A Paleozoic perspective of Western Australia

by

Arthur J Mory

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

Geological Survey of Western Australia

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with contributions from Yijie Zhan, Peter W Haines, Roger M Hocking,
Charmaine M Thomas, and Iain A Copp

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Geological Survey of
Western Australia

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Photographs:

Front cover: Cenozoic karst in the Lower Permian Callytharra Formation, Bidgemia Station, Southern Carnarvon Basin

Back cover and adjacent page: (from left to right) Carbonaceous stringers in wave ripples in the Irwin River Coal Measures, northern Perth Basin; a lobe-fish *Onychodus* sp. from the Upper Devonian reef complex, Canning Basin (length of head is 145 mm); honeycomb weathering in the Middle Permian Coolkilya Sandstone, Kennedy Range, Southern Carnarvon Basin; view looking west across a tessellated sandstone surface in the Lower Permian Grant Group, Poole Range, Canning Basin; limestone nodules in the Upper Devonian Gogo Formation, Canning Basin

Preface: Flat-lying sandstone of the Lower Permian Grant Group, looking southwest across Carolyn Valley, central Saint George Ranges, Canning Basin

A Paleozoic perspective of Western Australia

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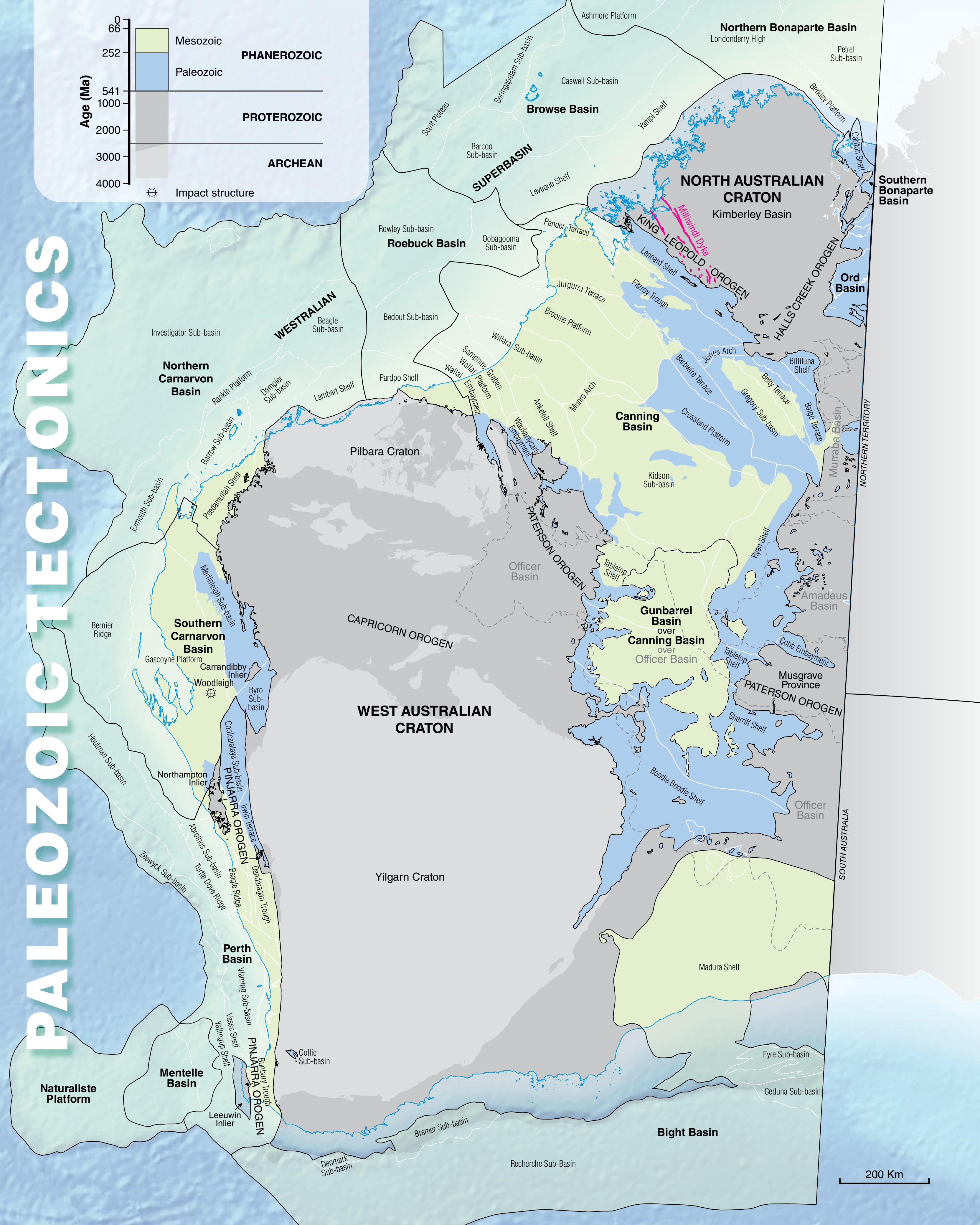
Preface

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

This volume, *A Paleozoic perspective of Western Australia,* is the third of five volumes to be published, following on from *The birth of supercontinents and the Proterozoic assembly of Western Australia* and *Australia goes it alone — the emerging island continent 100 Ma to present*. Two future volumes will cover the Archean cratons of the State and the Mesozoic rocks. These books are aimed at trainee and professional geologists, and particularly newcomers to Western Australia, to provide an introduction to the geology and economic potential of the diverse terrains that make up the State. Each book sets out our current ideas on the geological history of Western Australia, and a list of recommended references is provided for follow-up reading. GSWA has amassed knowledge on the geology and resources of Western Australia over more than 125 years. This book is a summary of that information, which is available through our website — the next step is to access the web: <www.dmp.wa.gov.au/GSWA>.

Rick Rogerson
Executive Director

January 2017



PALEOZOIC TECTONICS
Age (Ma)
0
66
252
541
1000
2000
3000
4000
Mesozoic
Paleozoic
PHANEROZOIC
PROTEROZOIC
ARCHEAN
Impact structure
Ashmore Platform
Northern Bonaparte Basin
Londonderry High
Petrel Sub-basin
Caswell Sub-basin
Seringapatam Sub-basin
Browse Basin
Berkley Platform
Yampi Shelf
Scott Plateau
Barcoo Sub-basin
SUPERBASIN
Carlton Shelf
Southern Bonaparte Basin
NORTH AUSTRALIAN CRATON
Kimberley Basin
Leveque Shelf
Milliwindi Dyke
Pender Terrace
KING LEOPOLD OROGEN
Rowley Sub-basin
Roebuck Basin
Oobagooma Sub-basin
Lennard Shelf
HALLS CREEK OROGEN
Ord Basin
Jurgurra Terrace
Fitzroy Trough
WESTRALIAN
Beagle Sub-basin
Broome Platform
Bedout Sub-basin
Investigator Sub-basin
Willara Sub-basin
Jones Arch
Billiluna Shelf
Samphire Graben
Barbwire Terrace
Betty Terrace
Northern Carnarvon Basin
Rankin Platform
Dampier Sub-basin
Lambert Shelf
Pardoo Shelf
Wallal Platform
Wallal Embayment
Munro Arch
Gregory Sub-basin
Balgo Terrace
Murraba Basin
NORTHERN TERRITORY
Canning Basin
Crossland Platform
Anketell Shelf
Barrow Sub-basin
Waukarlycarly Embayment
Pilbara Craton
Kidson Sub-basin
Peedamullah Shelf
Exmouth Sub-basin
PATERSON OROGEN
Ryan Shelf
Officer Basin
Tabletop Shelf
Merlinleigh Sub-basin
Amadeus Basin
Gunbarrel Basin
over
Canning Basin
over
Officer Basin
Bernier Ridge
Southern Carnarvon Basin
CAPRICORN OROGEN
Cobb Embayment
Gascoyne Platform
Carrandibby Inlier
Tabletop Shelf
Musgrave Province
Woodleigh
Byro Sub-basin
PATERSON OROGEN
WEST AUSTRALIAN CRATON
Sherriff Shelf
Coolcalalaya Sub-basin
Houtman Sub-basin
Northampton Inlier
PINJARRA OROGEN
Boodie Boodie Shelf
Officer Basin
Irwin Terrace
Abrolhos Sub-basin
SOUTH AUSTRALIA
Zeewyck Sub-basin
Turtle Dove Ridge
Beagle Ridge
Dandaragan Trough
Yilgarn Craton
Perth Basin
Madura Shelf
Vlaming Sub-basin
Vasse Shelf
Yallingup Shelf
PINJARRA OROGEN
Bunbury Trough
Collie Sub-basin
Eyre Sub-basin
Mentelle Basin
Naturaliste Platform
Ceduna Sub-basin
Leeuwin Inlier
Bremer Sub-basin
Bight Basin
Denmark Sub-basin
Recherche Sub-Basin
200 Km

Prelude to the Paleozoic

Gondwana assembled along Pangea's southern margin between about 650 and 520 Ma by numerous spatially and temporally distinct collisions, rather than by a single collision between two large pre-assembled continental blocks (Fig. 1). The configuration of continental blocks within Gondwana (see pull-out boxes *Gondwana vs Gondwanaland*, page 2 and *Evidence for Gondwana*, page 4) implies that the supercontinent formed mostly by collisions between dispersing continental fragments from the margins of the older supercontinent Rodinia, which included Proto-Laurasia, Proto-Gondwana, and the smaller Congo Craton.

