprint magnetizations
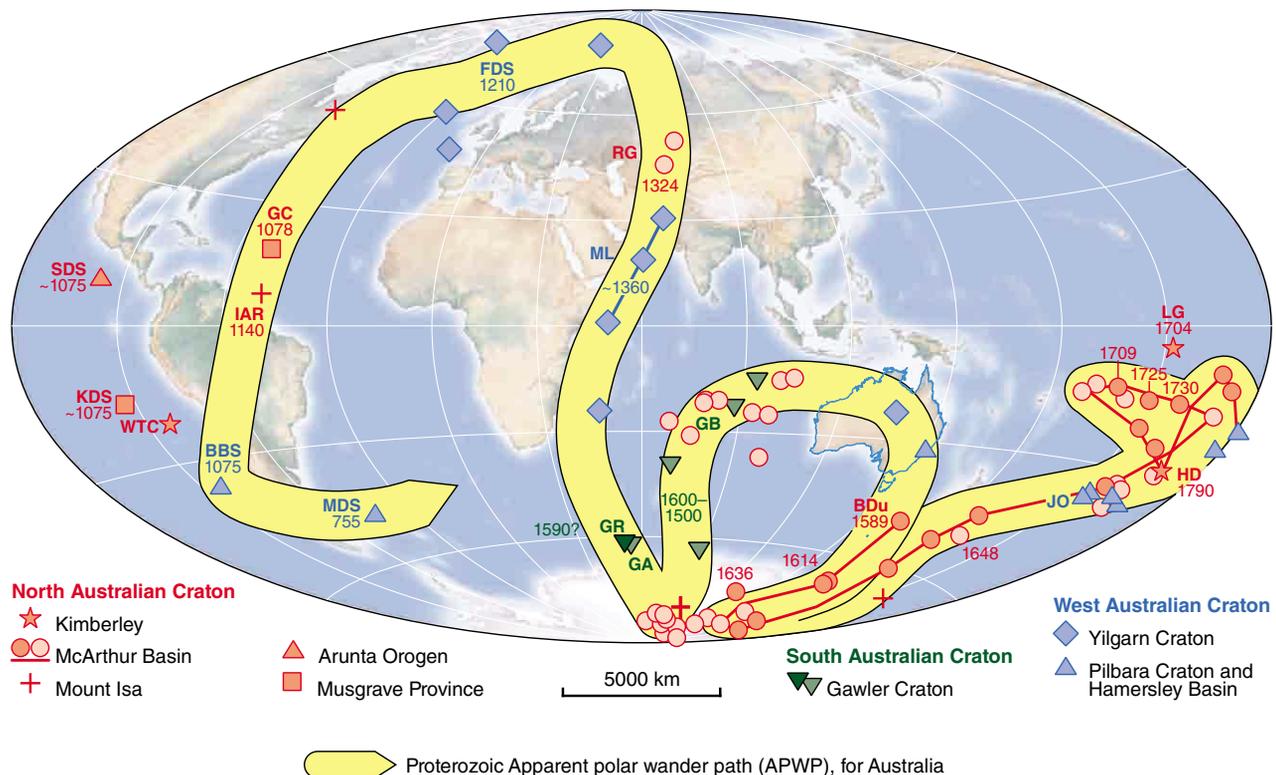
The assembly, stabilization, and break-up of Rodinia (1150–750 Ma)

MANY LINES OF GEOLOGICAL EVIDENCE POINT to the existence of a major supercontinental landmass during the late Mesoproterozoic to earliest Neoproterozoic. This supercontinent, known as Rodinia, is speculated to have contained most of the Earth's cratons, including Proterozoic Australia. In the latest reconstructions, Proterozoic Australia is interpreted to lie along the periphery of the supercontinent with the western margin of the West Australian Craton facing an open ocean (Fig. 58). Geological evidence relating to the collision of the Australian block with Rodinia is sparse, but it is thought that Proterozoic Australia was one of the last cratons to amalgamate with the supercontinent, sometime between c. 1000 and c. 950 Ma. Although most Rodinia reconstructions indicate that the western margin of Proterozoic Australia faced an open ocean during Rodinia assembly, numerous tectono-metamorphic and tectono-magmatic events affected this region during both the assembly and break-up phases of the supercontinent cycle, implying that this margin may not have been entirely passive.

Events during the assembly of Rodinia

The Warakurna Large Igneous Province (LIP)

The Warakurna LIP outcrops over 1.5 million km^2 of central and Western Australia (Fig. 59). The province mostly comprises mafic igneous dykes and sills emplaced at c. 1075 Ma. In the west Musgrave Province, extensive mafic and felsic intrusive rocks, as well as mainly felsic extrusive rocks of the Bentley Supergroup — the Warakurna Supersuite — were generated during the Giles Event (Figs 3, 60, 61). Geochemical and isotopic data from the mafic dykes and sills are interpreted to reflect melting of a subduction-modified mantle source.

West Musgrave Province
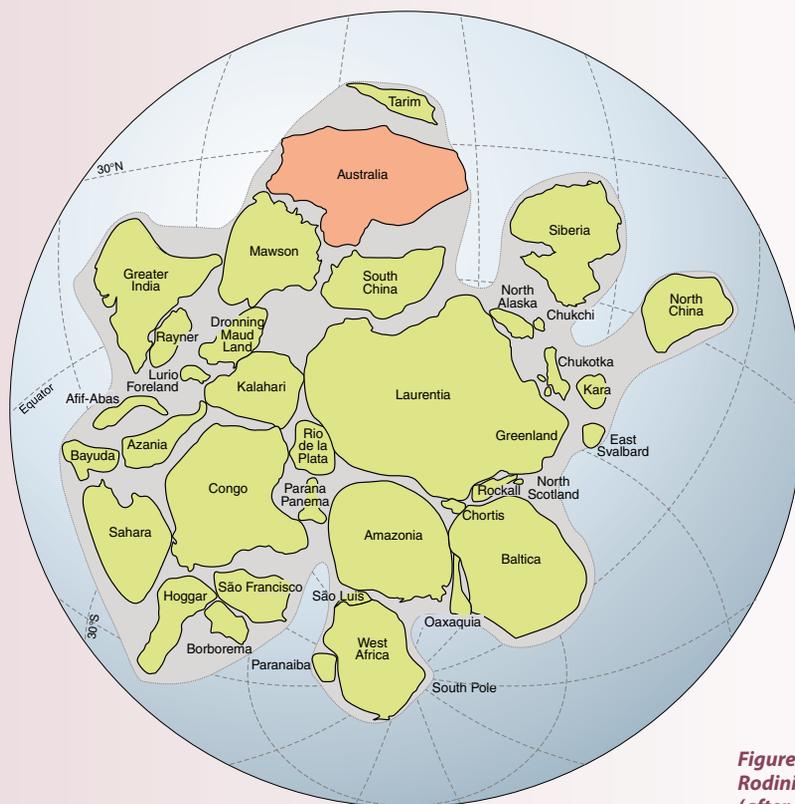
Figure 58. Reconstruction of the Rodinia supercontinent at c. 950 Ma (after Li et al., 2008)
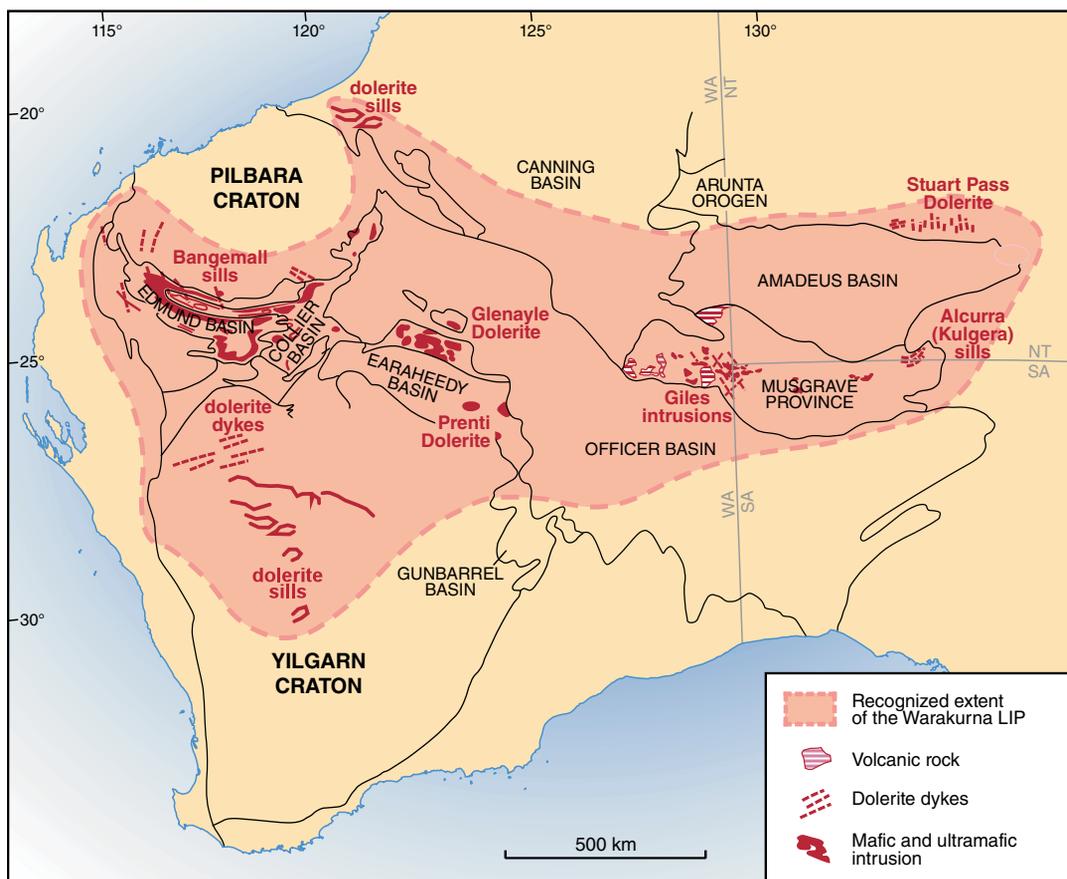
Figure 59. *Distribution of mafic rocks associated with the Warakurna LIP (modified from Wingate et al., 2004)*

The intrusive rocks of the Giles Event comprise the giant, layered mafic–ultramafic 'Giles intrusions', massive gabbros mixed and mingled with granite, the Alcurra Dolerite, and various granite plutons (Fig. 60). The volcanic components include both mafic and felsic lavas, and volcaniclastic rocks (as well as siliciclastic and minor calcareous sedimentary rocks) that are grouped within the Bentley Supergroup (Fig. 62). All the magmatic components are thought to be associated with the formation of a long-lived, but failed, intracontinental rift known as the Ngaanyatjarra Rift.

The giant, layered mafic–ultramafic 'Giles intrusions' form one of the oldest components of the magmatic system, and comprise intrusions that are mainly troctolitic or gabbroic in composition with minor peridotite. The intrusions reach a maximum cumulative thickness of ~10 km, but it is likely that the different bodies represent the tectonically dismembered parts of a single, large intrusion that may have been up to 170 km long, 25 km wide, and 10 km thick.

At c. 1075 Ma, large bodies of massive unlayered gabbro were emplaced along a near-continuous

synmagmatic shear zone, which marks the northern boundary of the Tjuni Purlka Tectonic Zone (Fig. 60). Associated leucogranite intruded mainly as dykes, but also forms larger bodies such as the Tollu Pluton. At c. 1070 Ma, the province was intruded by a series of iron-rich tholeiitic mafic rocks of the Alcurra Dolerite. Most of these rocks were emplaced as dykes or sills, although larger intrusions such as the Saturn pluton may also be part of this suite. Importantly, these intrusions host the orthomagmatic Ni–Cu–PGE mineralization of the Nebo–Babel deposit, 120 km east of Warburton (see shaded box).

In the Blackstone Sub-basin in the southeastern to central part of the province (Fig. 43), the Bentley Supergroup includes the basal Kunmarnara Group, into which the layered 'Giles intrusions' were emplaced. This succession is interpreted to represent the basal succession of the Ngaanyatjarra Rift. The Talbot Sub-basin in the western part of the province comprises the Palgrave and Scamp areas, which are now separated by major faults (Fig. 62). The Palgrave area is a north-trending region ~70 km in length and up to 35 km wide. It includes, on its eastern flank, the Winburn Granite that either intrudes

Nebo–Babel nickel–copper(–PGE) — Western Australia's Voisey's Bay?

The Nebo–Babel intrusion in the west Musgrave Province is a concentrically zoned, tube-shaped mafic–ultramafic body 1×0.5 km in cross section and 5.5 km in length, that hosts world-class magmatic nickel–copper (–platinum group element) sulfide deposits. The intrusion has been dated at c. 1068 Ma, and is cogenetic with other ultramafic–mafic intrusions of the Giles Complex that form part of the regionally extensive Warakurna Super-suite. Estimated resources obtained from 90 drillholes are 392 Mt at 0.30% Ni and 0.33% Cu, with about 70% of the total resource hosted in the Babel sector. Platinum group elements (PGE) within sulfides have combined contents ranging between 103 and 488 ppb (mostly platinum and palladium). These estimated resources place the Nebo–Babel deposit as one of the largest nickel sulfide discoveries since Voisey's Bay in Canada.

The dominant rock types of the intrusion are gabbronorite and leucogabbronorite, which were emplaced during three temporally distinct, but cogenetic, magma pulses. These rocks were emplaced into granitic country rocks of the 1220–1150 Ma Pitjantjatjara Supersuite. The initial magma pulse formed the marginal, and most contaminated, units of the intrusion, whereas successive magma pulses were emplaced into the core of the intrusion and were progressively less contaminated. The last magmatic pulse underwent in situ crystal fractionation resulting in the variety of rocks types observed in the intrusion, although the production of rhythmically layered magmatic rocks is minor. The mineralization in the Babel sector of the intrusion is within rocks of gabbronoritic composition, although unmineralized gabbronorite forms a major component of the Nebo sector.

The mineralized gabbro–norite rocks consist of 55–65 vol. % plagioclase, 15–25 vol. % orthopyroxene, and 5–10 vol. % clino-pyroxene with minor minerals ilmenite, magnetite, biotite, and apatite. The sulfide mineralization, consisting of pyrrhotite, pentlandite, chalcopyrite, and pyrite, exhibits two styles: massive with associated sulfide breccias and stringers; and disseminated, generally interstitial, blebs. The $\delta^{18}O$ compositions of plagioclase and orthopyroxene from the igneous rocks, as well as the sulfur isotope ratios and whole-rock chemical compositions, unequivocally demonstrate an entirely mantle-derived origin for the sulfur, thus questioning the validity of other ore genesis models for deposits such as Voisey's Bay.

West Musgrave Province

or is overlain by felsic volcanic rocks of the Mount Palgrave and Kaarnka Groups; both are dominated by rhyolitic volcanic and pyroclastic rocks, with minor intercalations of basalt and sedimentary rocks. To the northwest, the Scamp area comprises mainly extrusive rhyolitic volcanic rocks and, based on the similarity in age and composition of these rocks with those in the Mount Palgrave Group, are thought to form a component of that group. Volcanic rocks in both areas have ages between c. 1070 and c. 1064 Ma.