Within Proterozoic Western Australia, the main tectono-metamorphic events that contributed to the formation of Gondwana were the 650–600 Ma Miles Orogeny and overlapping 635–540 Ma Paterson Orogeny (both in the northeastern Pilbara region), the 670–510 Ma King Leopold Orogeny in the Kimberley region, the 580–520 Ma Petermann Orogeny in central Australia, and the c. 570 Ma Mulka Tectonic Event in the Gascoyne region. Of these events, the ages for the Miles and Petermann Orogenies and Mulka Tectonic Event are well constrained. The final stages of the Petermann Orogeny are some of the youngest tectono-metamorphic episodes associated with the amalgamation of Gondwana, implying that Proterozoic Australia was one of the last continental blocks to be incorporated into the supercontinent. Late events comparable to those at the end of the Petermann Orogeny are recorded in the Leeuwin Inlier and equivalent terranes in the Prydz Bay and Denman Glacier regions of Antarctica. They have been interpreted as the result of continental collision between India and Proterozoic Australia, possibly synchronous with major sinistral strike-slip movement along the Darling Fault System in southwestern Australia.

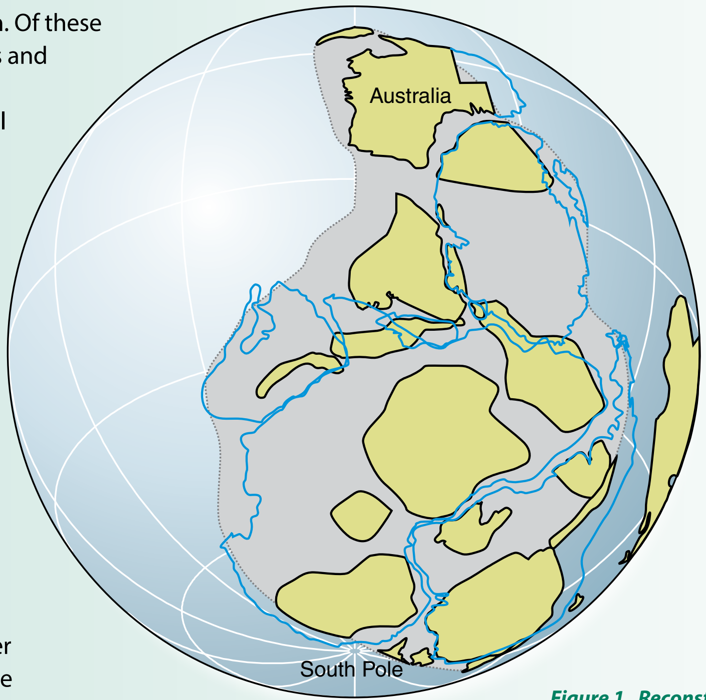


Figure 1. Reconstruction of Gondwana following final assembly at c. 530 Ma (after Collins and Pisarevsky, 2009); Precambrian terranes are green, and present-day continents are outlined in blue

Overview of the Paleozoic

Paleozoic strata are preserved across about 30% of onshore Western Australia (Fig. 2). Igneous rocks, either volcanic or intrusive, are minimal and orogenic events were subdued compared with the Precambrian, leading to little-deformed, largely unmetamorphosed sedimentary successions in both interior and coastal basins. The lower Paleozoic in these basins provides a record of supercontinental stabilization and intracratonic sedimentation. By comparison, tectonism changed dramatically in the Middle Devonian, seemingly related to events along the northern margin of the supercontinent that preceded various blocks (now in Southeast Asia) separating from Gondwana during the Permian. Four main phases of basin evolution are evident, of which the Ordovician – Early Devonian and Middle Devonian – mid-Carboniferous are coeval with the Alice Springs Orogeny in Central Australia:

a) Cambrian intracratonic synorogenesis–sag, probably associated with the Centralian Superbasin (Fig. 2);
b) Ordovician to Early Devonian intracratonic rifting–sag;
c) Middle Devonian to mid-Carboniferous renewed rifting–sag, probably associated with events north of Gondwana; and
d) Latest Carboniferous to Permian rifting and sag, with an east–west component of extension associated with the rifting and separation of the Cimmerian continent and associated blocks from northern Gondwana.

This book details the Paleozoic depositional and structural history of Western Australia illustrated by a series of statewide paleogeographic reconstructions and isopach images based mostly on outcrop and well sections. Correlations between basins (Fig. 3) are constrained by paleontological–biostratigraphic studies (summarized in Fig. 4). The volume concentrates on the onshore successions, as the offshore Paleozoic sequence is generally too deeply buried below Mesozoic and younger strata to be reached by drilling or to be of economic interest: even where seismic reflection surveys effectively image deep offshore Paleozoic successions, their interpretation can be ambiguous due to the lack of well control.

Paleozoic rocks have yielded a significantly smaller proportion of the State's petroleum and mineral resources compared with Precambrian terranes and offshore Mesozoic basins. In the case of mineralization, this is due to the subdued nature of orogenic events and the relative lack of volcanism, whereas for hydrocarbon accumulations many traps with Paleozoic reservoirs may not have been charged, or were breached or flushed during the Mesozoic and Cenozoic. Onshore petroleum exploration of the Paleozoic may be inhibited by issues such as the relative difficulty in acquiring good-quality seismic reflection data, and distance to infrastructure.

Gondwana vs Gondwanaland

Although not fully delineated at the time, the distribution of the Permian gymnosperm *Glossopteris* in India, South America, and Australia was first explained in an 1875 unpublished report by HF Blanford, who invoked an Indo-Oceanic continent that he assumed existed from the Early Permian to the end of the Miocene. In a synthesis of this idea, the Austrian scientist Eduard Suess (in 1885 and 1888) proposed the name 'Gondwána-Land' for the once-united southern continental landmass. The name 'Gondwana' had previously been applied in 1872 by Henry B Medlicott to upper Carboniferous – Mesozoic strata in northern India as the 'Gondwána System', and the term 'Gondwána flora' was used in 1876 by Ottokar Feistmantel for rocks containing *Glossopteris*. Suess presumably added the suffix '-land' to distinguish the supercontinent from strata referred to as the 'Gondwana System' (or 'series'). Although clearly referring to the Gonds, a tribe from northern India first mentioned by Afghan traders around the 11th or 12th century, there has been some debate about the etymology and correct usage of the name for the supercontinent. 'Gondwana' likely means 'land/forest/kingdom of the Gonds' in Sanskrit, and 'Gondwanaland' was at one stage thought to be a tautology. This led delegates at the 5th International Gondwana Symposium, held in 1980 in Wellington New Zealand, to officially adopt the term 'Gondwana' instead. Whatever the reasons, the '-land' suffix is falling from favour: online searches for 'Gondwanaland' typically yield under a tenth of the hits returned by 'Gondwana'.

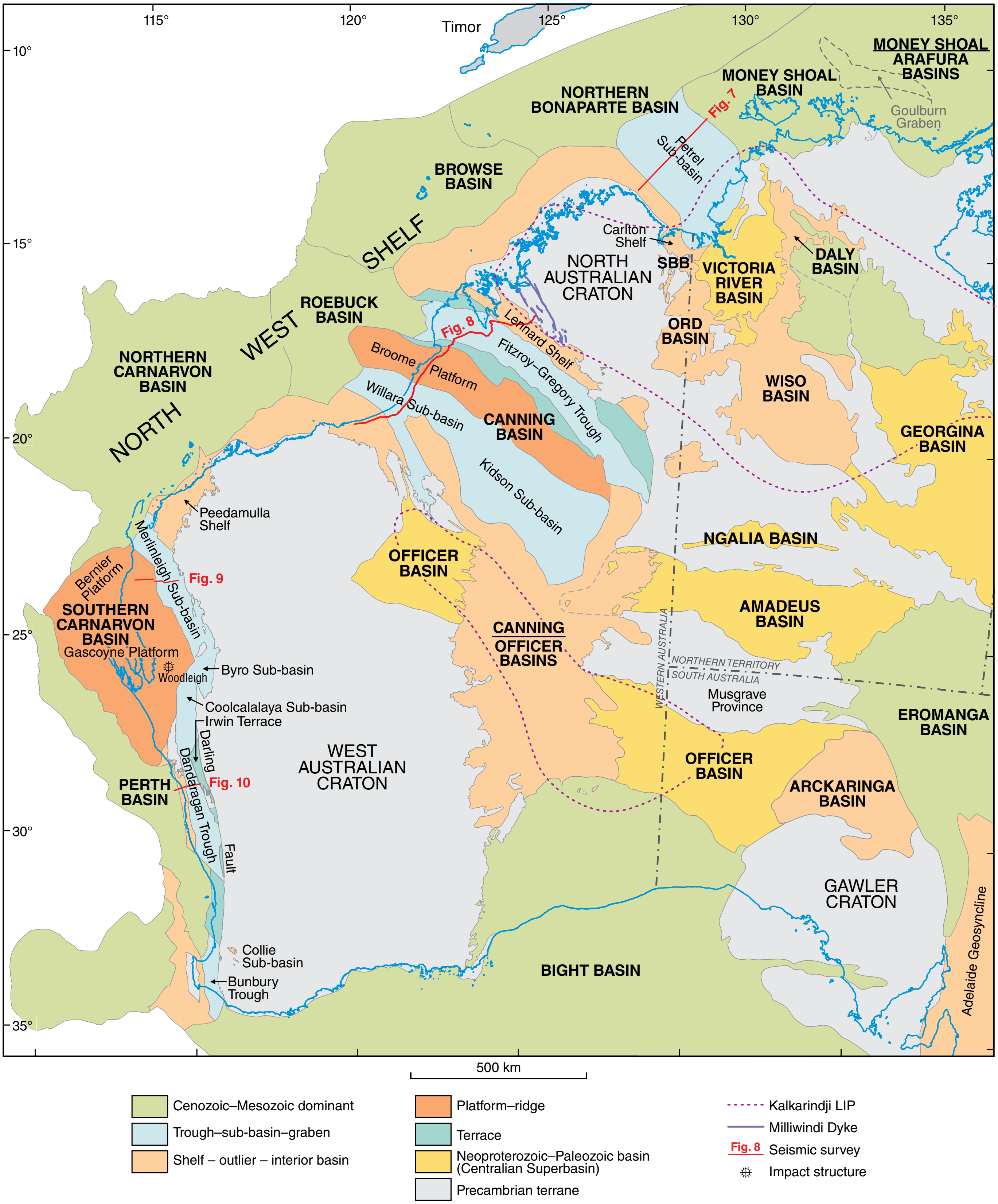


Figure 2. Simplified tectonic elements map of Western Australia emphasizing Paleozoic structure (from Mory and Haines, 2013, fig. 1), and showing the locations of seismic reflection lines. Abbreviations: SBB = Southern Bonaparte Basin; LIP = Large igneous province

Evidence for Gondwana

The main evidence for the existence of Gondwana comes from a combination of how the continents fitted before the present oceanic crust was extruded, plus paleomagnetic, paleobiogeographic and, to a lesser extent, provenance studies. Oceanic crust is seldom older than 200 Ma (Early Jurassic) and is magnetically 'striped' from reversals of the Earth's magnetic poles. The stripes and, in many cases, the geology on adjoining continents (conjugate margins) can be matched across the mid-ocean ridges. Paleomagnetism can track the relative position of continents but there is relatively little such data from Phanerozoic Western Australia, other than recent analyses of Devonian rocks in the Canning Basin. The paleobiogeographic distribution of non-marine species can also show how closely juxtaposed continents were. Lastly, provenance of sedimentary deposits can assist if there is a commonality in mineral assemblages between now widely separated regions, especially if supported by paleocurrent measurements. For example, recent zircon provenance studies on terranes such as Lhasa in Tibet and western Qiangtang in China support previous reconstructions placing these continental fragments outboard of northwestern Australia throughout much of the Paleozoic. There is general agreement on how the major continents fitted within Gondwana, but not on the relative positions of continental fragments along the Tethyan margin and when they separated from Gondwana. Only the southern margin of Australia can be well matched to specific terranes in another continent — in this case Antarctica, which broke away from Australia in the Cretaceous (94–84 Ma).

Biotic evidence for Gondwana

Examples of plant and animal distributions that point to the Gondwanan connection of southern continents include:

- several genera of Givetian—Frasnian (mid-Late Devonian) extinct armoured jawed freshwater fish, restricted to eastern Australia, Antarctica, South America, and Saudi Arabia;
- *Glossopteris*, an extinct genus of the seed ferns (one of the six divisions of the gymnosperms, a group with unprotected seeds) restricted to Permian strata in South America, southern Africa, Madagascar, India, Australia, New Zealand, and the edges of Antarctica;
- *Dicroidium*, a Triassic fork-leaved seed fern genus, in South Africa, Australia, New Zealand, South America, and Antarctica;
- various fossil reptiles such as the genera *Cynognathus* (Early–Middle Triassic) and *Mesosaurus* (Early Permian) in South America and Africa, and *Lystrosaurus* (Late Permian – Early Triassic) in Africa, India, and Antarctica;
- the Proteaceae, which evolved in the Cretaceous, and include Australian banksias, macadamias, and hakeas, and South African proteas;
- marsupials, whose distribution and genetic affinities indicate migration of the group from Asia and North America into South America in the Late Cretaceous, and then across Antarctica to reach Australia in the Paleogene;
- *Nothofagus*, the southern beeches, now extend across South America and Australasia but are recorded only as Eocene fossils in Antarctica; and
- the perching birds or Passerines, which molecular genetics and Eocene fossils indicate evolved in Antarctica and Australia, and then spread across Gondwana prior to their present global distribution.

Such connections do not necessarily suggest that the above groups originated on, and evolved entirely within, the confines of the southern continents. This is particularly true for highly mobile organisms like birds, bats, and insects. Any of these may have obtained global or near-global distributions before their ranges were later changed or confined by complex histories of variance, dispersal, and selective extinction due to climatic and biotic pressures.

Glossopteris sp. from Victoria, Australia

Panthalassa and Pangea

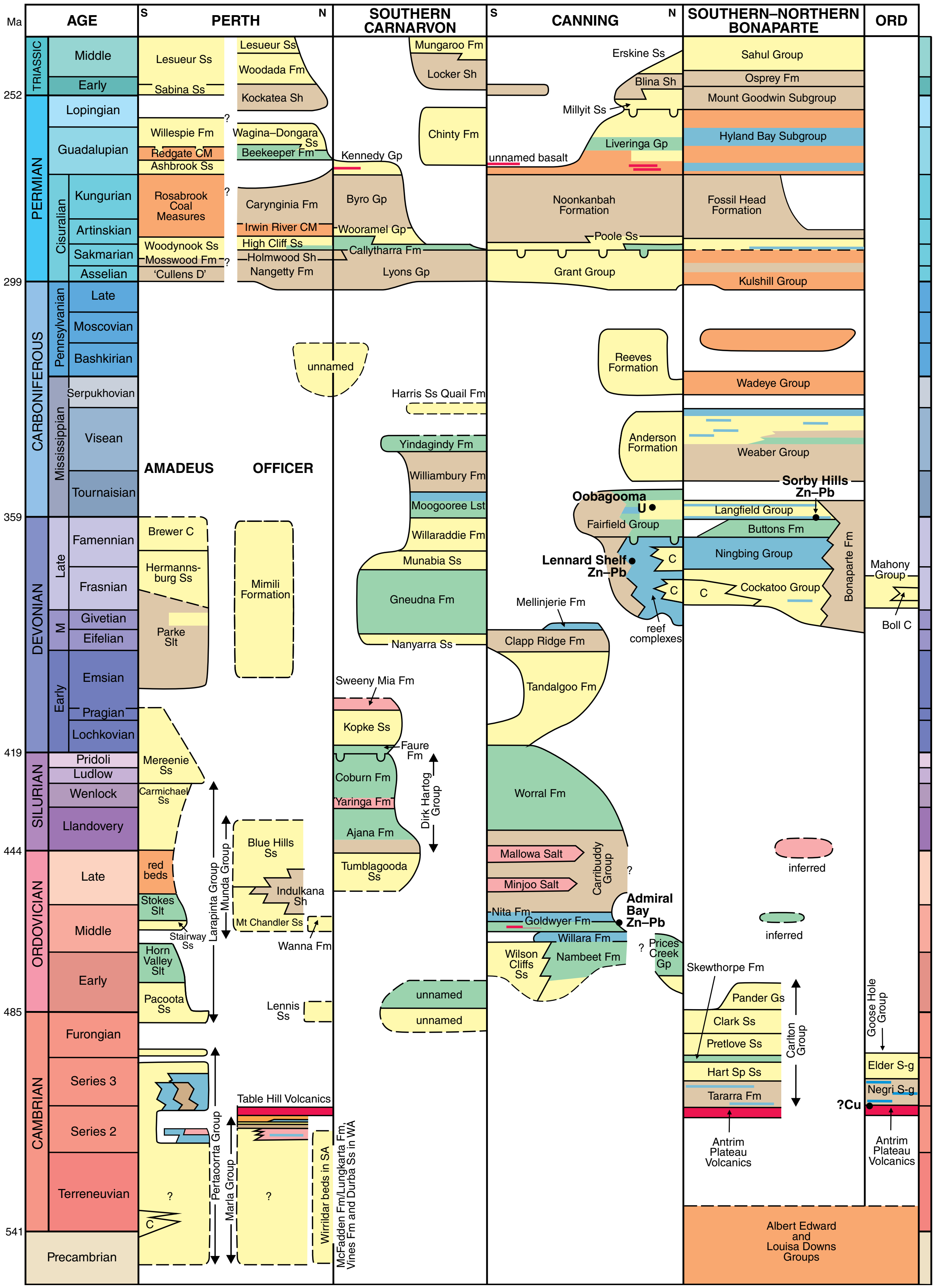
Panthalassa was the ancestral ocean. It surrounded Pangea, the supercontinent formed by the combination of Gondwana and Laurasia following their collision in the late Carboniferous. This collision reflects the late stages of the formation of the Appalachian, Meseta, and Mauritanide Mountains in North America, northwestern Africa, and western Africa, respectively, along the northwestern margin of Gondwana. Pangea began to disassemble in the Triassic when passive rifting between Gondwana and Laurasia commenced, followed by sea-floor spreading in the Jurassic. At that time Panthalassa's oceanic crust was subducted under the North American and Eurasian plates, leading to the development of the Pacific Ocean.