The southern part of the Talbot Sub-Basin includes the south-dipping and younging volcano-sedimentary succession of the Pussy Cat, Cassidy, and Mission Groups. This succession has a cumulative thickness of several kilometres, and forms a stratigraphically continuous, arcuate, southeast-trending outcrop. The Pussy Cat Group is represented by volcaniclastic rocks and minor amygdaloidal basalt of the Glyde Formation, intercalated with flow-banded ignimbrites of the ~500 m-thick Kathleen Ignimbrite. The ages of felsic extrusive rocks in the Pussy Cat Group range from c. 1071 to c. 1065 Ma. The overlying Cassidy Group is probably unconformable on the Pussy Cat Group and is an approximately 3000 m-thick succession of alternating rhyolitic and basaltic units that have been dated between

Giles Event
Warakurna Supersuite
- Granite
- **Bentley Basin** Bentley Supergroup
- Gabbro
- Layered 'Giles intrusions'
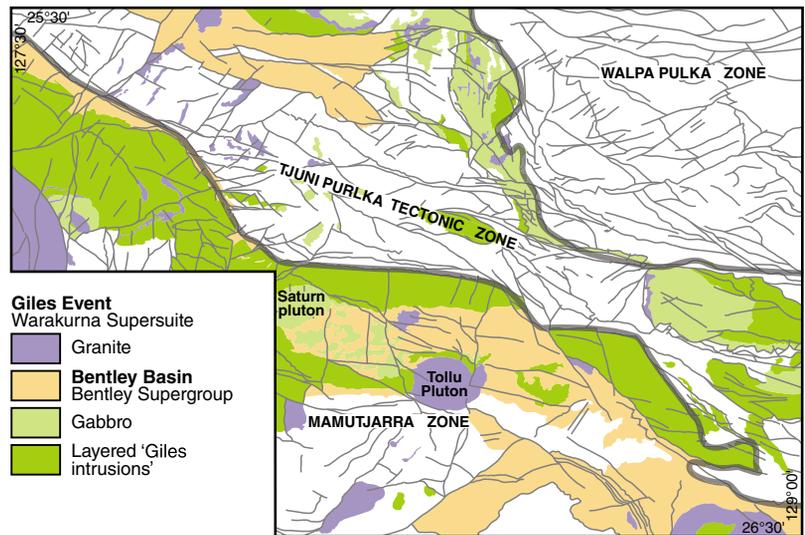
Figure 60. Distribution of intrusive and extrusive igneous rocks associated with the 1075–1045 Ma Giles Event, west Musgrave Province

c. 1065 and c. 1057 Ma. The conformably over-lying Mission Group — the youngest stratigraphic unit in the Bentley Supergroup — is up to 4000 m thick. The lowermost part of the group is dominated by a fining-upward and deepening succession of sedimentary rocks, including conglomerates, sandstones, and shales, whereas the uppermost part of the group is dominated
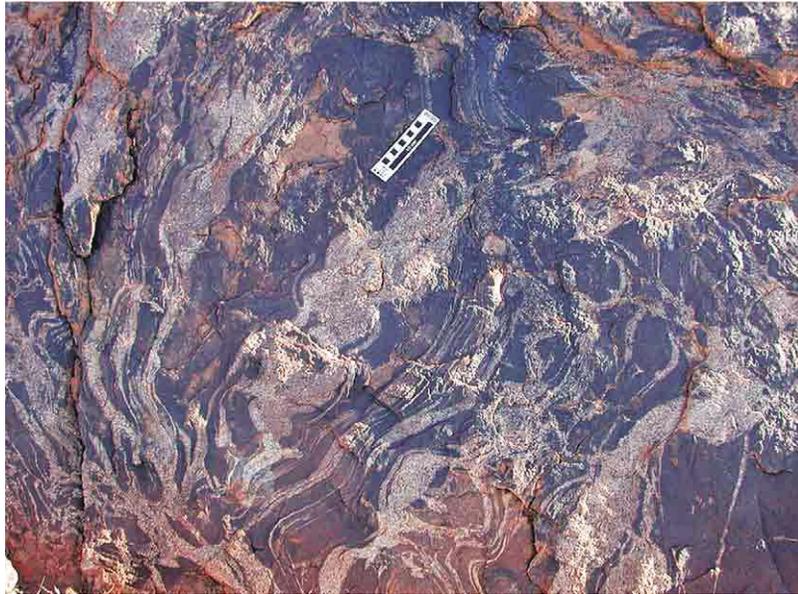
Figure 61.   Outcrop photograph showing ductile deformation associated with mingling of partially to largely solidified gabbro and leucogranite magma, Warakurna Supersuite, west Musgrave Province

by basalt. No felsic volcanic rocks have yet been identified. Constraints on the age of the group are the age of the underlying felsic volcanic rocks in the Cassidy Group (c. 1057 Ma) and the unconformably overlying Bitter Springs Formation (825–800 Ma) of the Amadeus Basin (Fig. 3).

Although the Bentley Supergroup is dominated by felsic volcanic rocks, their geochemical and isotopic signatures require that they were derived from the fractionation of parental mafic magmas deep in the crust. The cumulative volume of mafic intra- and underplate material — not including the other major magmatic components of the Giles Event such as the Warakurna LIP, the giant layered Giles (G1) intrusions and the associated massive gabbros (G2) of the Warakurna Supersuite — generated during the evolution of the Bentley Supergroup alone, reflect a huge transfer of mantle material (possibly as much as 2 000 000 km^3) into the
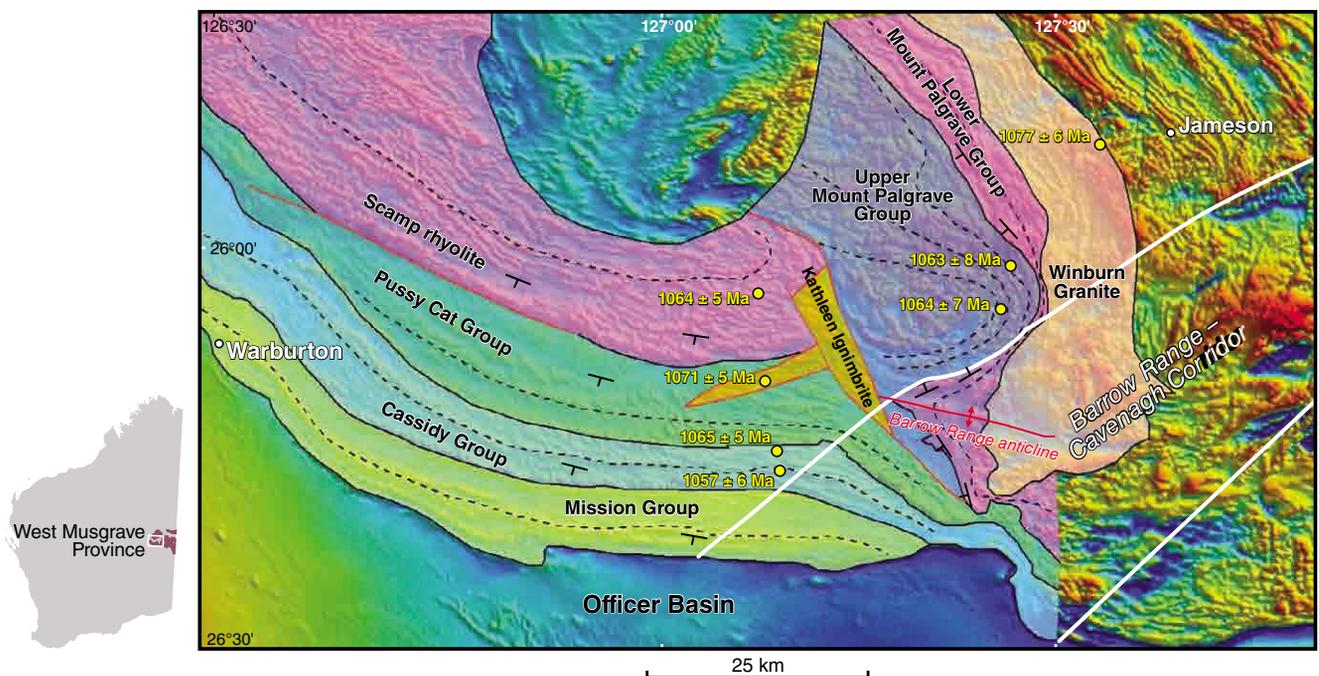
Figure 62.   Interpreted bedrock geological map (draped over TMI aeromagnetic map) showing the main litho-stratigraphic units of the Bentley Supergroup, west Musgrave Province

crust. The Giles Event has previously been linked to the impingement of a mantle plume beneath the central part of the West Australian Craton. In the case of the Talbot Sub-basin, however, the >30 Ma duration of mantle-derived magmatism at a single isolated region is difficult to relate to a mantle plume. Even a conservative drift rate of 2 cm/yr removes the crustal plate by >600 km from an initial stationary asthenospheric plume source. Although a mantle plume may have initiated mantle melting, it was certainly not the sole driver for extended magmatism in this region.

Intracratonic basins

The Collier Group (Fig. 41) is a ~2000 m-thick succession of shallow-marine to shelfal siliciclastic sedimentary rocks that unconformably overlie the sedimentary rocks of the Edmund, Bryah, and Earaheedy Basins, as well as basement rocks of the Yilgarn and Pilbara Cratons (Fig. 4). The age of the basin is relatively poorly constrained. An older limit for sedimentation is c. 1200 Ma, because the sedimentary rocks do not appear to have been affected by the 1385–1200 Ma Mutherbukin Tectonic Event (Fig. 3). The younger limit is defined by the age of intrusive dolerite sills — the Kulkatharra Dolerite — that form part of the c. 1070 Ma Warakurna LIP. However, the formation of extensive peperite in the lower part of the succession (in the Backdoor Formation), implies that the dolerite sills were intruded into wet sediments, and thus the age of deposition of the entire package may have been much closer to c. 1070 Ma than to c. 1200 Ma.

The Collier Group (Fig. 41, and panorama below) comprises Depositional Packages 5 (the Backdoor and Calyie Formations) and 6 (the Ilgarari Formation). The Backdoor and Calyie Formations consist of an upward-shallowing succession of predominantly deep-marine to fluvial–deltaic siliciclastic sedimentary rocks. Drowning of the uppermost deltaic units records the transition into the deep-marine Ilgarari Formation. Paleo-current directions and the U–Pb ages and Lu–Hf isotope compositions of detrital zircons indicate

Collier
Basin

Interbedded siltstones and sandstones of the Collier Group in the eastern Capricorn Orogen

that much of the detritus was sourced directly from erosion of the underlying Edmund Basin.

Siliciclastic sedimentary rocks — the Manganese Group — along the eastern margin of the Pilbara Craton to the north of the Collier Basin, are thought to be temporal equivalents of the Collier Group. These sediments, which form part of the Oakover Basin, are also intruded by dolerites of the c. 1070 Ma Warakurna LIP, and contain economically significant manganese deposits (Fig. 3).

South of the Manganese Group, the Salvation Group rims the northwest Officer Basin and overlies the Scorpion Group and possibly the lower Collier Group. As with the Collier Group, the lower age limit is defined by widespread intrusive dolerite sills of the Glenayle Dolerite, which is also part of the Warakurna LIP (Fig. 3). No peperites have been found in the Salvation Group, only indications of intrusion into lithified rocks, so the group appears to wholly predate dolerite intrusion. The Salvation Group is sand-rich compared to the Collier Group, and had a west-facing paleoslope, suggesting that it was a proximal correlative or precursor to the Collier Group. Westward paleocurrents in both the Salvation and the underlying Scorpion Groups indicate a hinterland presently covered by the southern Officer and Canning Basins, with sediment derivation probably from the tectonic high linking the Rudall and Musgrave Provinces.

Plate-margin and intracratonic deformation

The Pinjarra Orogen lies along the westernmost margin of the West Australian Craton. The orogen underlies most of the Perth and Carnarvon Basins and is exposed in three isolated Proterozoic inliers — the Northampton, Mullingarra, and Leeuwin Inliers — and also extends offshore as the Naturaliste Plateau (Fig. 63). The orogen also includes a number of

Pinjarra
Orogen

disparate sedimentary successions that border the Darling Fault (Fig. 63), which separates the orogen from the Archean Yilgarn Craton. Although the geology of the inliers is poorly known, reconnaissance U–Pb dating of zircon and monazite reveals that this orogen was subject to multiple tectonic and magmatic events at c. 1300 Ma, during the 1205–1150 Ma Darling Orogeny, and the 1095–990 Ma Pinjarra Orogeny, as well as a much younger period recorded only in the Leeuwin Inlier during the 780–520 Ma Leeuwin Orogeny (Fig. 3).