The first general observations on Paleozoic strata in Western Australia were published by Gregory and von Sommer, both in 1849, who reported on 'Carboniferous' fossils (since shown to be Permian) from exposures along the Irwin and Lyons Rivers (in the Perth and Southern Carnarvon Basins respectively). The first significant Paleozoic mineral resources discovered in the State were the Permian coal measures at Collie in 1883, with mining commencing in 1898. It was not until the 1930s that systematic studies of the Paleozoic began in earnest, and included mapping of sedimentary basins for petroleum exploration and paleontological studies, all based on outcrop and limited drilling for water and coal. In the late 1940s and 1950s West Australian Petroleum Pty Ltd (WAPET) and the Australian Bureau of Mineral Resources (BMR, now Geoscience Australia) began systematic mapping of sedimentary basins, mostly at 1:250 000 scale. Much of this work was later incorporated into government publications, in part to encourage petroleum and mineral exploration after World War II, and included systematic paleontological and biostratigraphic studies (see pull-out box, *Dating the Paleozoic*, page 9), geophysical surveys, and BMR stratigraphic and petroleum exploration drilling. The Geological Survey of Western Australia (GSWA) became active in systematic remapping programs in the late 1960s, which became a major thrust of the Survey's work in the 1970s.

Following the furore generated by the initial promising discovery of oil at Rough Range in 1953, early onshore petroleum exploration results were disappointing and this, combined with significant offshore discoveries, inhibited continued onshore investigations, especially of the Paleozoic succession (see pull-out box, *Oil and gas,* page 44). Onshore petroleum activities have been subdued apart from in the Perth Basin, where work since the 1960s has identified significant gas reserves in Permian sandstone reservoirs, and in the Canning Basin where there were several small economic discoveries during the early 1980s and also since the late 2000s. Interest in the Canning Basin waned in the 1990s, but was revived with increasing oil prices in the mid-2000s, the Ungani oil discovery in 2011, and a favourable assessment of the basin for shale-gas resources as part of a worldwide assessment for the United States Department of Energy in 2011. Similarly, exploration for Mississippi Valley-type (MVT) mineralization (see pull-out box, *Lead and zinc mineralization,* page 27) and coal (see pull-out box, *Coal*, page 39) peaked in the 1970s and 1980s with a minor resurgence throughout the 2000s. Even so, much of the Paleozoic in Western Australia has not been systematically or exhaustively explored for hydrocarbons or mineralization — in part because of its remoteness from both infrastructure and markets.

Geothermal energy

Hydrothermal resources are based on low-temperature reservoirs (65–85°C) at depths shallower than 3500 m, whereas hot-rock resources are economic where the depth to 200°C is less than 5 km. The former has direct-heat use applications, such as heating or cooling, whereas the latter can be converted to other forms of energy, such as electricity. Western Australia lacks active geological processes (such as volcanism, rifting, or uplift) to generate geothermal energy at shallow depths. Nevertheless, heat-generating granitic rocks or other basement rocks below the sedimentary basins may provide hydrothermal and hot-rock resources from which geothermal energy could be drawn, especially if overlain by insulating strata such as shale. So far, hydrothermal resources are used only for heating swimming pools in urban parts of the Perth Basin, and at Carnarvon. Other uses incorporating heat pumps, such as regulating temperatures in buildings, are still at the planning stage. Elsewhere, hot-rock resources could be viable, especially where thick Paleozoic shale blankets heat-generating basement rocks. Preliminary evaluation of geothermal data from petroleum exploration wells across the State indicates the most prospective areas are within the northern Perth Basin especially the Beagle Ridge, the onshore Peedamullah Shelf of the Northern Carnarvon Basin, and the central Canning Basin, mostly along the Broome Platform. However, further assessment is required.



Ma
AGE
PERTH
SOUTHERN CARNARVON
CANNING
SOUTHERN–NORTHERN BONAPARTE
ORD
TRIASSIC
Middle
Early
PERMIAN
Lopingian
Guadalupian
Cisuralian
Kungurian
Artinskian
Sakmarian
Asselian
CARBONIFEROUS
Pennsylvanian
Late
Moscovian
Bashkirian
Mississippian
Serpukhovian
Visean
Tournaisian
DEVONIAN
Famennian
Frasnian
Givetian
Eifelian
Emsian
Pragian
Lochkovian
SILURIAN
Pridoli
Ludlow
Wenlock
Llandovery
ORDOVICIAN
CAMBRIAN
Furongian
Series 3
Series 2
Terreneuvian
Precambrian
252
299
359
419
444
485
541
Lesueur Ss
Sabina Ss
Woodada Fm
Kockatea Sh
Willespie Fm
Redgate CM
Ashbrook Ss
Wagina–Dongara Ss
Beekeeper Fm
Rosabrook Coal Measures
Carynginia Fm
Irwin River CM
High Cliff Ss
Woodynook Ss
Mosswood Fm
Holmwood Sh
'Cullens D'
Nangetty Fm
Mungaroo Fm
Locker Sh
Chinty Fm
Kennedy Gp
Byro Gp
Wooramel Gp
Callytharra Fm
Lyons Gp
Erskine Ss
Blina Sh
Millyit Ss
Liveringa Gp
unnamed basalt
Noonkanbah Formation
Poole Ss
Grant Group
Sahul Group
Osprey Fm
Mount Goodwin Subgroup
Hyland Bay Subgroup
Fossil Head Formation
Kulshill Group
Reeves Formation
unnamed
Wadeye Group
Harris Ss Quail Fm
Yindagindy Fm
Anderson Formation
Weaber Group
AMADEUS
OFFICER
Williambury Fm
Sorby Hills Zn–Pb
Moogooree Lst
Oobagooma U
Langfield Group
Fairfield Group
Buttons Fm
Willaraddie Fm
Brewer C
Mimili Formation
Lennard Shelf Zn–Pb
Ningbing Group
Munabia Ss
Hermannsburg Ss
C
Cockatoo Group
Bonaparte Fm
Mahony Group
Gneudna Fm
Mellinjerie Fm
Parke Slt
Boll C
Nanyarra Ss
Clapp Ridge Fm
reef complexes
Tandalgoo Fm
Sweeny Mia Fm
Kopke Ss
Faure Fm
Mereenie Ss
Coburn Fm
Dirk Hartog Group
Worral Fm
Carmichael Ss
Yaringa Fm
Ajana Fm
Blue Hills Ss
Larapinta Group
Munda Group
Mallowa Salt
Carribuddy Group
inferred
red beds
Tumblagooda Ss
Indulkana Sh
Minjoo Salt
Admiral Bay Zn–Pb
Stokes Slt
Mt Chandler Ss
Nita Fm
Goldwyer Fm
inferred
Stairway Ss
Wanna Fm
Willara Fm
Horn Valley Slt
Wilson Cliffs Ss
Nambeet Fm
Prices Creek Gp
Skewthorpe Fm
Pacoota Ss
Lennis Ss
unnamed
unnamed
Pander Gs
Clark Ss
Goose Hole Group
Pretlove Ss
Carlton Group
Elder S-g
Hart Sp Ss
Table Hill Volcanics
Negri S-g
Tararra Fm
?Cu
Pertaoorrta Group
Marla Group
Wirrildar beds in SA
McFadden Fm/Lungkarta Fm, Vines Fm and Durba Ss in WA
Antrim Plateau Volcanics
Antrim Plateau Volcanics
Albert Edward and Louisa Downs Groups

Dominant lithotype

- Sandstone (conglomerate)
- Mixed sandstone, mudstone, and (Permian only) coal
- Mudstone
- Carbonate–mudstone
- Carbonate
- Volcanics
- Halite, evaporite
- Disconformity
- C Conglomerate
- Ck Creek
- CM Coal Measures
- D Diamictite
- Fm Formation
- Gp Group
- Gs Greensand
- Lst Limestone
- S-g Subgroup
- Sh Shale
- Slt Siltstone
- Sp Spring
- Ss Sandstone
- • Significant mineralization

Figure 3 (adjacent page, left). Correlation of the Paleozoic in the western part of Australia (after Mory and Haines, 2013, fig. 2) and location of mineral deposits. Legend for Figure 3 is above

Figure 4 (right). Summary of the biostratigraphic resolution for the western part of Australia, based on Figure 3 (after Mory and Haines, 2013, fig. 3), showing the intervals for the paleogeographic maps and isopach images, and available radiometric dates. Legend for Figure 4 is below

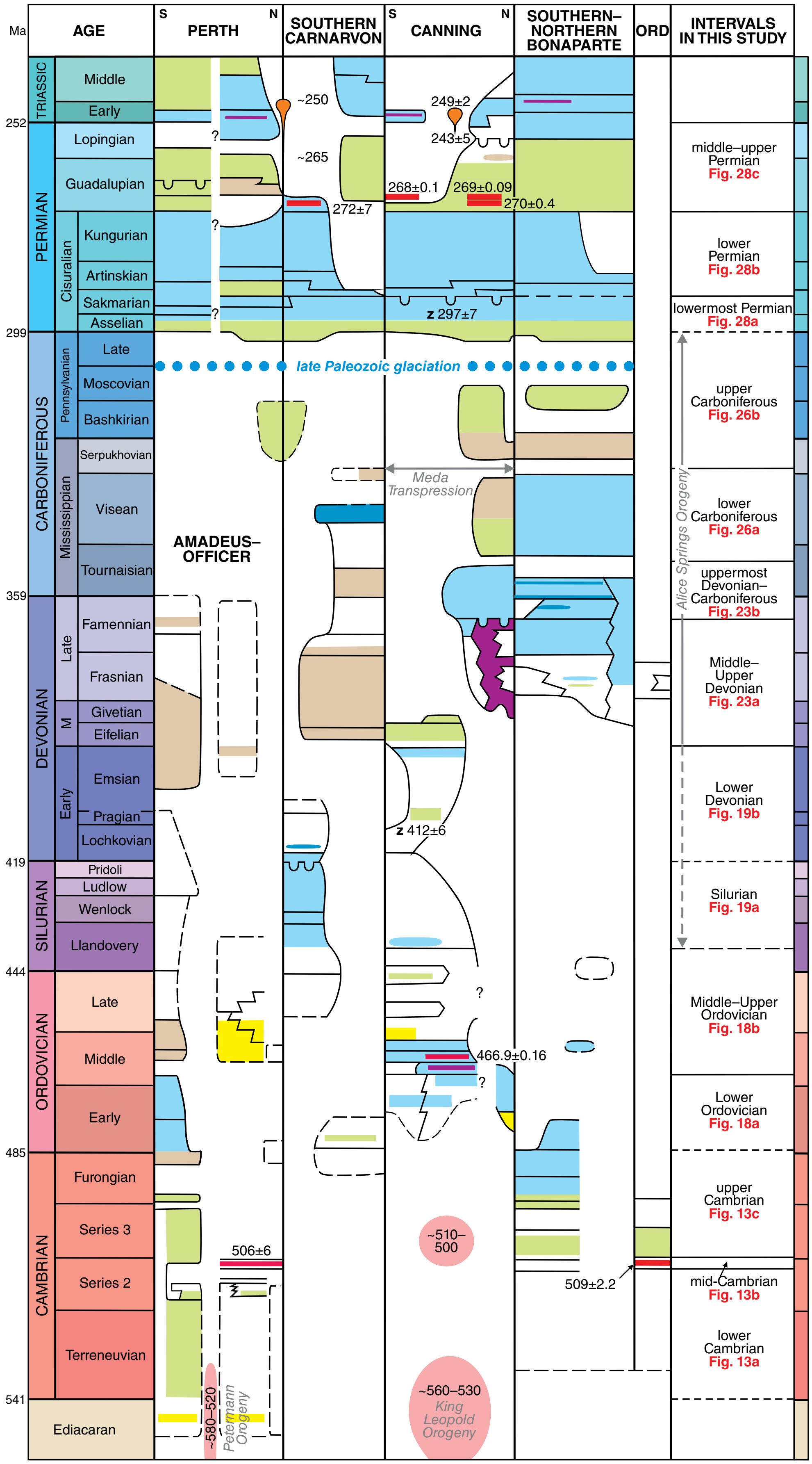
Biostratigraphic resolution

Span of local zones:

- International zone
- Substage
- Stage–substage
- Stage
- Epoch
- Period
- No internal evidence
- Disconformity
- *Orogeny* Orogenic or tectonic event
- • • • Glacial deposit

Radiometric age (Ma)

- Extrusion or tuff
- Intrusion
- Basement-heating event
- z Youngest zircon date from provenance study



Basin distribution and architecture

Paleozoic strata in Western Australia cover about 1 300 000 km^2 within five main sedimentary basins. From north to south these basins (Fig. 2) are the Northern Bonaparte Basin (mostly the Petrel Sub-basin) and adjoining Southern Bonaparte Basin (70 000 km^2*), the Ord Basin (7000 km^2*), Canning Basin (720 000 km^2), Southern Carnarvon Basin (190 000 km^2), and Perth Basin (305 000 km^2). The southern Officer Basin, much of which lies beneath the Canning Basin, also contains a widespread, albeit poorly known, pre-Permian Paleozoic succession hundreds of metres to perhaps three km thick. Lower Paleozoic rocks constitute about half of the area of the western Amadeus Basin (60 000 km^2*) that also in part underlies Permian strata of the Canning Basin.

The Southern Bonaparte, Ord, Canning, Southern Carnarvon, and Perth Basins originally were differentiated onshore based on their potential for artesian water and their geographical separation by Precambrian terranes (Fig. 5).

* These area calculations exclude portions of the basins in the Northern Territory.

Following the expansion of petroleum exploration into offshore areas in the late 1950s these basins were extended to the continental–oceanic crust boundary supposedly following presently expressed structural elements. Such extrapolation can be unsatisfactory due to the lack of clear structural features along which these basins can be partitioned, especially for Paleozoic strata where they lie below thick Mesozoic successions. Similarly, onshore basin divisions, initially based on outcrop and water drilling, have been refined based largely on petroleum exploration data that have become available since the 1960s. However, it is already clear that modifications to existing sub-basin definitions are necessary. For example, units such as the Jones Arch between the Fitzroy Trough and the Gregory Sub-basin in the Canning Basin (see *Frontispiece*), and many small sub-basins in the northern Perth Basin, could be incorporated into adjacent sub-basins — later work shows that the structures on which they were originally defined are discontinuous or invalid.

Figure 5. 1916 map showing extent of the artesian basins in Western Australia (from Jutson, 1916, fig. 9)

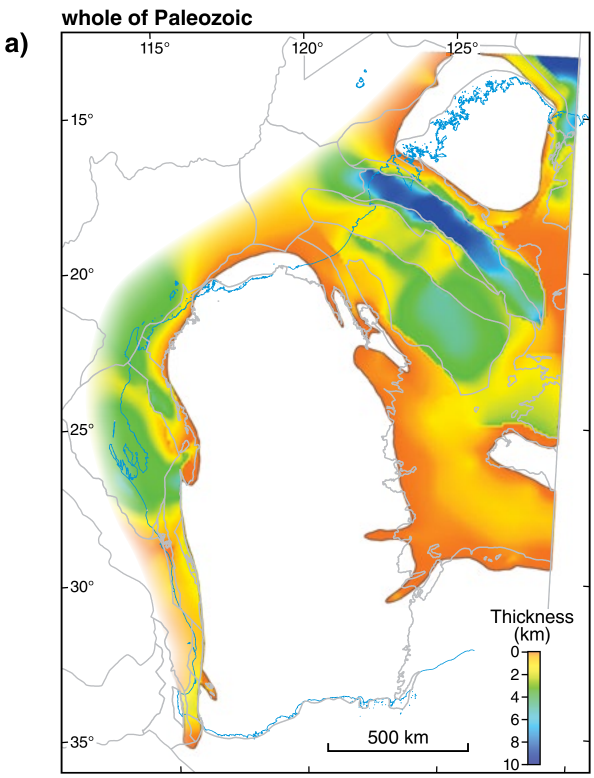


Figure 6a. Isopach image of the Paleozoic for the whole of Western Australia

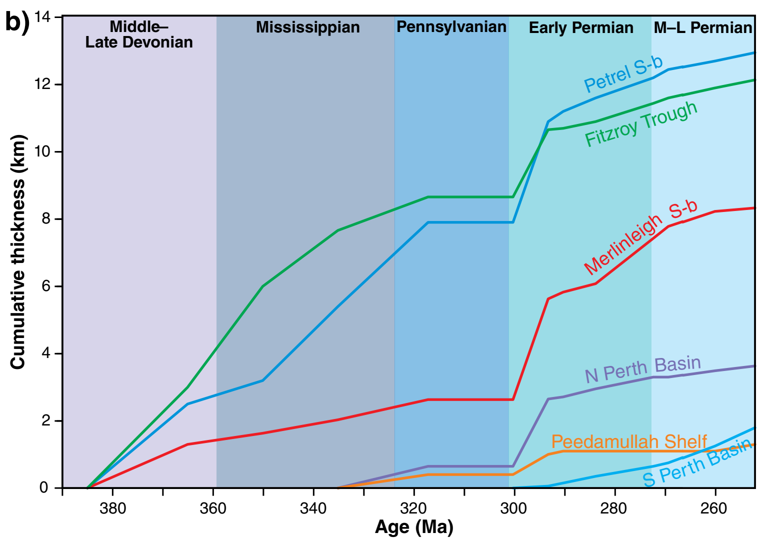


Figure 6b. Cumulative thicknesses in Middle Devonian – Permian depocentres in Western Australia. Abbreviation: S-b = Sub-basin

Other sub-basins have arbitrary boundaries (see *Frontispiece*), such as between the Broome and Crossland Platforms in the Canning Basin, and the Byro Sub-basin – Coolcalalaya Sub-basin – Irwin Terrace between the Southern Carnarvon and Perth Basins — largely due to a lack of outcrop and subsurface data. Historically the Perth and Southern Carnarvon Basins were differentiated by their divergent half-graben geometry with strata in the Perth Basin dipping east as opposed to west-dipping strata in the Southern Carnarvon Basin. However, the boundary between these basins remains elusive especially when viewed in terms of their respective depositional successions.

In the 1980s, offshore portions of basins were segregated from their onshore counterparts based on the marked thickening of Mesozoic strata offshore, and the growing recognition of the North West Shelf as a major hydrocarbon province. Thus the 'Bonaparte' and 'Carnarvon' Basins were split into northern and southern parts, and the Roebuck Basin was differentiated from the now mostly onshore Canning Basin. By comparison, the Perth Basin was not subdivided as it contains a significant onshore Mesozoic section.