The most northerly of the inliers, the Northampton Inlier, is dominated by granulite-facies paragneisses that have been multiply deformed and intruded by granite and pegmatite during the 1095–990 Ma Pinjarra Orogeny. Basement rocks to the paragneiss are not exposed. However, metagranitic rocks of possible basement origin were intersected in the Woodleigh 1 drillhole farther north in the Carnarvon Basin (Fig. 63). U–Pb zircon dating indicates that these rocks crystallized at c. 1300 Ma and were strongly deformed and metamorphosed during the 1205–1150 Ma Darling Orogeny. The overlying metasedimentary rocks exposed in the Northampton Inlier are dominated by detrital zircons with ages <2000 Ma, and include major components at c. 1450 Ma to c. 1150 Ma, indicating that sediment deposition took place after granite intrusion and deformation during the Darling Orogeny. Although the detrital-zircon age modes are consistent with a sediment source predominantly from the Albany–Fraser Orogen, the discovery of basement rocks of similar age in Woodleigh 1 make it more likely that the sedimentary rocks were derived from these presently unexposed basement rocks, rather than the Albany–Fraser Orogen some 1000 km away. The metasedimentary rocks were deformed and metamorphosed at high temperature (800–900° C) and moderate pressure (500–600 MPa) during the Pinjarra Orogeny, the timing of which is recorded by the growth of metamorphic monazite and rare metamorphic zircon at c. 1083 to c. 1024 Ma. Syn-tectonic granite was emplaced at c. 1068 Ma and post-tectonic pegmatite at c. 989 Ma, which constrains the end of deformation and metamorphism. Cooling of the inlier to below 500° C took place at c. 920 Ma.
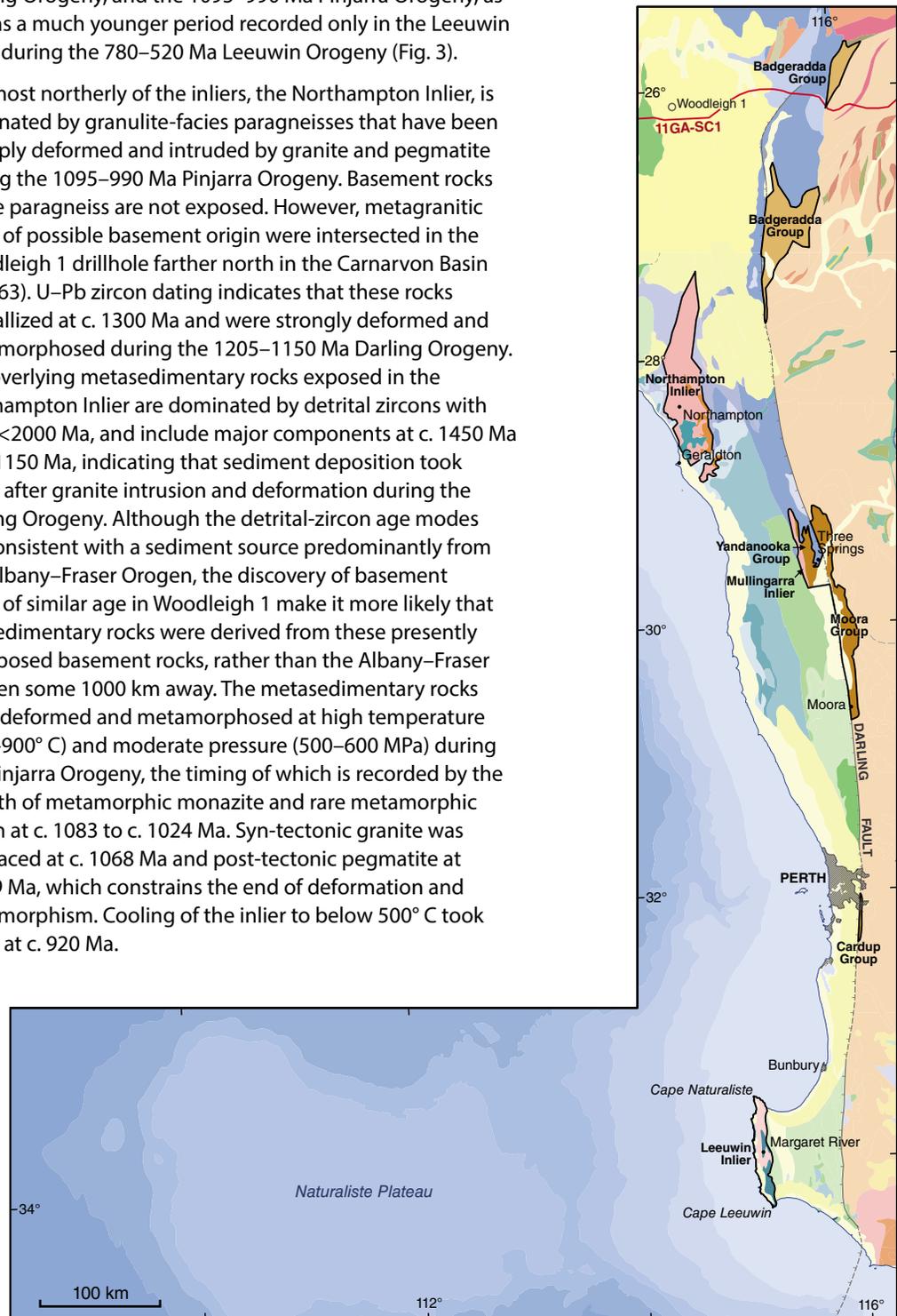
Figure 63.   Location of the Northampton, Mullingarra, and Leeuwin Inliers, the Naturaliste Plateau, and several sedimentary successions within the Pinjarra Orogen. Seismic line 11GA-SC1 is also shown

The Mullingarra Inlier comprises medium- to high-grade metasedimentary rocks, including quartzite and psammitic gneiss as well as minor interlayered amphibolites, which overlie a monzogranite-dominated basement dated at c. 2180 Ma. As with the metasedimentary rocks in the Northampton Inlier, the Mullingarra metasedimentary rocks are dominated by detrital zircons with the majority of ages <1810 Ma. Major detrital components have dates of c. 1800 to c. 1600 Ma and c. 1300 Ma. The maximum age of deposition is based on the youngest detrital zircon dated at c. 1115 Ma. High-grade metamorphism is interpreted to have peaked at 660 °C and 600 MPa, the timing of which is constrained by the growth of metamorphic zircon dated at c. 1058 Ma.

The Leeuwin Inlier in the far south of the orogen is dominated by granitic gneisses (Fig. 64) that formed during the Neoproterozoic break-up of the Rodinia supercontinent (see below). However, emplacement of granite — now garnet–biotite orthogneiss — at c. 1090 Ma, as well as abundant c. 1100 Ma inherited zircons, imply the reworking of Mesoproterozoic crust similar in age to that in the Northampton and Mullingarra Inliers.

The similarity in age and structural and metamorphic evolution of the Northampton and Mullingarra Inliers, and the similar age of inherited zircons within granites of the Leeuwin Inlier, suggest that all three inliers form part of the same orogen. A recent deep-crustal seismic-reflection survey through the Pinjarra Orogen — 11GA-SC1 (Fig. 65) — has shown that the contact between the Pinjarra Orogen and the Narryer
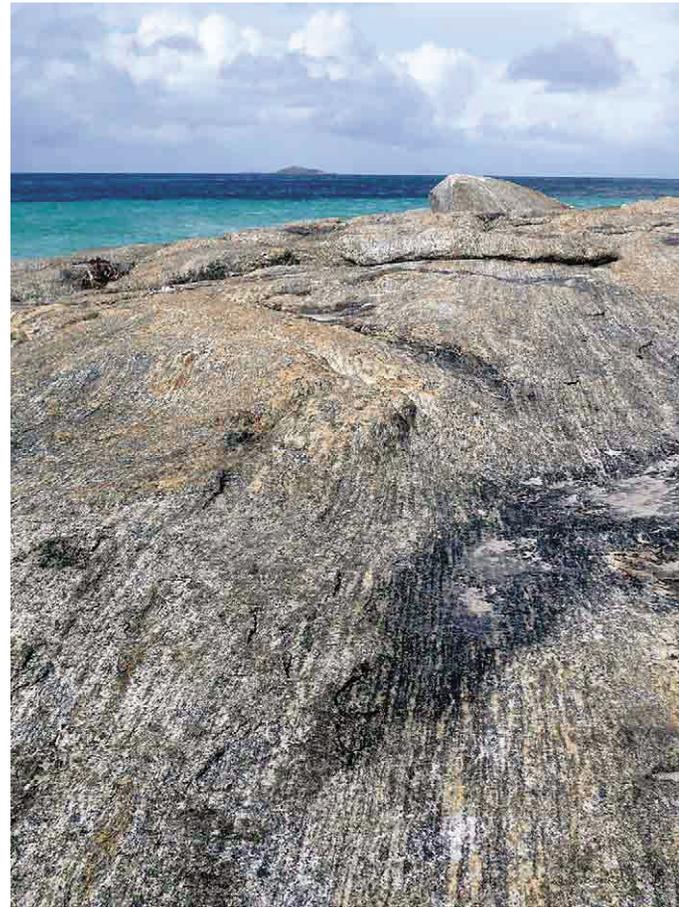
Figure 64.   Banded granulite facies orthogneisses of the Leeuwin Inlier at Cape Leeuwin, Pinjarra Orogen
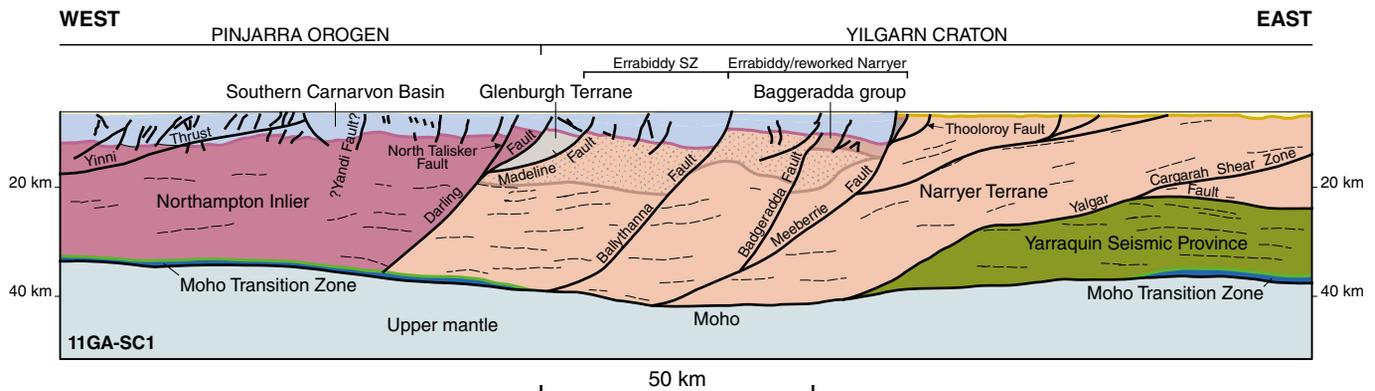
Figure 65.   Interpretation of deep-crustal seismic-reflection data across the western margin of the Yilgarn Craton, through the Pinjarra Orogen. The Narryer Terrane of the Yilgarn Craton is separated by a major crustal-scale fault — the Darling Fault — which may represent a former suture zone between the Pinjarra Orogen and the Yilgarn Craton. Location of seismic line 11GA-SC1 is shown on the map of Western Australian Proterozoic elements (p. vi)

Terrane in the Yilgarn Craton lies along the Darling Fault. This fault is interpreted to transect the entire crustal profile — and may represent a former suture zone — and shows that the Narryer Terrane does not extend at depth beneath the orogen (Fig. 65). These data imply that the Pinjarra Orogen had an entirely exotic origin with respect to the West Australian Craton. However, the timing of punctuated granite magmatism at c. 1300 Ma, and high-grade metamorphism during the Darling Orogeny, are coincident with Stages I and II of the Albany–Fraser Orogen, the Mount West and Musgrave Orogenies of the west Musgrave Province, and with the emplacement of voluminous mafic dykes of the Marnda Moorn LIP along the western margin of the Yilgarn Craton (Fig. 54). Ultimately, unexposed basement rocks of the Pinjarra Orogen may have an exotic origin, and represent the remnants of an unknown crustal block that lay to the west of the West Australian Craton in the Nuna supercontinent (Fig. 32). However, the post c. 1400 Ma tectonic history of this orogen is characterized by a series of punctuated high-grade crustal reworking events in a (para-)autochthonous setting.

Following compressional deformation and high-grade metamorphism during the Pinjarra Orogeny, basement rocks of the Gascoyne Province and sedimentary rocks of the Edmund and Collier Groups were subjected to faulting and folding during the 1030–955 Ma Edmundian Orogeny (Fig. 3). In the Gascoyne Province basement, deformation and metamorphism were restricted to a narrow, <20 km-wide corridor along the southern margin of the Ti Tree Shear Zone. Within this corridor, metasedimentary rocks were metamorphosed at medium grade (500–550 °C and 300–500 MPa), first at c. 1030 Ma, and then at c. 1000 Ma. Deformation and metamorphism were accompanied by the intrusion of leucocratic metamonzogranite, tourmaline-bearing granite and pegmatite, and rare earth element-bearing pegmatites of the 1030–925 Ma Thirty Three Supersuite. During this time, sedimentary rocks of the Edmund and Collier Groups were subjected to low- and very low grade metamorphism associated with contemporaneous transpressional folding and faulting. The similar orientations of the major fold and fault structures to those in the underlying Gascoyne Province basement, indicate that deformation in the upper crust was controlled principally by larger scale structures in the underlying basement.

Capricorn
Orogen

Proterozoic Australia and the amalgamation of Rodinia

The tectonic history of Proterozoic Australia after c. 1200 Ma is relatively complex. The tectonic activity recorded between c. 1080 and c. 1060 Ma comprises both extensional activity in the interior of Proterozoic Australia (with the emplacement of the Warakurna LIP and formation of the Ngaanyatjarra Rift) and deposition of the Collier Basin. Contemporaneous (c. 1085 to c. 1070 Ma) high-grade compressional deformation and magmatism affected the craton's western margin in the Pinjarra Orogen. These events were followed by low- to medium-grade deformation and metamorphism and associated magmatism in the Gascoyne Province, and low-grade folding and faulting of the Edmund and Collier Groups during the 1030–955 Ma Edmundian Orogeny.

During these events, Proterozoic Australia is interpreted to have been disparate from the Rodinia supercontinent, amalgamating with it, along its eastern margin, at c. 950 Ma (Figs 66, 67). Extensional deformation and emplacement of the Warakurna LIP is commonly attributed to the passing of the craton over a mantle plume, whereas compressional tectonism is interpreted to record the oblique collision of the Indian continent's eastern margin (the Eastern Ghats Belt) with the West Australian Craton during its rapid southward migration. However, the age of ultra-high-grade metamorphism in the Eastern Ghats Belt, at c. 980 Ma, does not support this model because the timing of deformation and metamorphism in these areas is separated by ~100 m.y. Equally, neither of these interpretations adequately explains the synchronicity of extensional and compressional tectono-metamorphism and magmatism within Proterozoic Australia, nor the duration of the Giles Event magmatism.