Many sub-basins in Western Australia have quasi-geographical descriptors such as 'shelf', 'platform', 'arch', and 'trough'. These designations refer to present structural configurations rather than having a paleogeographic connotation. As such, many basin divisions are not relevant for the Paleozoic, especially given the significant structural events in the Mesozoic that have reactivated older structures, thereby effectively masking Paleozoic structure. By comparison, unconformities within the Paleozoic indicate at least some local structural events, but their significance — especially for low-angle discontinuities — are difficult to evaluate, and attempts to associate them with tectonic events can be problematic. Isopach maps provide a better understanding of Paleozoic structure and highlight local and regional depocentres due to sag or extensional (or at times trans-tensional) tectonics throughout the Era. The divisions of the Paleozoic made here are likely equivalent to second-order sequences and as such should be related to regional structural or climatic events, or both (see pull-out box, *Ice ages and climate cyclicity*, page 36).

Dating the Paleozoic

Given the rarity of volcanic rocks within onshore Paleozoic strata, age controls on basin stratigraphy are largely based on biostratigraphic studies rather than precise radiometric dates. Alternative techniques such as magnetostratigraphy, chemostratigraphy, and isotope stratigraphy have been little tested. In addition, climatic events, where evident as regional sedimentological or faunal changes or both, can provide indirect age control (see *Controls on climate* box).

Biostratigraphy

In Western Australia, biostratigraphic correlations are underpinned by faunal and floral studies of diverse Paleozoic groups, but without systematic studies, such age determinations and correlations are inherently unreliable. The biostratigraphic resolution depicted for the major successions in Figure 4 is ranked from high (where international zones can be recognized) to none (for units with no internal evidence of their age). Of these successions, inter-basin correlations of the Middle Devonian to Permian are the most robust, as marine facies are more prevalent within this interval than within the lower Paleozoic.

Of particular note are the high-resolution ages available for the Canning Basin based on abundant Ordovician and Late Devonian conodonts, and Famennian (Late Devonian) ammonoids. By comparison, rare goniatites in the Permian of the northern Perth, Southern Carnarvon, and Canning Basins support ages based on other groups for which the species are endemic, such as brachiopods, spore–pollen, and bryozoans, even though the goniatite species also are endemic. Of other groups, recent studies indicate that the foraminifera allow the best independent assessment of ages for Carboniferous–Permian marine facies, apart from for the late Visean – early Sakmarian when the cooler climate across mainland Australia and local fluvial facies (Figs 26b, 28a) were unfavourable for the group.

Radiometric dates

Apart from the mid-Cambrian Kalkarindji Large Igneous Province (dated at 509 ± 2.2 Ma from the Antrim Plateau Volcanics and 506 ± 6 Ma from the Table Hill Volcanics) Paleozoic extrusive or intrusive rocks are rare in Western Australia — available radiometric ages from such rocks are summarized in Figure 4. The Milliwindi Dyke in the west Kimberley (see *Frontispiece*), considered co-magmatic with the Kalkarindji LIP, provides the highest precision date from this province at 510.7 ± 0.6 Ma using U–Pb IDTIMS. In the Canning Basin, the lower Middle Ordovician Goldwyer Formation contains at least three tuff beds of which two have yielded IDTIMS zircon ages close to 466.9 ± 0.16 Ma. Ash beds from the southwestern Canning Basin have yielded early Wordian IDTIMS zircon ages of 268.35 – 268.1 ± 0.1 Ma, slightly younger than Roadian ages from ash beds within coal seams low in the Lightjack Formation (269.1 – 268.9 ± 0.1 Ma) 350–400 km farther northeast, but still within the Canning Basin.

Provenance studies utilizing ages from zircons occasionally include young grains that help constrain the age of a unit. At present, there are two dates from the Canning Basin (Fig. 4): most other such dates are either older than indicated by biostratigraphy or stratigraphic constraints, or have excessively large uncertainties thereby limiting their value as age constraints. Nevertheless the many zircons dated as Paleozoic for provenance studies imply igneous activity throughout the Era. Whether that was in eastern Australia, Antarctica, blocks such as Cimmeria, or farther afield is unclear.

Offshore, Paleozoic rocks are too deep to drill, apart from some near-shore locations; where deeply buried they are poorly imaged in all but some recent seismic reflection surveys. Despite this, Paleozoic strata are inferred to onlap the Precambrian hinterland of the offshore basins (especially along the margins of the North West Shelf where Cretaceous strata are unconformable on Precambrian basement). An inference made here from the onshore — where Paleozoic strata onlap Precambrian basement and have a low thermal maturity — is that such onlap and sediment thinning were also typical of these margins prior to the Mesozoic. Note that areas shown as nondeposition or erosion on the paleogeographic maps were not necessarily continental in nature.

Major depocentres

The major Paleozoic depocentres in the western part of Australia* have a cumulative thickness of up to about 10 km (Fig. 6a) with many similarities in rates of accumulation (Fig. 6b). These depocentres are:

- the Petrel Sub-basin (Northern Bonaparte Basin, Fig. 7)
- Ord Basin, which could be considered as a set of outliers of the Southern Bonaparte Basin

* Note that 'west Australia' and 'western part of Australia' include parts of the adjacent States, i.e. are within the western portion of the continent, whereas 'Western Australia' is used for features within the confines of this State.

Paleozoic geological time scale is located inside the back cover of book.