The Neoproterozoic tectonic evolution of the Leeuwin Inlier and intrusion of the c. 755 Ma Mundine Well Dolerite Suite (see below), suggest that a craton lay off the western margin of Proterozoic Australia, rifting away during the break-up of the supercontinent. The timing of ultra-high-grade metamorphism in the Eastern Ghats Belt, combined with paleomagnetic data for the Indian continent at c. 770 to c. 750 Ma, indicates that this crustal block lay much further south (Fig. 58), and thus could not have formed the conjugate margin to Proterozoic Australia. The identity of this counterpart cratonic entity
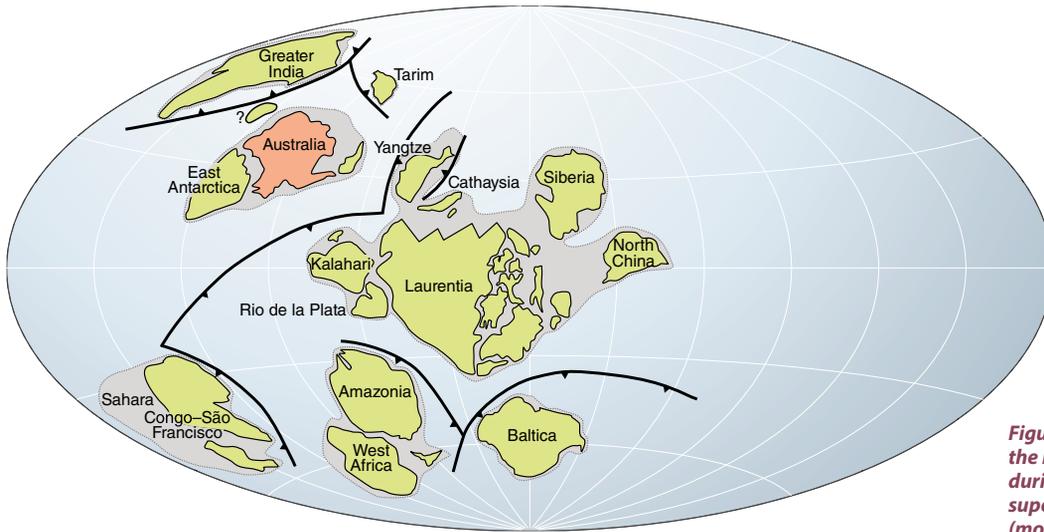
Figure 66. Reconstruction showing the location of continental blocks during assembly of the Rodinia supercontinent at c. 1050 Ma (modified from Li et al., 2008)
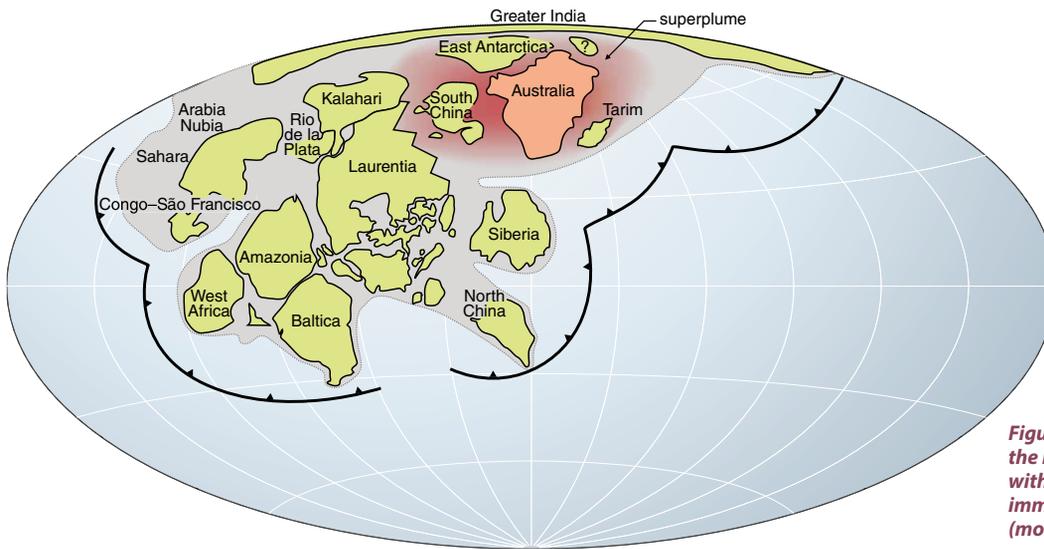
Figure 67. Reconstruction showing the location of continental blocks within the Rodinia supercontinent immediately prior to break-up (modified from Li et al., 2008)
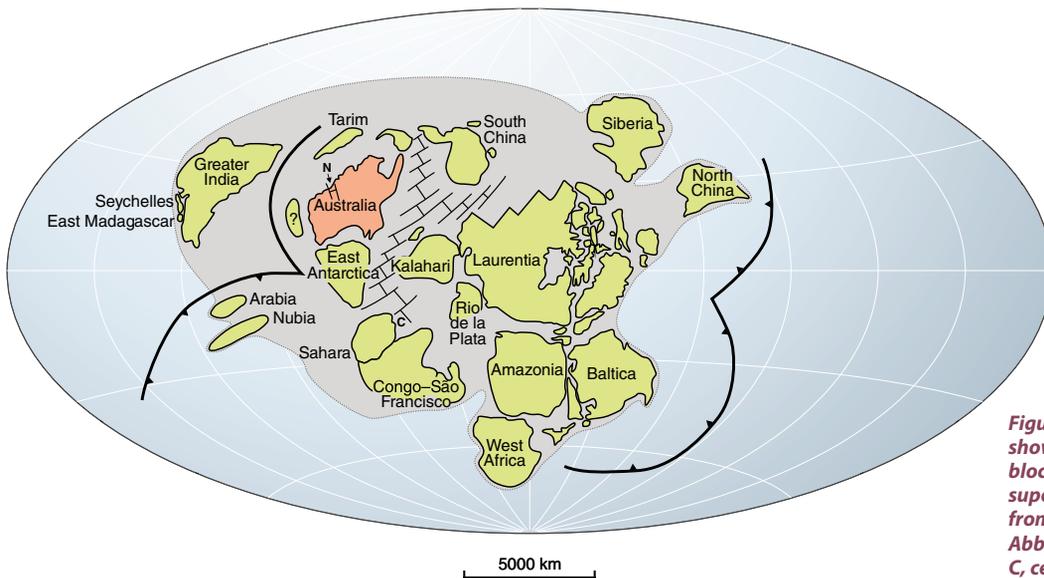
Figure 68. Reconstruction showing the location of continental blocks after the break-up of the supercontinent at c. 825 Ma (modified from Li et al., 2008). Abbreviations: N, Nifty deposit; C, central African Copperbelt

57

currently remains enigmatic. However, these data do imply that an unknown craton collided with the western margin of Proterozoic Australia between c. 1080 and c. 1060 Ma. The driver of coeval extensional deformation and mafic magmatism is not fully understood, but it should be noted that these extensional events essentially represent a continuance of existing high-temperature deformation and magmatism associated with the Musgrave Orogeny and Stage II of the Albany–Fraser Orogeny. Such an extended period of high-temperature deformation and magmatism is unprecedented in Earth history, and is difficult to explain entirely in a mantle-plume-driven model. Subsequent low- to medium-grade intracontinental deformation, metamorphism, and magmatism during the 1030–955 Ma Edmundian Orogeny, may have been related to the collision of Proterozoic Australia's eastern margin with the Rodinia supercontinent (Fig. 58).

Break-up of Rodinia and Snowball Earth

The first indication of the break-up of Rodinia is recorded by widespread mantle-plume activity in the polar regions of the supercontinent at c. 825 Ma, with the emplacement of voluminous mafic dyke swarms in eastern Australia (Gairdner Dykes), South China, Tarim, India, Kalahari, and the Arabian–Nubian terranes (Fig. 67). Continental rifting is also noted in Laurentia and Baltica between c. 800 and c. 700 Ma. In Australia, this plume activity was near-synchronous with rifting and the onset of sedimentation within the Adelaide Rift Complex and Centralian Superbasin. Although deposition in these intracontinental basins was near-continuous for ~300 m.y., this early rifting episode does not appear to have advanced to the full separation of continental blocks. The effects of plume activity quickly receded until renewed mantle-
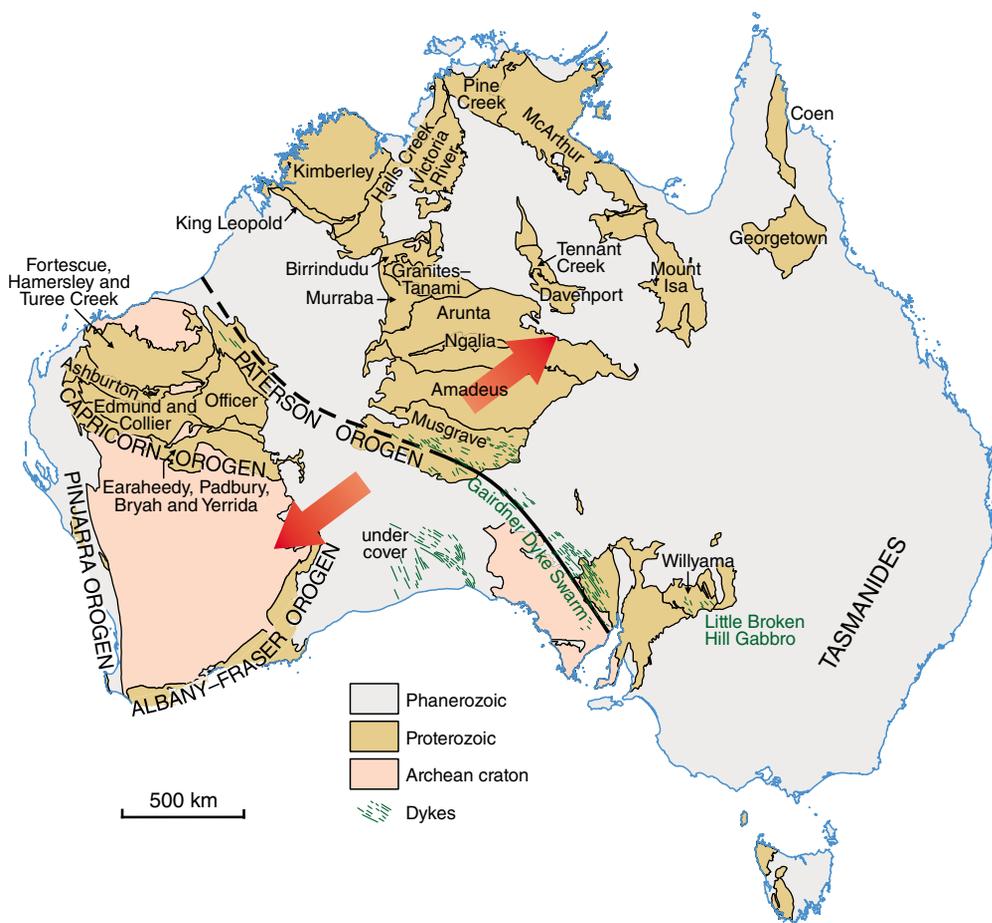
Figure 69. Tectonic map of Australia showing the location and orientation of mafic intrusive rocks associated with extensional activity at c. 825 Ma. Red arrows shown direction of extension

plume activity at c. 770 to c. 750 Ma affected the supercontinent, which was now at equatorial latitudes (Fig. 68). This plume event heralded the end for Rodinia and ushered in an unstable climatic period dominated by two global-scale ice ages, or Snowball Earth events. The oldest of these, the 725–700 Ma Sturt glaciation, coincided with the main phase of Rodinia break-up, whereas the second, the 635 Ma Marinoan glaciation (now commonly called the Elatina glaciation), was synchronous with the rifting and separation of Baltica from Laurentia. Ongoing research suggests that additional glaciations continued until at least c. 585 Ma, with multiple smaller events rather than just two global-scale events. Global-scale frozen oceans may have severely limited the development and evolution of multicellular life, but the recovery from these snowball events resulted in the remarkable diversification of multicellular organisms throughout the Neoproterozoic through to the Ediacaran radiation.

No stone unturned

Attractive high-quality dimension stones for use in the cladding of buildings, paving for streetscapes, and monumental works come from a variety of rock types, with a range of ages, and spread across the State.

Dimension stones from the Albany–Fraser Orogen range from syenogranites and monzogranites used for local monumental masonry to metagabbroic rocks forming gneiss, charnockite, and mafic granulite, as well as metadolerite with evocative names such as **Verde Austral**, **Gold Leaf Black**, and **Garnet Ice**. Garnet Ice is a foliated, white to cream garnet–biotite gneiss containing coarse-grained quartz and feldspar interspersed with numerous wine-red garnets up to 5 mm in diameter, and irregular elongated zones of dark grey to black schistose biotite. The swirling black and white zones dotted with garnets give this rock its spectacular appearance (see image). Paving slabs of Verde Austral and Garnet Ice have been used together in the foyer of the Perth Town Hall.

Jet-black dolerites from the Mesoproterozoic Warakurna Supersuite in the Capricorn Orogen are prospective for high-quality stone, known as **Glen Florrie Black**. Paleoproterozoic dolerite dykes in the Kimberley region have produced very fine grained dolerites suitable for export. Although actually dolerite, these rocks are termed black granite by the stone trade — they are very black, take a very high mirror-like polish, and are much sought-after for prestige buildings, bench tops, figurines, and the funerary industry.

Numerous marble deposits in the Paleoproterozoic Ashburton Basin, the Mesoproterozoic Edmund Basin, and the Gascoyne Province of the Capricorn Orogen have been quarried at different times over the past 40 years, and there is still considerable potential. The marbles are dolomitic and display a wide range of colours and textures from pure white Carrara-like marble to deep reds and greens, with banded, veined, and brecciated textures (see image). Dolomitic marbles are generally harder than calcitic marbles, giving a finer cut finish and resistance to acid attack.

25 mm

Rifting of Proterozoic Australia from Rodinia

In Western Australia, the record of Rodinia break-up is relatively fragmentary because most activity took place along Proterozoic Australia's eastern margin. However, basin formation and intrusion of mafic dykes also occurred in the west of the craton (Fig. 69). Deposition within the Centralian Superbasin and the associated Yeneena Basin in the northwestern part of the Paterson Orogen began at c. 850 Ma (Figs 3, 70, 71). This was shortly followed by intrusion of mafic dykes into the west Musgrave Province (c. 825 Ma Gairdner Dolerite), and c. 835 Ma gabbros and dolerite dykes within the Yeneena Basin. This rifting event is restricted to a narrow corridor across Proterozoic Australia, stretching from the northeast Pilbara Craton to the eastern side of the Gawler Craton, and represents a ~2500 km-long failed intracontinental rift system (Fig. 69). Although plume activity ceased soon after c. 825 Ma, sedimentation in the Centralian Superbasin and Adelaide Rift Complex continued almost uninterrupted throughout the remainder of the Proterozoic. Away from this rift corridor, locally diamondiferous lamprophyres and kimberlites (including the Maude Creek and Aries kimberlite intrusions) were intruded across the Kimberley region at c. 815 Ma (Figs 3, 50).

Tectono-magmatic activity resumed at c. 755 Ma with the intrusion of the Mundine Well Dolerite Suite mafic dykes and voluminous granites (now granulite-facies orthogneisses) that comprise much of the Leeuwin Inlier in the Pinjarra Orogen (Fig. 3). Although this event is nominally associated with the rifting of Proterozoic Australia's eastern margin from Rodinia, these magmatic rocks are concentrated along the western margin of the West Australia Craton, implying that their emplacement may be related to the separation of an unknown continent from the craton's western margin.

The Centralian Superbasin: The Centralian Superbasin extended over at least 2 600 000 km[2] of central and northern Australia, from the Kimberley in Western Australia to the Flinders Ranges in South Australia (Fig. 70). Deposition began at c. 850 Ma, in a series of linked basins, during the onset of Rodinia break-up, and continued through to a 570–540 Ma orogeny that marks the start of assembly

Centralian Superbasin

Figure 70. Location of the Officer Basin within the Centralian Superbasin

Figure 71. Stratigraphy of the Centralian Superbasin in Western Australia.
Abbreviations: Cgl., Conglomerate; Fm., Formation; Gp, Group; Mb., Member; Sst., Sandstone

Centralian Superbasin

of the Gondwana supercontinent (Figs 2, 71). This orogeny is referred to as the Petermann, Paterson, or King Leopold Orogeny, or the Mulka Tectonic Event, depending on its location (Fig. 3). Uplift and basin inversion during the orogeny completed the dissection of the superbasin into several discrete basins, including the Amadeus, Georgina, Ngalia, Officer, and Yeneena Basins. The superbasin succession is commonly divided into four 'supersequences', all of which are present in the Officer Basin and western Amadeus Basin in Western Australia. Only the older supersequences are recorded in the Yeneena Basin.

The oldest part of the succession (Supersequence 1) was deposited between c. 850 and c. 700 Ma and records local tectonism at the start of subsidence, with basal sandstones in areas adjoining tectonically active basin margins (Fig. 71). This was followed by alternating siliciclastic and mixed carbonate–evaporite deposition, mostly in coastal to shallow-shelfal settings, culminating in significant eolian deposition in the northwest Officer Basin. These facies suggest a regional, episodically arid climate probably controlled by Australia being positioned in a subtropical-arid global-climate belt. Supersequence 1 includes the Heavitree and Dean Quartzites and Bitter Springs Formation of the Amadeus Basin; the Tarcunyah, Buldya, and Sunbeam Groups in the Officer Basin; the Lamil and Throssell Range Groups in the Yeneena Basin; assorted units in other small basins; and probably the Redcliff Pound Group in the Murraba Basin (Fig. 3). As in the Amadeus Basin in the Northern Territory, widespread thick salt intervals accumulated, and have since controlled the tectonic evolution of the Officer Basin, as later movement on underlying Proterozoic structures triggered salt movement and expulsion. Several diapirs reached the surface, and a seismic profile across the Officer Basin reveals major west-facing flower-like structures east of Lake Disappointment that may result from evaporite expulsion.

In Western Australia (Figs 3, 71), the c. 700 to c. 600 Ma Supersequence 2 has been found only in the western Amadeus Basin (lower 'Boord Formation', informal name) and southern Officer Basin near the South Australian border (Pirrilyungka and

1cm

Figure 72.   Dropstone in red-brown rhythmite mudstone — representative of the 725–700 Ma Sturt glaciation — from the Vines 1 drillhole, Officer Basin, Centralian Superbasin

Proterozoic uranium mineralization occurs as vein type (unconformity-related) in schists, such as at Kintyre, Angelo River, and Ashburton–Turee Creek; and carbonatite-hosted and pegmatite-hosted, found in the Cummins Range, Halls Creek Orogen, and Gascoyne Province.

The largest uranium deposit is hosted at Kintyre in the Paterson Orogen and was formed during the 650–600 Ma Miles Orogeny. The indicated and inferred resources total 5.26 Mt of mineralization containing about 64.8 million pounds of contained U_3O_8, with the indicated resources (4.3 Mt) averaging an impressive 0.58% U_3O_8 (as at 31 December 2012). The deposit is 'far and away' the highest grade uranium deposit in the State, whereas the deposit size is third largest after Yeelirrie

(surficial/regolith-hosted) and Mulga Rock (roll-front-related and sandstone–lignite-hosted). The uranium at Kintyre is typically colloform and massive pitchblende hosted in carbonate–chlorite veins within low-grade metasedimentary rocks of the Rudall Province. The mineralized veins were emplaced during deformation and regional folding close to the unconformity with the overlying Coolbro Sandstone, which forms the basal unit of the Neoproterozoic Yeneena Basin.

The Neoproterozoic Cummins Range diatreme forms part of a small alkaline complex intruding the Olympio Formation in the Eastern Zone of the Lamboo Province, south of Halls Creek. Uranium is a minor component relative to the rare earth elements of the carbonatite.

Lupton Formations). Deposition was in shallow to deeper marine settings (Amadeus and Officer Basins respectively), and was dominated by the 725–700 Ma Sturt glaciation, well established from the sedimentary record in South Australia and the Northern Territory. This was the start of a globally colder climate, referred to by many as Snowball Earth and characterized, globally, by glacially related deposition in all known deposits of this age. In Vines 1 drillhole, near the South Australian border, this glacial interval is more than 1200 m thick, and poorly preserved palynomorphs hint that deposition may have been continuous from Supersequence 1 (Fig. 72). The diamictites are dominantly grey, and monomictic in composition, compared to the varicoloured, polymictic diamictites of the overlying Supersequence 3.

Supersequence 3 (600–550 Ma) is widespread across Western Australia, and is similarly dominated by diamictite, deposited during the c. 635 Ma Elatina glaciation (Figs 3, 71, 73). In the Officer Basin and in the Kimberley, carbonates are locally exposed above the diamictite. In the western Amadeus Basin, well-exposed glacigene diamictites are overlain by ~300 m of red-brown

Figure 73.   Glacial diamictite representative of the c. 635 Ma Elatina glaciation from the Vines 1 drillhole, Officer Basin, Centralian Superbasin

siltstone and shale, capped by a succession of interbedded limestone, siltstone, and sandy carbonate horizons showing shallow-marine, shallowing-upward cycles up to 550 m.

Supersequence 4 (550–545 Ma) records the orogeny at the start of the assembly of Gondwana, following the widespread glaciations of Supersequences 2 and 3 (Figs 3, 71). It is dominated throughout the Centralian Superbasin by a distinctive lower unit of red-brown sandstone to pebbly conglomerate, and

(in places) an upper unit dominated by conglomerate and coarse-grained sandstone, such as at Kata Tjuta (The Olgas in the Northern Territory) and in the Sir Frederick Range in the western Amadeus Basin. In central Australia, these form part of the foreland-basin deposits of the Petermann Orogeny. In the western Amadeus Basin, the lower deltaic succession is up to 1700 m thick, and, in the southern part of the basin, rests unconformably on the upper part of Supersequence 1. This suggests that synorogenic uplift and erosion of intervening Supersequence 2 and 3 rocks during the Petermann Orogeny had begun by c. 550 Ma. The overlying coarse-grained conglomerate and sandstone are the coarse-clastic foreland-basin material derived from this orogenic event. In the Officer Basin, widespread eolian sandstones, such as those that form Durba Hills are capped by fluvial pebbly sandstone (Fig. 74).

Rodinia and the birth of the supercontinent cycle

Although modern-style plate tectonics has operated on Earth since at least 3200 Ma, the regular 300–500 million-year periodicity of the formation, stabilization, and break-up of supercontinents, namely the supercontinent cycle, does not appear to have begun until the Mesoproterozoic, with the break-up of Nuna and its transition into the assembly of Rodinia. Even though large crustal entities approaching the size of supercontinents (alternatively known as supercratons) may have existed in the late Archean and Paleoproterozoic, the regular pulse of the supercontinent cycle was only established once most of the Earth's cratons were assembled into stable Phanerozoic-size blocks. The significant increase in length of subduction margins along these enlarged cratons may have caused fundamental changes in mantle-convection dynamics, with the initiation of super-downwellings beneath the assembling supercontinents, followed 100–200 m.y. later by upwelling mantle superplumes that tore the supercontinents apart.

Figure 74.   Giant eolian cross-beds in latest Neoproterozoic to Cambrian McFadden Formation overlain by Durba Sandstone, Durba Hills, Officer Basin, Centralian Superbasin. Eolian foresets are the height of Durba Hills, more than 60 m

Growing Gondwana: the heart of a supercontinent (570–500 Ma)

THE LATE NEOPROTEROZOIC TO CAMBRIAN Gondwana supercontinent contained most of the Earth's cratons (Fig. 75) — except for Laurentia, which had previously formed the core of the Rodinia supercontinent. The configuration of continental blocks within Gondwana implies that the supercontinent formed mostly by the extroversion of Rodinia, i.e. the exterior margins of the dispersing continental fragments collided during the subsequent assembly of Gondwana. Recent high-quality paleomagnetic data, combined with a better understanding of the assembly history of individual cratonic blocks, demonstrate that Gondwana was assembled much like Rodinia, that is, from a multitude of spatially and temporally distinct collisional events, rather than the collision between two large pre-assembled continental blocks — East Gondwana and West Gondwana — along a single suture defined by the East African –

Antarctic Orogen (EAAO). Such a protracted assembly history is evident from the geological evolution of Proterozoic Australia, which records a series of deformational episodes spanning the period between c. 650 and c. 520 Ma. Apart from the youngest tectonic events recorded in the Leeuwin Inlier of the Pinjarra Orogen (that may represent a continental suture), these episodes of deformation and variable-grade metamorphism represent intracratonic orogeny. Within Proterozoic Australia, two main tectono-metamorphic events are recorded: the Miles Orogeny at 650–600 Ma, and the King Leopold – Petermann – Paterson Orogeny at 570–520 Ma (Figs 2, 3, 76).
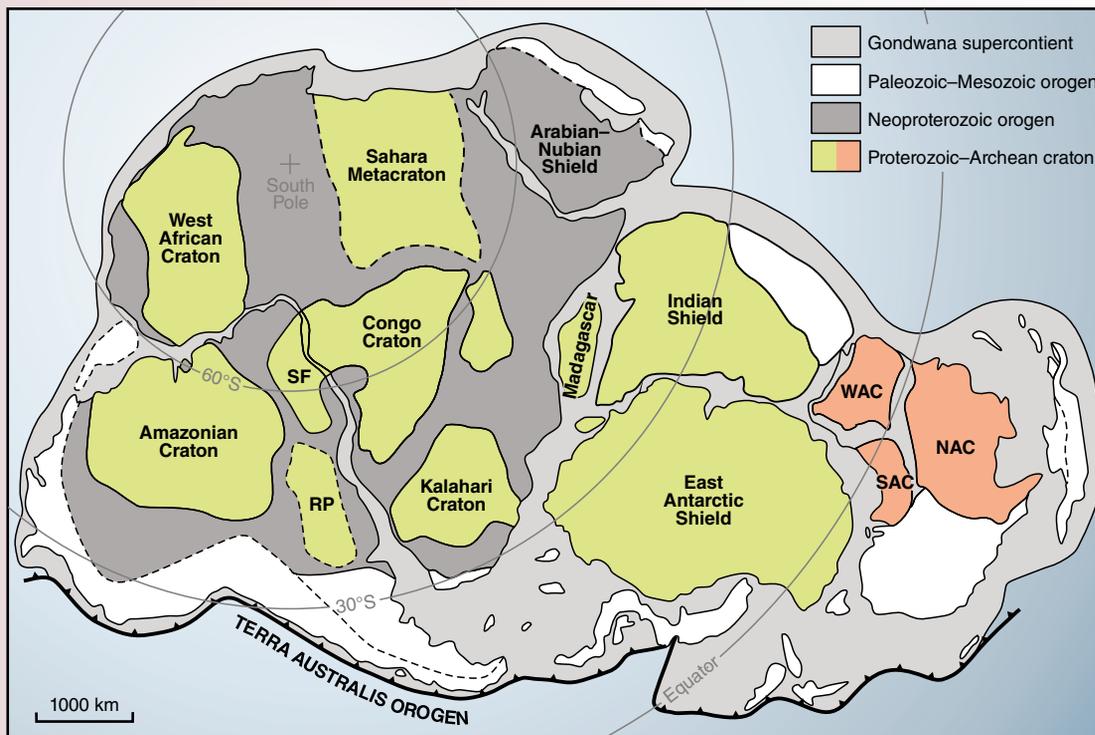
Figure 75.   Reconstruction of the Gondwana supercontinent at 520 Ma (modified from Meert and Lieberman, 2007). Abbreviations: NAC, North Australian Craton; RP, Rio de la Plata; SAC, South Australian Craton; SF, São Francisco; WAC, West Australian Craton

Pre-Gondwana assembly events

The oldest Gondwana-related event, the 650–600 Ma Miles Orogeny, occurred during a period of arc assembly and accretion along the present-day East African margin. At this time, Proterozoic Australia is interpreted to have been distal to the central African blocks and so the driver of this c. 650 Ma orogenic activity is currently unknown (Fig. 77). Deformation during the Miles Orogeny affected sedimentary rocks of the Lamil and Throssell Range Groups of the Yeneena Basin in the Paterson Orogen, and the Sunbeam and Tarcunyah Groups of the northwest Officer Basin. In the Paterson Orogen, deformation resulted in northwest-trending folding and faulting in the Rudall Province, and thrusting and recumbent folding of the Throssell Range Group. Deformation was accompanied by lower greenschist-facies metamorphism, although in the Tarcunyah Group of the northwest Officer Basin, the grade of metamorphism was significantly lower. The age of metamorphism is constrained directly by multiple $^{40}Ar/^{39}Ar$ muscovite ages of c. 655 Ma from newly grown muscovite in the Coolbro Sandstone of the Throssell Range Group, as well as muscovite from underlying meta-igneous rocks of the Rudall Province. Subsequent to folding and metamorphism, the Lamil Group was intruded by granites of the 655–630 Ma O'Callaghans Supersuite, which may be associated with significant copper–gold mineralization at Telfer (see shaded box). Basin inversion and metamorphism were responsible for remobilization and upgrading of syn-diagenetic base metals in the Yeneena Basin to form the Nifty deposit, and unconformity-related uranium at Kintyre (see shaded boxes).
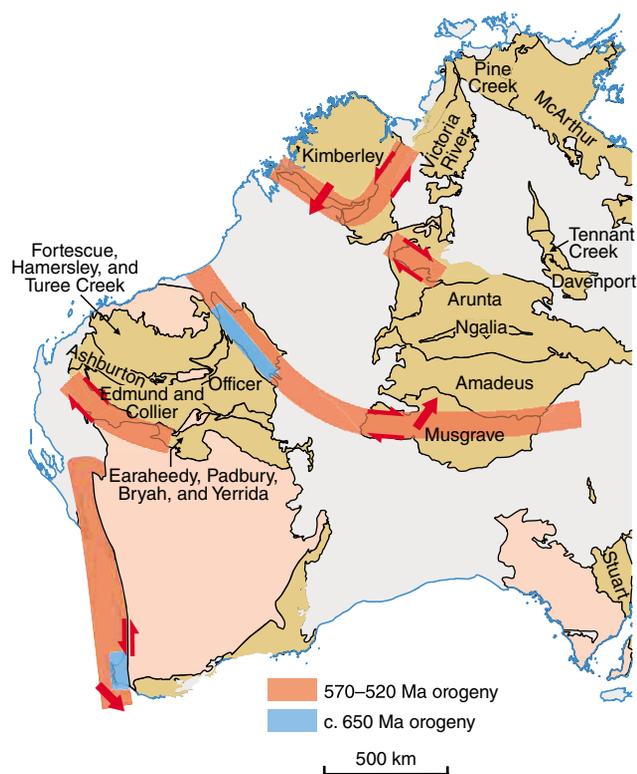
Figure 76.   Tectonic map showing the distribution of Neoproterozoic orogenic events in Western Australia

c. 630 Ma
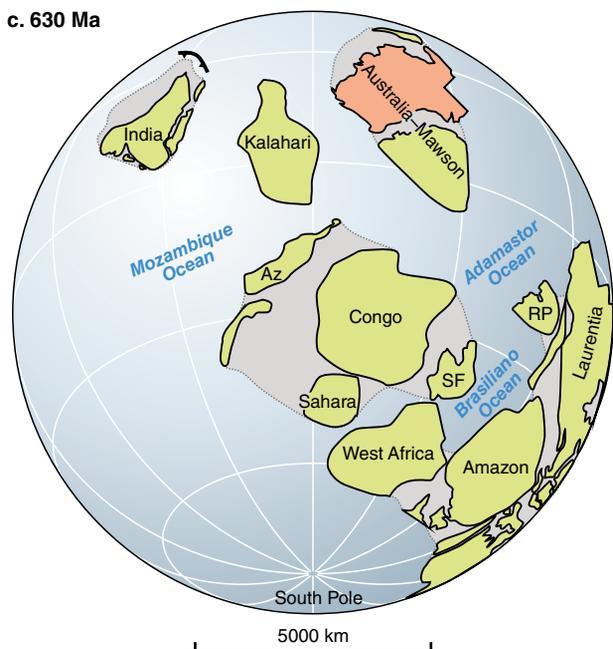
Figure 77.   Reconstruction of tectonic plates prior to the final assembly of the Gondwana supercontinent (after Collins and Pisarevsky, 2009). Abbreviations: Az, Azania; RP, Rio de la Plata; SF, São Francisco

c. 530 Ma
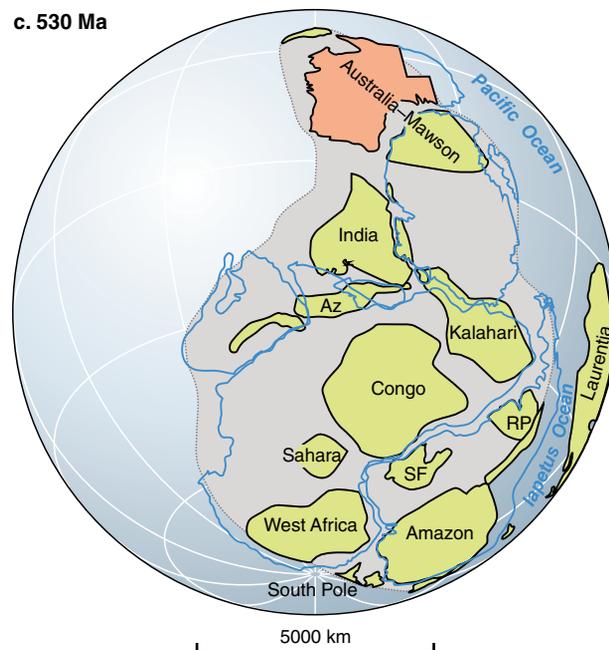
Figure 78.   Reconstruction of the Gondwana supercontinent following final assembly (after Collins and Pisarevsky, 2009). Abbreviations as for Figure 77