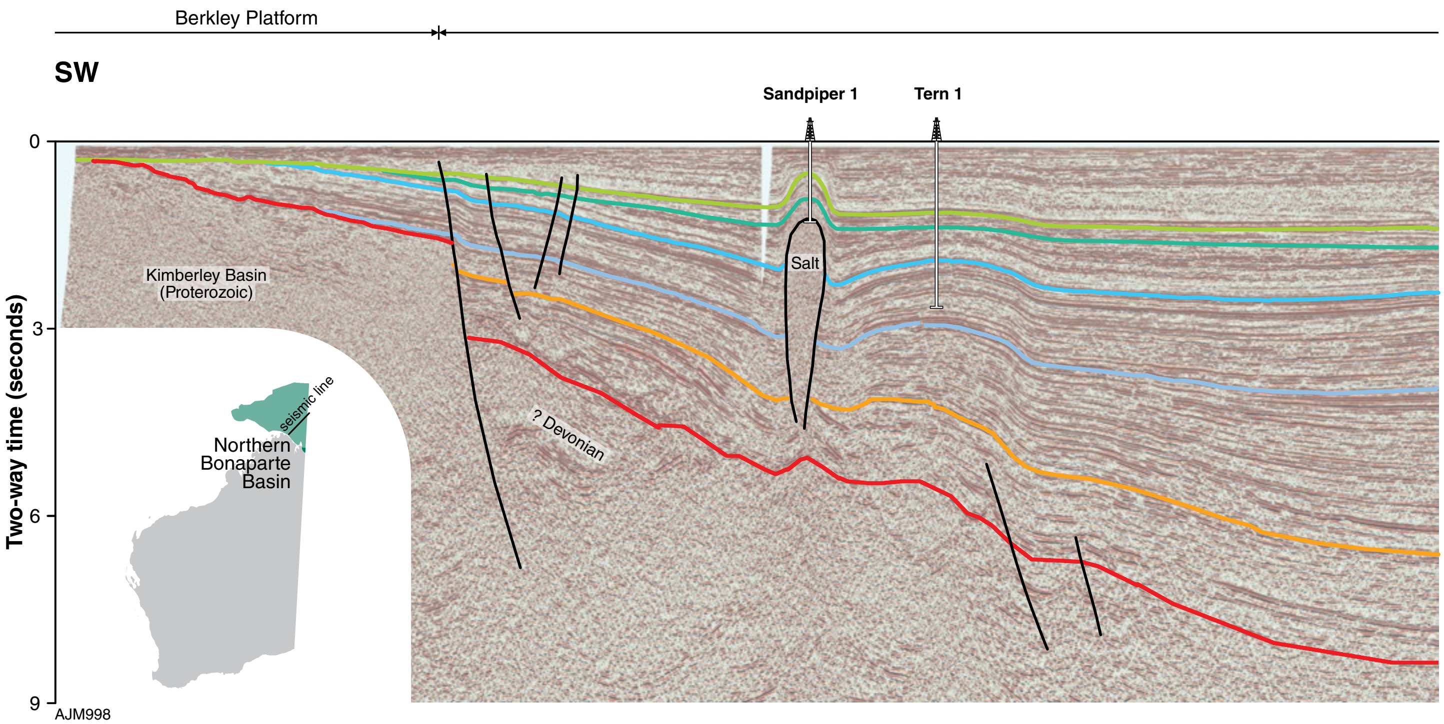


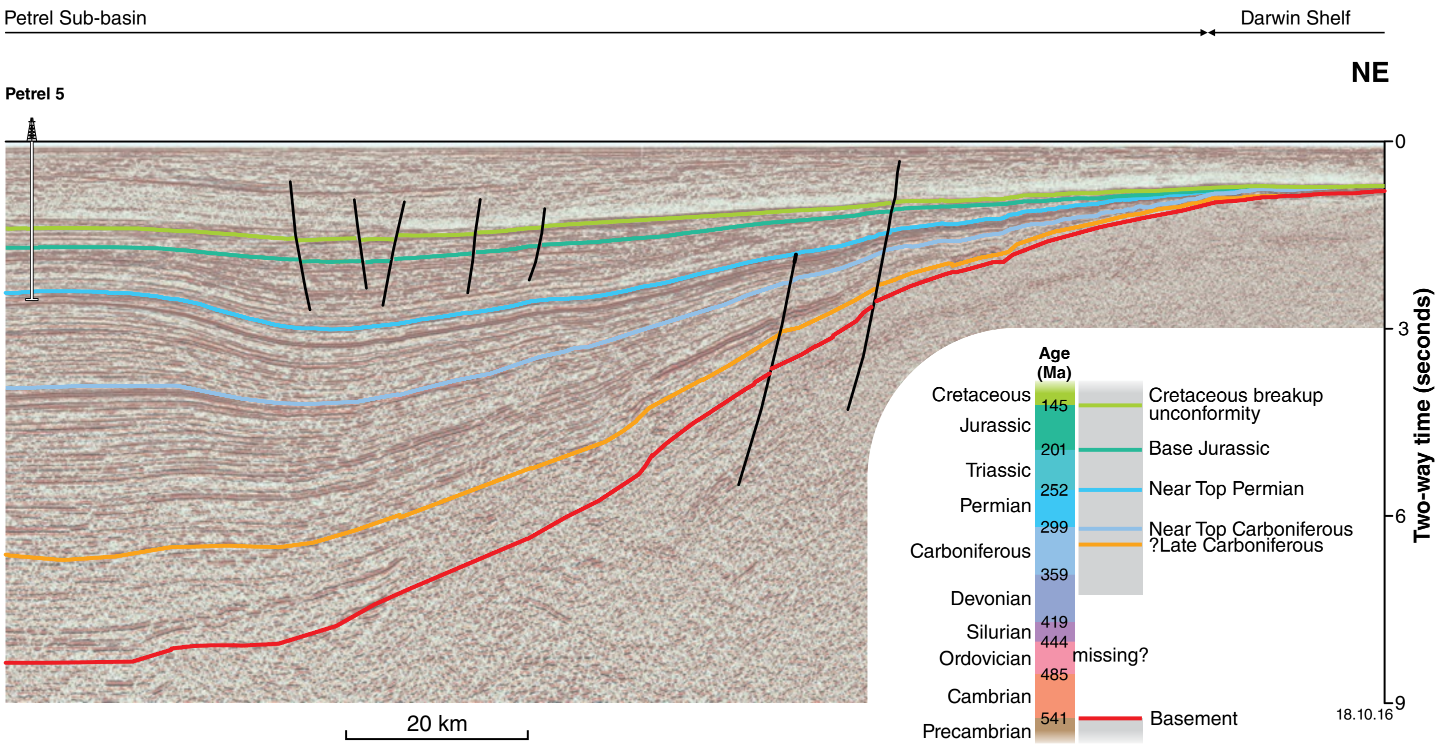
Figure 7. Thick Paleozoic strata in the Petrel Sub-Basin, Northern Bonaparte Basin shown by AGSO (now Geoscience Australia) seismic section 100r/03 (after Colwell et al., 1996, seismic folio, enclosure 3); see Figure 2 for location

- Fitzroy Trough – Gregory Sub-basin and Willara–Kidson Sub-basins (Canning Basin, Fig. 8)
- Merlinleigh–Byro Sub-basins and Gascoyne Platform (Southern Carnarvon, Fig. 9) and
- Coolcalalaya Sub-basin – Irwin Terrace (northern Perth Basin, Fig. 10).

The greater Bonaparte, Ord, and Officer Basins extend significant distances eastward into adjacent States. Farther afield, but still within the Australian Plate, the Arafura Basin and Timor also contain Paleozoic strata that are directly relevant to west Australian basins (Fig. 2). The former contains up to seven km of Paleozoic strata within the Goulburn Graben, a trough with a similar west-northwesterly orientation to the Petrel Sub-basin and Fitzroy Trough, but relatively little information is available as just seven wells in this basin have reached strata of this age. Within Timor all but the northernmost belt of highly deformed rocks are Gondwanan, but the only Paleozoic strata known are of Ghezelian (latest Carboniferous) – Permian age and are strongly faulted.

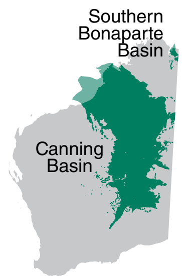
Both the Southern Bonaparte and Canning Basins, which lie 350 km apart on the northeastern and southwestern margins of the Paleoproterozoic Kimberley Basin and Halls Creek and King Leopold Orogens respectively, are northwesterly trending fault-bound grabens flanked by Precambrian basement. The margins of both basins contain lower Paleozoic strata at relatively shallow depths and upper Paleozoic strata that onlap older rocks (Figs 7, 8).

The Petrel Sub-basin in the Northern Bonaparte Basin contains the thickest Paleozoic section in the State (Fig. 7), estimated at 15 km from seismic reflection surveys (Fig. 6a), but its age is poorly constrained and the thickness is anomalous compared with other basins. Although the sub-basin seems to have been active throughout much of the Paleozoic, its history prior to the Late Devonian is poorly understood as that part of the succession, if present, is deeply buried



offshore. Carboniferous–Permian strata make up just over half of this section, consistent with the Fitzroy Trough in the Canning Basin where coeval strata comprise about half the Paleozoic fill (Fig. 6a), but deformation in the Petrel Sub-basin is far less than in the Fitzroy Trough apart from where associated with salt movement (Fig. 7).

The northern upper Paleozoic depocentre, the Fitzroy Trough – Gregory Sub-basin, of the Canning Basin, possibly contains up to 12 km of Devonian–Permian strata (Fig. 6a). Ordovician–Silurian strata cannot be differentiated within these sub-basins, and may be absent (see alternative interpretations of basement in Fig. 8). The depocentre abuts the Broome–Crossland Platform to the south along the Fenton Fault System and the Lennard Shelf to the north along the Pinnacle Fault System. South of the Broome–Crossland Platform, the Kidson Sub-basin forms a separate lower Paleozoic sag-like depocentre (Fig. 8) with 8 km of Ordovician – Lower Devonian strata and a comparatively thin unconformably overlying Permian section. The relatively low thermal maturity of the Ordovician section across the Broome Platform and Willara Sub-basin is inconsistent with the thick Devonian–Permian