The giant Telfer copper–gold system

Significant Au–Cu deposits are contained within interbedded siltstone and sandstone units of the Lamil Group in the Yeneena Basin. Mineralization is restricted to the 'Telfer Dome', which has produced about 17.5 million ounces of gold during several operating phases since 1975. Current resources and reserves contain a further 20.2 million ounces of gold within about 984 Mt of ore, an average head grade of 0.6 g/t Au. So Telfer truly represents a giant Au–Cu mineralizing event.

The gold is found as small inclusions within pyrite as well as along fractures. Gold is commonly associated with small amounts of chalcopyrite and trace amounts of pyrrhotite. Fine-grained gold with disseminated euhedral to subhedral pyrite, and minor chalcopyrite and galena is also in narrow silica–dolomite alteration zones at wallrock contacts with the mineralization zones.

The origin of the mineralization at Telfer has been explained by either syngenetic exhalative or epigenetic models, as mineralization appears to be both stratabound and structurally controlled. However, more recent explanations have focused on direct or indirect magmatic models linked to the intrusion of voluminous, highly fractionated I-type granites of the 655–630 Ma O'Callaghans Supersuite that intruded the Yeneena Basin during the earliest stages of the Miles Orogeny.

Syn-Gondwana assembly events

Younger c. 570 to c. 520 Ma events recorded within Proterozoic Australia (Figs 2, 3, 76) occurred during the main phase of Gondwana assembly (Fig. 78). Within Proterozoic Australia, these events are recorded by a transcontinental network of mainly brittle to brittle–ductile faults and variable-grade shear zones.

In the west Kimberley region, greenschist-facies metamorphism, folding, and brittle–ductile deformation at c. 550 Ma, during the King Leopold Orogeny, affected rocks of both the western Lamboo Province and overlying Speewah and Kimberley Basins in the King Leopold Orogen. The boundary between the medium- to high-grade western Lamboo Province basement and the overlying sedimentary rocks of the Speewah and Kimberley Basins is sheared and faulted (Fig. 79). Deformation resulted in the thrusting of the sedimentary rocks southwestward over the basement, producing tight folding and back-thrusting of cover rocks in the hangingwall of the main thrust structure — the Inglis Fault. In the east Kimberley, the effects of the King Leopold Orogeny appear to be largely restricted to strike-slip reactivation of pre-existing faults in the Lamboo Province basement. Some of these faults were reactivated during the Phanerozoic.

Northwest-trending brittle faults, such as the Tanami and Mongrel Faults in the Granites–Tanami Orogen are associated with the c. 550 Ma King Leopold Orogeny.

Pervasive deformation associated with the 570–530 Ma Petermann Orogeny affected basement rocks of the northern Musgrave Province as well as sedimentary rocks of the Amadeus Basin, and was responsible for the uplift and dissection of parts of the Centralian Superbasin. Outside this region, such
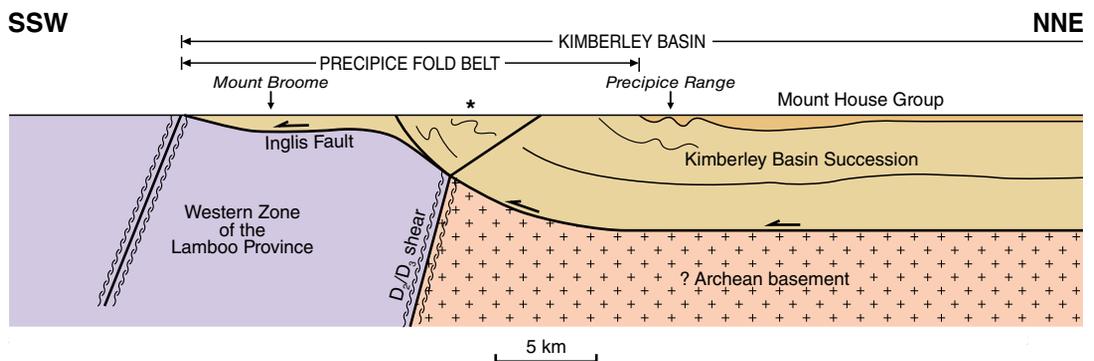
Figure 79.   Geological cross section through the King Leopold Orogen of the southwestern part of the Kimberley region. Asterisk marks folded King Leopold Sandstone, shown on cover. Location of cross section shown on Figure 22

A Nifty comparison with the Central African copper belt

The Nifty copper deposit is currently the largest producer of copper in Western Australia. The copper is hosted in chloritic and pyritic carbonaceous shales and siltstones of the Throssell Range Group within the Neoproterozoic Yeneena Basin, which unconformably overlies Mesoproterozoic basement rocks of the Rudall Province. The sedimentary rocks were deposited in an extensional continental rift basin along the eastern margin of the Pilbara Craton sometime between c. 980 and c. 845 Ma. The deposit contains an inferred resource of 99 Mt grading 1.7% copper, mainly within chalcopyrite, but with accessory pyrite, sphalerite, and galena. Primary mineralization is interpreted to have accompanied late basinal diagenesis, and possibly the emplacement of mafic dykes dated at c. 830 Ma. Structural reworking and upgrading of the ore into regional-scale fold hinges and structurally controlled corridors, probably took place during basin inversion of the 650–600 Ma Miles Orogeny.

The central African Copperbelt in Zambia and the Democratic Republic of Congo is the largest, and highest grade, sediment-hosted stratiform copper province known on Earth. Copper deposits are hosted within Neoproterozoic carbonaceous siltstones and shales of the Lower Roan Group of the Katangan Basin. These unconformably overlie Mesoproterozoic to early Neoproterozoic basement rocks of the Zambezi and Irumide Belts. The sedimentary rocks were deposited in an extensional basin sometime between c. 870 and c. 825 Ma. Primary, diagenetically controlled stratabound Cu–Co mineralization consists predominantly of chalcopyrite and bornite, with accessory chalcocite and pyrite. Mineralization may also have been enhanced by the intrusion of abundant syn-diagenetic mafic sills dated at c. 855 and c. 740 Ma. The primary ore has been structurally reworked and upgraded into axial-planar cleavage planes as well as discordant post-folding veins.

Deformation and basin inversion occurred during the 570–520 Ma Damara–Lufilian–Zambezi Orogeny.

The synchronicity as well as similar style and setting of mineralization between Nifty and the African Copperbelt deposits appears to imply a spatial relationship between the two. However, in all reconstructions of Rodinia, the Congo and West Australian Cratons are separated by ~60° of latitude (Fig. 68). It is possible that these reconstructions are incorrect and that both formed part of the same continental-rift sequence during the earliest phase of Rodinia break-up. Alternatively, mineralization may be a direct result of the continental rifting and mafic magmatism process, and thus all rift belts associated with the early break-up of Rodinia could contain significant copper mineralization.

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as in the Rudall Province, Yeneena Basin, and northwestern parts of the Officer Basin, effects of the Petermann Orogeny are much less intense.

In the Musgrave Province, deformation was focused along the northern margin as a series of east-trending shear zones that dissected the deep crust, dividing the province into two main zones, the Fregon and Mulga Park Zones (Fig. 43). The Mulga Park Zone north of the main thrust — the Woodroffe Thrust — is characterized by amphibolite-facies metamorphism, and is structurally dominated by the Petermann Nappe Complex in the Northern Territory.

The Fregon Zone between the Woodroffe Thrust and Mann Fault is considered to be the core of the Petermann Orogen. It is characterized by granulite-facies metamorphism and contains several important faults that were active over short periods up to 1.4 m.y. Of these various shear zones, only the Woodroffe Thrust shows a reverse sense of movement. Pressure–

temperature estimates, combined with the structural evolution of the Fregon Zone, imply uplift and exhumation of crust in the order of 40 km or more, within a crustal-scale, dextral transpressive system (Figs 80–81). Deformation and metamorphism has been dated at c. 570 Ma. North-directed transport was accommodated by the Woodroffe Thrust, and south-directed overthrusting was concentrated along the Mann Fault and wider Davenport–Cockburn Shear Zone. Successive exhumation of this block resulted in the inversion of sedimentary rocks within the Centralian Superbasin, and the deposition of abundant arkose and conglomerate in localized basins that dominate Supersequence 4 — for example the Bloods Range Group that forms the rocks at Kata Tjuta and Uluru in the Northern Territory. Prolonged contractional deformation and low-grade metamorphism associated with the Petermann Orogeny, presumably in the c. 550 to c. 530 Ma period, resulted in the continued folding and thrusting of these foreland-basin deposits.

Figure 80. Deformed leucosome containing coarse (centimetre-scale) garnet porphyroblasts, Spaghetti Hill, west Musgrave Province

Gascoyne Province

In the western part of Proterozoic Australia, rocks of the Gascoyne Province and overlying Edmund and Collier Basins were dissected by an anastomosing network of brittle to brittle–ductile faults and shear zones during the Mulka Tectonic Event (Figs 2, 3). They commonly have well-developed dextral strike-slip shear-sense indicators, and dextrally offset mafic dykes of the c. 755 Ma Mundine Well Dolerite Suite. Although individual fault offsets are mainly in the order of 1 to 10 m, cumulative movements of up to ~35 km occur across major crustal structures such as the Chalba and Ti Tree Shear Zones, within which Mulka-age faults are concentrated. ^{40}Ar/^{39}Ar dating of muscovite from coarse-grained C-planes within one of the shear zones

provides a date of c. 570 Ma, indicating major dextral movements during the early parts of the Petermann Orogeny.

The youngest tectonic events in the Petermann Orogeny are in the Leeuwin Inlier of the Pinjarra Orogen. Metagranitic rocks emplaced between c. 750 and c. 720 Ma were metamorphosed in the granulite facies at c. 520 Ma during the Leeuwin Orogeny (Figs 2, 3). The structural evolution of these gneisses demonstrates that they were subjected to three major phases of ductile, progressive deformation, all of which were synchronous with high-grade metamorphism.

Pinjarra Orogen

South **North**

WOODROFFE THRUST (WT)

Low-grade synorogenic metamorphism; well-preserved pre-channel deformation

Top-to-hinterland shear

Pervasively deformed high-strain orogenic core; high-grade metamorphism and migmatization (700–800°C; 1000–1400 MPa)

WANKARI DETACHMENT ZONE (WDZ)

PILTARDI DETACHMENT ZONE (PDZ)

PETERMANN NAPPE COMPLEX

Discrete upper crustal shear zones; low-grade synorogenic metamorphism (≤640°C; ≤650 MPa)

BLOODS BACKTHRUST ZONE (BBZ)

MANN FAULT

Shear-strain distribution

620–730°C 900–1200 MPa

Present-day erosion level

Foreland basin

Top-to-foreland shear

⊗ Fault movement away from observer
⊙ Fault movement towards observer

●➔ Schematic velocity vector

Channel flow zone

Amadeus Basin

Musgrave Province

Figure 81. Conceptual cross section through the western margin of the Petermann Orogen (modified from Raimondo et al. , 2009). Location of cross section shown on Figure 43

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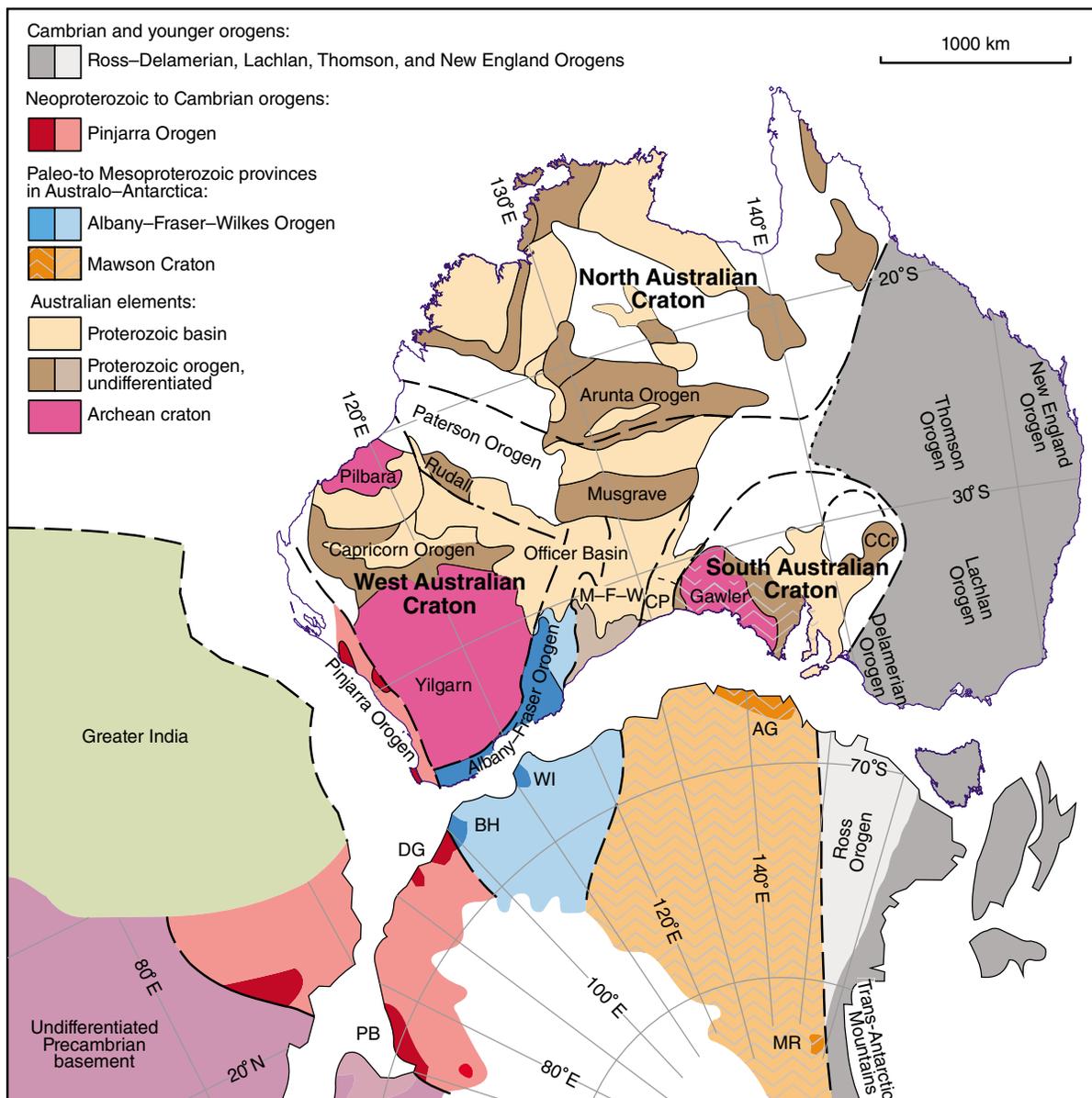
Figure 82. *Tectonic map of eastern Gondwana showing the continuity of tectonic belts across the present-day continental margins (modified from Fitzsimons, 2003; Geoscience Australia,1998; Tyler, 2005).*
Abbreviations: AG, Terre Adélie – King George V Land; BH, Bunger Hills; CCr, Curnamona Craton; CP, Coompana Province (concealed by the Officer and Eucla Basins); DG, Denman Glacier region; M–F–W, Madura, Forrest, and Waigen Provinces (undivided; concealed by the Gunbarrel, Officer, and Eucla Basins); MR, Miller Range; PB, Prydz Bay; WI, Windmill Islands

Early subvertical shortening led to subhorizontal east–west shortening, and then north-northwest contractional deformation, the latter of which may have been synchronous with major sinistral strike-slip movements on the Darling Fault. Neoproterozoic deformation of the Leeuwin Inlier, including its extension into the Prydz Bay and Denman Glacier regions of Antarctica, has been interpreted to be the result of continental collision between India and Proterozoic Australia (Fig. 82).

The final stages of the Petermann Orogeny mark some of the youngest tectono-metamorphic episodes associated with Gondwanan amalgamation, implying that Proterozoic Australia was one of the last continental blocks to amalgamate into the supercontinent.

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Maps of Western Australia

Tectonics of Western Australia

Geology of Western Australia

Proterozoic mineralization — selected highlights

Localities in Western Australia

TECTONICS

Legend

Age (Ma)

0	**PHANEROZOIC**
1000	**NEOPROTEROZOIC**
	MESOPROTEROZOIC
2000	**PALAEOPROTEROZOIC**
3000	**ARCHEAN**
4000	

Sedimentary and volcanic rocks
Igneous and metamorphic rocks
Granite/greenstone rocks

CAPRICORN OROGEN — Overprint patterns are used to define the extent of each orogen

Map labels

Northern Bonaparte Basin

Browse Basin

Kimberley and Speewah Basins

Bastion Basin

Mount House Group

Southern Bonaparte Basin

Carr Boyd Basin

Ord Basin

KING LEOPOLD OROGEN

Lamboo Province

HALLS CREEK OROGEN

Louisa Basin

Wolfe Creek Basin

Browns Range Dome

Birrindudu Basin

GRANITES–TANAMI OROGEN

Roebuck Basin

Northern Carnarvon Basin

Canning Basin

Murraba Basin

PILBARA CRATON

Yeneena Basin

Rudall Province

ARUNTA OROGEN

Hamersley, Fortescue, and Turee Creek Basins

Manganese Group

PATERSON OROGEN

Ashburton Basin

Bresnahan Basin

Sylvania Inlier

Officer Basin

Amadeus Basin

Gascoyne Province

Edmund Basin

Collier Basin

Scorpion Group

Salvation Group

Gunbarrel Basin

CAPRICORN OROGEN

Southern Carnarvon Basin

Marymia Inlier

OROGEN

Earaheedy Basin

Bryah and Padbury Basins

Yerrida Basin

Musgrave Province

PATERSON OROGEN

Badgeradda Group

NARRYER TERRANE

Northampton Inlier

PINJARRA OROGEN

Officer Basin

YILGARN CRATON

Mullingarra Inlier

YOUANMI TERRANE

EASTERN GOLDFIELDS SUPERTERRANE

Murchison Domain

Southern Cross Domain

Yandanooka Group

Moora Group

Eucla Basin

Perth Basin

Woodline Formation

Cardup Group

SOUTH WEST TERRANE

onshore Eucla Basin

Biranup Zone

FRASER OROGEN

Nornalup Zone

Leeuwin Inlier

PINJARRA OROGEN

Stirling Range Formation

Mount Barren Group

ALBANY OROGEN

Biranup Zone

Nornalup Zone

Eucla Basin

200 Km

NORTHERN TERRITORY

SOUTH AUSTRALIA

Age (Ma)

0 5 100 500 1000 2000 3000 3700

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

GEOLOGY

200 km

125°   129°

115°   120°   125°   129°

−15°

−20°

−25°

−30°

Proterozoic mineralization — selected highlights

⬤ PRECIOUS METAL

9   Citadel: Significant intersections at Corker include 0.13 m at 772.0 g/t Ag, 14.8% Pb, 1.86% Zn, 0.85 g/t Au, 0.52% Bi and 231.5 g/t Te. Calibre is a significant new Au–Cu deposit, with a principal intersection of 75.7 m at 0.73 g/t Au, 0.42% Cu, within 225.6 m at 0.50 g/t Au, 0.22% Cu and with some intersections of significant W. (Antipa Minerals Ltd)

20   Glenburgh: Drilling program of 40 000 m underway for feasibility study, with a substantial resource growth and exploration component. Current resource base is 17.4 Mt at 1.3 g/t Au. Early results at Zone 126 are 14 m at 5.9 g/t Au from 287 m downhole. (Gascoyne Resources Ltd)

23   Halloween: Initial drilling gave best 10 m at 3.56 g/t Au from 84 m, including 2 m at 10.4 g/t Au, testing gold–copper soil anomalies in the VHMS-prospective volcanic rocks that host DeGrussa. Au is associated with strong silica–carbonate–epidote–pyrite alteration with up to 25% disseminated/stringer pyrite and trace chalcopyrite. (Talisman Mining Ltd)

23   Hermes: Deeper drilling below the existing ~200 000 oz resource gave intersections such as 8 m at 24.75 g/t Au from 126 m below Trapper. (Alchemy Resources Ltd)

12   Paulsens: Best recent drilling at Belvedere gave 8 m at 14.7 g/t Au and 47 g/t Ag (including 4 m at 29 g/t Au and 91 g/t Ag). Results extend known mineralization, potential to grow maiden 18 000 oz resource. (Northern Star Resources Ltd)

32   Plumridge (Corvette): 3 m at 40.33 g/t Au from 97 m at Camaro prospect in the Albany–Fraser Orogen. (Corvette Resources Ltd)

27   Ruby Well: RC drill results include 4 m at 49.46 g/t Au from 40 m in a shear zone not associated with historic workings. More assays of 1 m at 77.6 g/t Au from 43 m at Ruby Anna prospect and 1 m at 65.3 g/t Au from 26 m at Bloodstone prospect. (Rubiana Resources Ltd)

30   Tropicana: A world-class deposit, discovered in 2002, has grown rapidly to become the fourth-largest gold deposit in Western Australia (after Boddington, Telfer, and the Golden Mile). Project resources total 118 Mt at an average grade of 2.08 g/t Au for 7.9 million ounces of contained gold. (Anglo Gold Ashanti Ltd)

31   Tropicana East: Spectacular gold intercepts from Hercules in shallow aircore drilling, with 15 m at 24.8 g/t Au from 50 m. Mineralization in NE-trending shear zone with quartz veining and strong alteration. (Beadell Resources Ltd)

⬤ IRON

34   Southdown: Successful completion of prefeasibility study. Construction cost of $2.57 billion for a 10 Mtpa of high-grade magnetite concentrate. (Grange Resources Ltd)

⬤ URANIUM

21   Kangaroo Ridge – Yarlarweelor: Recent drilling gave 35 m at 503 ppm U_3O_8 including 5 m at 1069 ppm U_3O_8 with uraninite, minor pyrite, pyrrhotite and magnetite in biotite–quartz–carbonate–chlorite schists in shear zones in granite. (FYI Resources Ltd)

10   Kintyre: New mineral resource announced in March 2011. Combined indicated and inferred resources total 5.7 Mt at 4800 ppm U_3O_8 for 61.7 Mlbs U_3O_8. A further 40 holes drilled to test the very high grade vein-style pitchblende mineralization at depth. (Cameco Australia, Mitsubishi Development Pty Ltd)

⬤ STEEL ALLOY METAL

26   Earaheedy: Significant drilling intersections at Red Lake are 5 m at 34.8% Mn, 6 m at 24.1% Mn, and 3 m at 32.6% Mn. (Zenith Minerals Ltd)

13   Flanagan Bore: Significant intersections from Little Richard prospect include 37 m at 12.8% Mn in manganiferous shale. (Consolidated Global Investments Ltd)

33   Nova: Discovery of nickel–copper mineralization at Nova in Fraser Range defines a new Ni–Cu province in the Albany–Fraser Orogen. Intersections include 64 m at 2.48% Ni and 0.95% Cu from 279 m, with encouraging metallurgy. (Sirius Resources NL)

11   South Woodie Woodie: Maiden resources for Contact and Contact North have combined inferred resource of 11.3 Mt at 15.0% Mn and 15.2% Fe. (Spitfire Resources Ltd)

2   Speewah: Australia's largest V–Ti deposit, with a resource of 4711 Mt at 0.3% V_2O_5 and 2% Ti in a layered mafic intrusion. (Speewah Metals Ltd)

18   Yanneri Ridge – Butcherbird: Maiden resource of 48.8 Mt at 11.8% Mn covers only one of six deposits discovered to date. (Montezuma Mining Company)

⬤ SPECIALITY METAL

7   Browns Range: Initial JORC indicated resource for Wolverine is 1.44 Mt at 0.73% TREO, dominated by high value HREE (89% of TREO), averaging 728 ppm Dy_2O_3 and 4739 ppm Y_2O_3. (Northern Minerals Ltd)

8   Cummins Range: Upgraded inferred resource of 4. 9 Mt at 1.74% TREO, 11.2% P_2O_5, with potential 145 ppm U_3O_8, 48 ppm Th. (Navigator Resources)

4   Hastings–Brockman: Scoping study confirms that the REE resource can be mined by open-cut methods over 25 years, based on resources of 36.2 Mt at 0.21% TREO. Ore would be processed on-site, with annual production exceeding 10 000 t.(Hastings Rare Metals Ltd)

3   John Galt: Follow-up sampling at the John Galt Main Zone has returned assays up to 42.1% TREO with up to 95% HREO. High-grade mineralization (up to 31.7% TREO) found in talus (scree) at the base of the Main Zone ridge — a new exploration target. In the NE, rock-chip assays returned up to 18.6% TREO from Gadolin and 1.4% TREO from Ytterby. (Northern Minerals Ltd)

16   Yangibana: Rock-chip sampling of ironstone lenses confirmed significant REE content, up to 12.8% TREO, with an average of 1.7–2.0% TREO. (Hastings Rare Metals Ltd)

⬤ BASE METAL

24   DeGrussa/Doolgunna: Stage 2 open pit completed in April 2013. Ramp-up of underground mine on schedule to complete the transition to wholly underground operations.   First production in June 2012 quarter. In 2012, second biggest producer of copper (39 773 t) in WA. Total probable reserves for DeGrussa, Conductor 1, and Conductor 4 volcanogenic massive sulfide deposits are 9.59 Mt at 5.1% Cu, 1.7 g/t Au, and the total measured, indicated, and inferred resources of the project are 11.91 Mt at 5.3% Cu and 1.8 g/t Au excluding stockpiles. (Sandfire Resources NL)

22   Horseshoe Lights: New total resources of 8.4 Mt at 1.06% Cu and 0.13 g/t Au (91 040 t Cu; 37 400 oz Au). Subsequent drilling returned thick, shallow, high-grade Cu mineralization at Motters Zone. (Horseshoe Metals Ltd)

17   Ilgarari: Maiden JORC inferred resource for the Ilgarari deposit of 1.108 Mt at 1.89% Cu, at a cut-off grade of 0.5% Cu. (Kumarina Resources Ltd)

5   Koongie Park: Sandiego deposit contains total indicated and inferred resources of 3.95 Mt at 3.8% Zn, 1.5% Cu. Onedin deposit contains an indicated resource of 4.46 Mt at 3.24% Zn and 0.81% Cu. Recent drillhole SRC061 at Sandiego intersected 71 m at 5.04% Cu, 7.69% Zn, 68 g/t Ag, and 0.43 g/t Au. (Anglo Australian Resources NL)

19   Kumarina: Significant intersections at Rinaldi prospect include 14 m at 4.4% Cu from 33 m, and 12.4 m at 1.1% Cu from 77.6 m. (Horseshoe Metals Ltd)

1   McLarty Range: Intersection of 7 m at 1.02% Cu, 0.65 g/t Ag at Bowerbird prospect suggests a new copper province, possibly characterized by Proterozoic sedimentary–exhalative and/or replacement mineralization. (Pegasus Metals Ltd)

6   Mt Angelo North: Thick intersection of 64 m at 2.72% Cu, 62 m at 2.41% Cu, 38 m at 2.65% Cu, plus 13 m at 6.74% Zn and 15 m at 6% Zn. Mineralization comprises massive and stringer copper sulfides characteristic of VHMS mineralization. (Cazaly Resources Ltd)

14   Mount Webb: Cu–Ag–Au–Pd association, perhaps of IOCG style. Broad drill intersections at Pokali prospect include 246 m at 0.22% Cu from 4 m, as well as 299 m at 0.10% Cu from surface. (Ashburton Minerals Ltd, 2010)

29   Northampton: Impressive intersections of 46 m at 5.7% Pb from 31 m, and 42 m at 3.4% Pb from 23 m at Mary Springs, and a new indicated and inferred resource of 394 419 t at 6.5% Pb. (Ethan Minerals Ltd)

15   Prairie Downs: Drilling at Wolf Prospect yielded further thick and high-grade intersections; 129 m at 1.6% Zn, including 17.4 m at 4.5% Zn and 124 m at 1.3% Zn. Host rocks have strong hematite–chlorite alteration within silicified volcaniclastic sedimentary rocks. (Prairie Downs Metals Ltd)

25   Thaduna / Ventnor: Maiden indicated and inferred JORC resource of 1.891 Mt at 1.34% Cu and 2.2 g/t Ag for Green Dragon deposit, and a new indicated and inferred resource of 4.355 Mt at 1.7% Cu and 3.1 g/t Ag for the Thaduna deposit. (Ventnor Resources Ltd)

28   Tollu prospect: Cu–Co mineralization related to a gabbroic intrusive of the Giles Complex. Chalcopyrite intersected in a reverse circulation hole with assays of 14 m at 3.5% Cu from 126 m, including 3 m at 0.14% Co from 130 m. (Redstone Resources Ltd)

11   Yeneena: Encouraging intersections at BM7 (34 m at 0.64% Cu, 793 ppm Co from 156 m, including 10 m at 1.64% Cu) and BM2 (26 m at 0.6% Cu from 100 m). (Encounter Resources Ltd)

Abbreviations: Mlbs, million pounds; Mt, million tonnes; pa, per annum; HREE, heavy rare earth elements; HREO, heavy rare earth oxides; REE, rare earth elements; TREO, total rare earth oxides

Legend

- Alumina
- Base metal
- Construction
- Energy
- Iron
- Precious metal
- Precious mineral
- Speciality metal
- Steel alloy metal

Port
- Operating
- Proposed

- Mine, deposit, or prospect
- Proterozoic mineralization — selected highlights

HIGHLIGHTS

1 McLarty Range
2 Speewah
3 John Galt
4 Hastings–Brockman
5 Koongie Park
6 Mt Angelo North
7 Browns Range
8 Cummins Range
9 Citadel
10 Kintyre
11 Yeneena, South Woodie Woodie
12 Paulsens
13 Flanagan Bore
14 Mount Webb
15 Prairie Downs
16 Yangibana
17 Ilgarari
18 Yanneri Ridge – Butcherbird
19 Kumarina
20 Glenburgh
21 Kangaroo Ridge – Yarlarweelor
22 Horseshoe Lights
23 Halloween, Hermes
24 DeGrussa / Doolgunna
25 Thaduna / Ventnor
26 Earaheedy
27 Ruby Well
28 Tollu prospect
29 Northampton – Mary Springs
30 Tropicana
31 Tropicana East
32 Plumridge (Corvette)
33 Nova
34 Southdown

Place names / Ports

Wyndham
Point Torment
Derby
Broome
Argyle Village
Fitzroy Crossing
Halls Creek
Port Hedland
Anketell
Cape Lambert
Dampier
Cape Preston
Onslow
Ashburton North
Exmouth
Marble Bar
Nullagine
Tom Price
Paraburdoo
Newman
Cape Cuvier
Carnarvon
Wingelinna
Shark Bay
Meekatharra
Wiluna
Cue
Northampton
Kalbarri
Yalgoo
Laverton
Leonora
Oakajee
Geraldton
Eneabba
Koolyanobbing
Kalgoorlie–Boulder
Kambalda
Meckering
PERTH
Fremantle
Kwinana
Boddington
Norseman
Bunbury
Busselton
Ravensthorpe
Margaret River
Augusta
Mount Barker
Esperance
Albany

NORTHERN TERRITORY
SOUTH AUSTRALIA

200 km

LOCALITIES

Legend

Wiluna ● Town
Ellendale □ Homestead/community
Eyre ○ Locality
— Major road
Watercourse
Lake

Commodities
- ● Base metal
- ○ Construction
- ● Energy
- ● Iron
- ● Precious metal
- ○ Precious mineral
- ● Speciality metal
- ● Steel alloy metal

INDIAN OCEAN

Cape Bougainville
Bonaparte Archipelago
Joseph Bonaparte Gulf
MITCHELL PLATEAU
Wyndham
Kimberley Research Station
Yampi Sound
Collier Bay
Cape Leveque
Speewah
Lake Argyle
Argyle
Argyle Village
John Galt
Savannah
Copernicus
Panton
Halls Creek
Hastings–Brockman
Derby
Aries
Ellendale
Ellendale
James Price Pt
Broome
Roebuck Bay
Fitzroy Crossing
Koongie Park
Pillara
Mt Angelo North
GREAT ANTRIM PLATEAU
Browns Range
Kapok West
Cummins Range
Wolfe Creek Crater
Kookaburra Sandpiper
Coyote
Fitzroy River
Eighty Mile Beach
NORTH WEST SHELF
De Grey River
GREAT SANDY DESERT
TANAMI DESERT
NORTHERN TERRITORY
Citadel
Port Hedland
Karratha
Pt Samson
Cape Lambert
Burrup Peninsula
Dampier
Roebourne
Barrow Is
Marble Bar
Nifty
Telfer
Nullagine
Yeneena, South Woodie Woodie
Kintyre
Rudall River
North West Cape
Exmouth
Learmonth
Paulsens
Robe River
Mt Brockman
HAMERSLEY RANGE
Mt Bruce
Fortescue River
Tom Price
Mt Meharry
Mt Newman
Flanagan Bore
Newman
Paraburdoo
Ashburton River
Hardey River
Mount Webb
GIBSON DESERT
Lake Disappointment
Tjukurla
Ningaloo Reef
ROUGH R.
Exmouth Gulf
Turee Ck
Yangibana
Prairie Downs
Mt Augustus
Ilgarari
Yanneri Ridge – Butcherbird
Kumarina
Warakurna Roadhouse
Carnarvon
Yinnietharra
Abra
Fortnum
Labouchere
Horseshoe Lights
Kangaroo Ridge –
Yarlarweelor
DeGrussa/Doolgunna
Thaduna / Ventnor
Red Bore
Earaheedy
Wingelinna
Nebo–Babel
Tollu prospect
Shark Bay
Gascoyne River
Glenburgh
Harmony
Peak Hill
Magnus–Wilgeena
Halloween, Hermes
Ruby Well
Paroo Station Lead
Wiluna
Lake Canegie
Dirk Hartog Is
Faure Sill
Murchison River
Meekatharra
Lake Way
GREAT VICTORIA DESERT
Steep Point
Zuytdorp Point
Hamelin Pool
Cue
Kalbarri
Northampton – Mary Springs
Lake Austin
Irwin River
Yalgoo
Windimurra
Laverton
Tropicana
Tropicana East
Geraldton
Oakajee
Pelsaert Group
Lake Barlee
Lake Raeside
Lake Ballard
Lake Carey
Leonora
Tjuntjuntjara
Eneabba
Houtman Abrolhos
Lake Moore
Mt Manning Range
Plumridge (Corvette)
NULLARBOR PLAIN
SOUTH AUSTRALIA
The Pinnacles
Koolyanobbing
Kalgoorlie–Boulder
PERTH
Fremantle
Kwinana
Rottnest Is
Meckering
DARLING RANGE
Kambalda
FRASER RANGE
Nova
Garnet
Ice
Gold Leaf Black
Verde
Austral
Eyre
Roe Plains
Boddington
Lake Cowan
Norseman
Lake Hope
Lake Dundas
GREAT AUSTRALIAN BIGHT
Bunbury
Cape Naturaliste
Saddleback Hill
Ravensthorpe
Busselton
Margaret River
Esperance
Archipelago of the Recherche
Augusta
Cape Leeuwin
STIRLING R.
Mount Barker
Southdown
Point D'Entrecasteaux
Albany
King George Sound
INDIAN OCEAN

200 km

Index to Localities map

Name	Category	Ref
Abra	Pb Cu Zn Au Ba	E7
Albany	Town	D12
Archipelago of the Recherche		
Argyle	Dmd	J3
Argyle Village	Town	J3
Aries	Dmd	I3
Ashburton River		E7
Augusta	Town	C12
Babel (Nebo–Babel)	Ni Cu PGE Co Au	I8
Barrow Island		C5
Boddington	Town	D11
Bonaparte Archipelago		H2
Broome	Town	G3
Browns Range	REE (heavy)	J4
Bunbury	Town	C11
Bungle Bungle Range		J3
Burrup Peninsula		D5
Busselton	Town	C11
Cape Bougainville		I1
Cape Lambert		D5
Cape Leeuwin		C12
Cape Leveque		G3
Cape Naturaliste		C11
Carnarvon	Town	B7
Citadel	Pb Zn Au Ag Bi Te	G5
Collier Bay		H3
Copernicus	Ni Cu Co	I3
Coyote	Au	J4
Cue	Town	D8
Cummins Range	REE Phos U Th	I4
Dampier	Town	D5
Darling Range		D11
De Grey River		E5
DeGrussa/Doolgunna	Cu Au Ag Zn Pd	E7
Derby	Town	G3
Dirk Hartog Island		B7
Earaheedy	Mn	F7
Eighty Mile Beach		F4
Ellendale 4	Dmd	H3
Ellendale	Homestead	H3
Eneabba	Town	C9
Esperance	Town	F11
Exmouth Gulf		C6
Exmouth	Town	C5
Eyre	Locality	I11
Faure Sill		C7
Fitzroy Crossing	Town	H4
Fitzroy River		H4
Flanagan Bore	Mn	F6
Fortescue River		D5

Name	Category	Ref
Fortnum	Au	E7
Fraser Range		G11
Fremantle	Town	C11
Garnet Ice	Gran	G11
Gascoyne River		C7
Geraldton	Town	C9
Gibb River		I3
Gibson Desert		H7
Glenburgh	Au	D7
Gold Leaf Black	Gran	G11
Great Antrim Plateau		J4
Great Australian Bight		I11
Great Sandy Desert		I5
Great Victoria Desert		H8
Halloween	Au Ag Cu	E7
Halls Creek	Town	I4
Hamelin Pool		C8
Hamersley Range		D6
Hardey River		D6
Harmony	Au	E7
Hastings–Brockman	REE (light)	I4
Hermes	Au	E7
Horseshoe Lights	Cu Au Ag	E7
Houtman Abrolhos	Islands	B9
Ilgarari	Cu	E7
Indian Ocean		C4
Irwin River		C9
James Price Point		G3
John Galt	REE (heavy)	J3
Joseph Bonaparte Gulf		J2
Kalbarri	Town	C8
Kalgoorlie–Boulder	Town	F10
Kambalda	Town	F10
Kangaroo Ridge – Yarlarweelor	U	E7
Kapok West	Pb Zn Ag	H4
Karratha	Town	D5
Kimberley Research Station		J2
King George Sound		E12
King Sound		G3
Kintyre	U	G6
Kookaburra	Au	J4
Koolyanobbing	Town	E10
Koongie Park	Cu Ag Au	I4
Kumarina	Cu	E7
Kwinana	Town	C11
Labouchere	Au	E7
Lake Argyle		J3
Lake Austin		E8
Lake Ballard		F9
Lake Carey		G9

Name	Category	Ref
Lake Carnegie		G8
Lake Cowan		F10
Lake Disappointment		G6
Lake Dundas		F11
Lake Hope		F11
Lake MacLeod		B7
Lake Moore		D10
Lake Raeside		F9
Lake Way		F8
Laverton	Town	G9
Learmonth	Town	C6
Leonora	Town	F9
Magnus–Wilgeena	Au	E7
Marble Bar	Town	E5
Margaret River	Town	C11
McLarty Range	Cu	H3
Meckering	Town	D10
Meekatharra	Town	E8
Mitchell Plateau		H2
Mount Augustus		D7
Mount Barker	Town	D12
Mount Brockman		D6
Mount Bruce		E6
Mount Manning Range		E9
Mount Meharry		E6
Mount Newman		E6
Mount Angelo North	Cu Zn	I4
Mount Webb	Cu Ag Au Pd	J6
Murchison River		D7
Newman	Town	E6
Nifty	Cu	F5
Ningaloo Reef		B6
Norseman	Town	F11
Northampton – Mary Springs	Pb Zn Au Ag Bi	C8
North West Cape		C5
North West Shelf	Offshore	G2
Nova	Ni Cu	G11
Nullagine	Town	F5
Nullarbor Plain		I10
Oakajee	Port	C9
Ord River		J3
Panton	Pt Pd Au Ni Cu	I3
Paraburdoo	Town	D6
Paroo Station Lead (Magellan)	Pb	E8
Paulsens	Au	D6
Peak Hill	Au	E7
Pelsaert Group	Islands	C9
Perth	City	C10
Pillara	Zn Pb	H4
Plumridge (Corvette)	Au	H10
Point D'Entrecasteaux		C12
Point Samson		D5

Name	Category	Ref
Port Hedland	Town	E5
Prairie Downs	Zn	E6
Ravensthorpe	Town	F11
Red Bore	Pb Cu Zn	E7
Robe River		C5
Roebourne	Town	D5
Roebuck Bay		G4
Roe Plains		I11
Rottnest Island		C10
Rough Range		C6
Ruby Well	Au	E7
Rudall River		G6
Saddleback Hill		D11
Sandpiper	Au	J4
Savannah	Ni Cu Co	J3
Shark Bay		B7
Southdown	Fe (magnetite)	E12
South Woodie Woodie	Mn	F6
Speewah	V Ti	I3
Steep Point		B8
Stirling Range		D12
Tanami Desert		J5
Telfer	Au Cu Ag	G5
Thaduna/Ventnor	Cu Ag	E7
The Pinnacles	Desert	C10
Tjukurla	Community	J7
Tjuntjuntjara	Community	I9
Tollu	Cu Co	J8
Tom Price	Town	D6
Tropicana	Au	H9
Tropicana East	Au	H9
Turee Creek	Homestead	E6
Verde Austral	Gran	G11
Warakurna Roadhouse		J7
Wiluna	Town	F8
Windimurra	Homestead	E9
Wingelinna	Town	J8
Wolfe Creek Crater		I4
Wyndham	Town	J2
Yalgoo	Town	D9
Yampi Sound		G3
Yangibana	REE	D6
Yanneri Ridge – Butcherbird	Mn	E7
Yeneena	Cu Ag Co	F6
Yinnietharra	Homestead	D7

Abbreviations:

Dmd, Diamonds; Gran, stone quarry; REE, rare earth elements;
    Phos, phosphate

About this book

At last, here is the definitive geological history of Western Australia during the Proterozoic.

The Proterozoic Eon — between 2500 Ma and 541 Ma — spans nearly two billion years of Earth history and represents a time of great change for Earth-systems processes. The geology of Western Australia records an almost uninterrupted history of Proterozoic tectonics, including the assembly and dispersal of the Archean cratons into global-scale supercontinents, as well as world-wide glaciations or 'Snowball Earth' events. By the end of the Proterozoic Western Australia was starting to take on a very familiar outline.

This book is the first under the banner of *Western Australia Unearthed*, a series that will progressively chronicle the geological evolution of Western Australia.