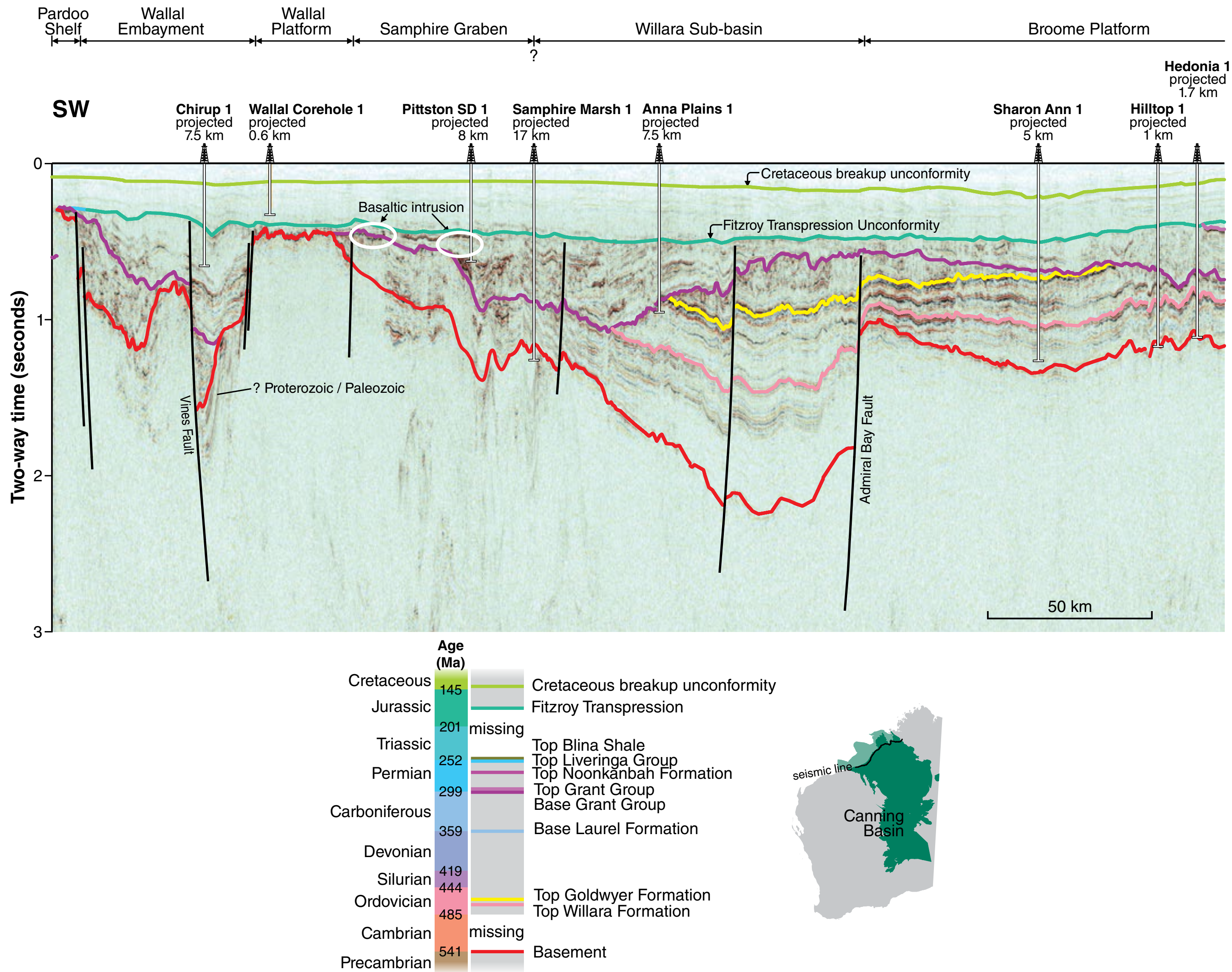
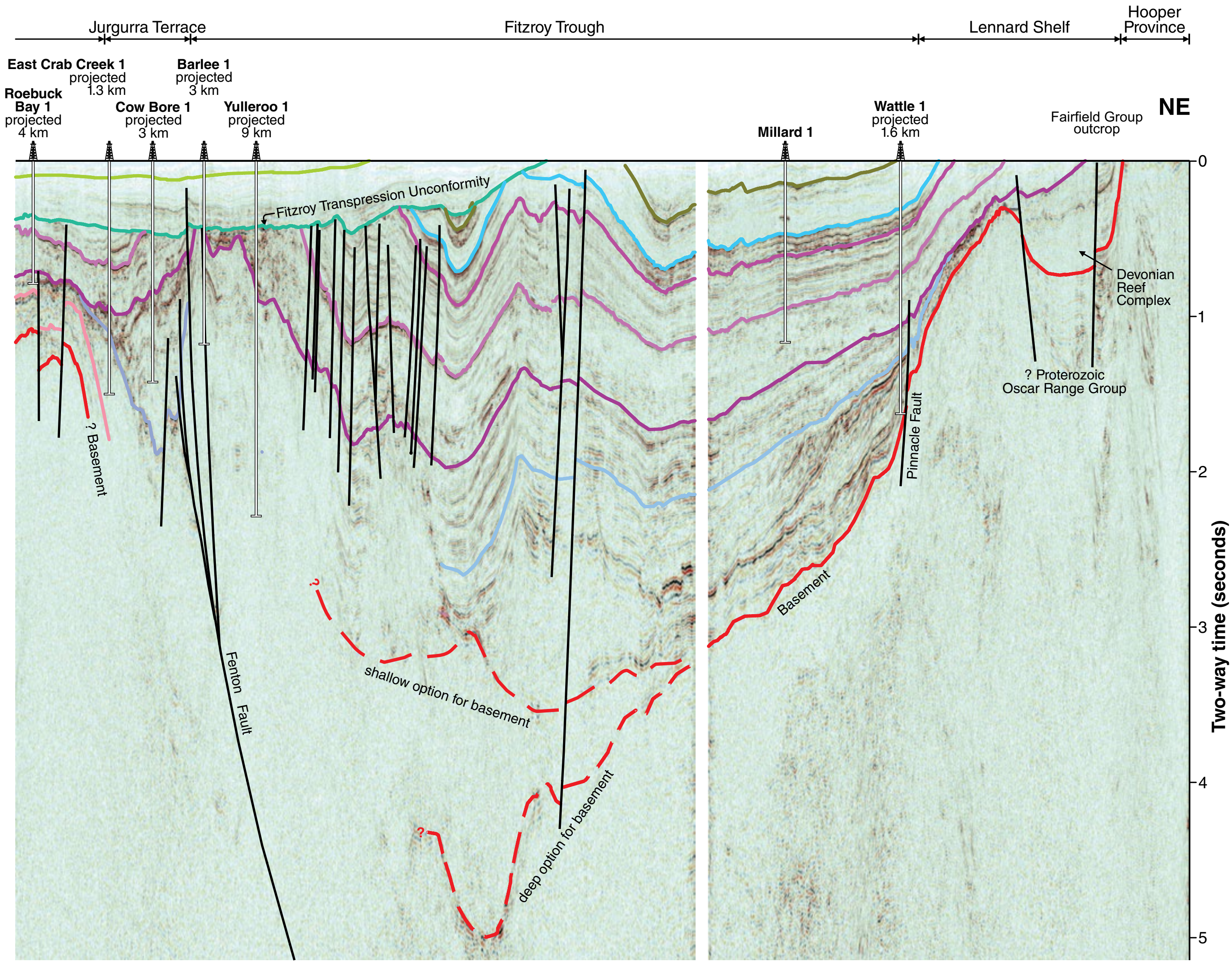


Figure 8. 2014 Canning Basin Coastal Seismic Survey with simplified interpretation; see Figure 2 for location

Groundwater

Groundwater in Paleozoic aquifers — largely stored in the pore space of siliciclastic rocks and locally along fractures in both siliciclastic and carbonate rocks — typically supplies livestock, mining and exploration activities, small settlements, and pastoral stations in the Southern Carnarvon, Canning, and Southern Bonaparte Basins, and at Collie in the southwest of the State. Elsewhere, water supplies are extracted from Mesozoic and younger strata (especially in the Perth Basin), fractured Precambrian rocks, and the Precambrian basins where permeability remains. Unconfined aquifers typically yield the highest supply of potable water — with increasing depth, salinities increase and supply decreases along with porosity and permeability.

Fitzroy Crossing and Kalbarri are the only towns in the State with a water supply extracted from Paleozoic strata. At Fitzroy Crossing the aquifer is strongly jointed and cemented sandstone of the Permian Grant Group in the Lennard Shelf, whereas at Kalbarri it is the Upper Ordovician – Lower Silurian Tumblagooda Sandstone in the Southern Carnarvon Basin; the bore-fields of both aquifers are unconfined.



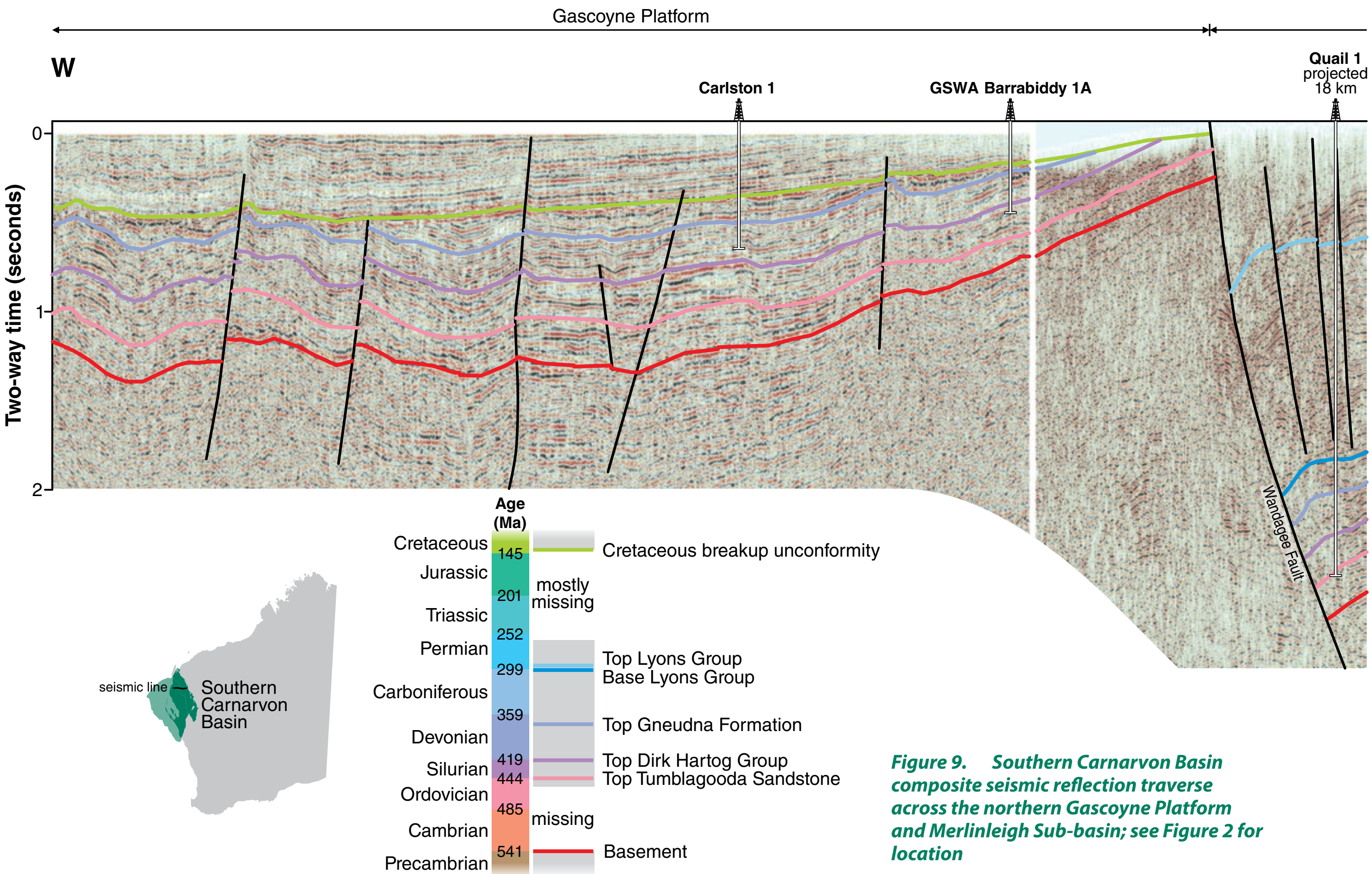
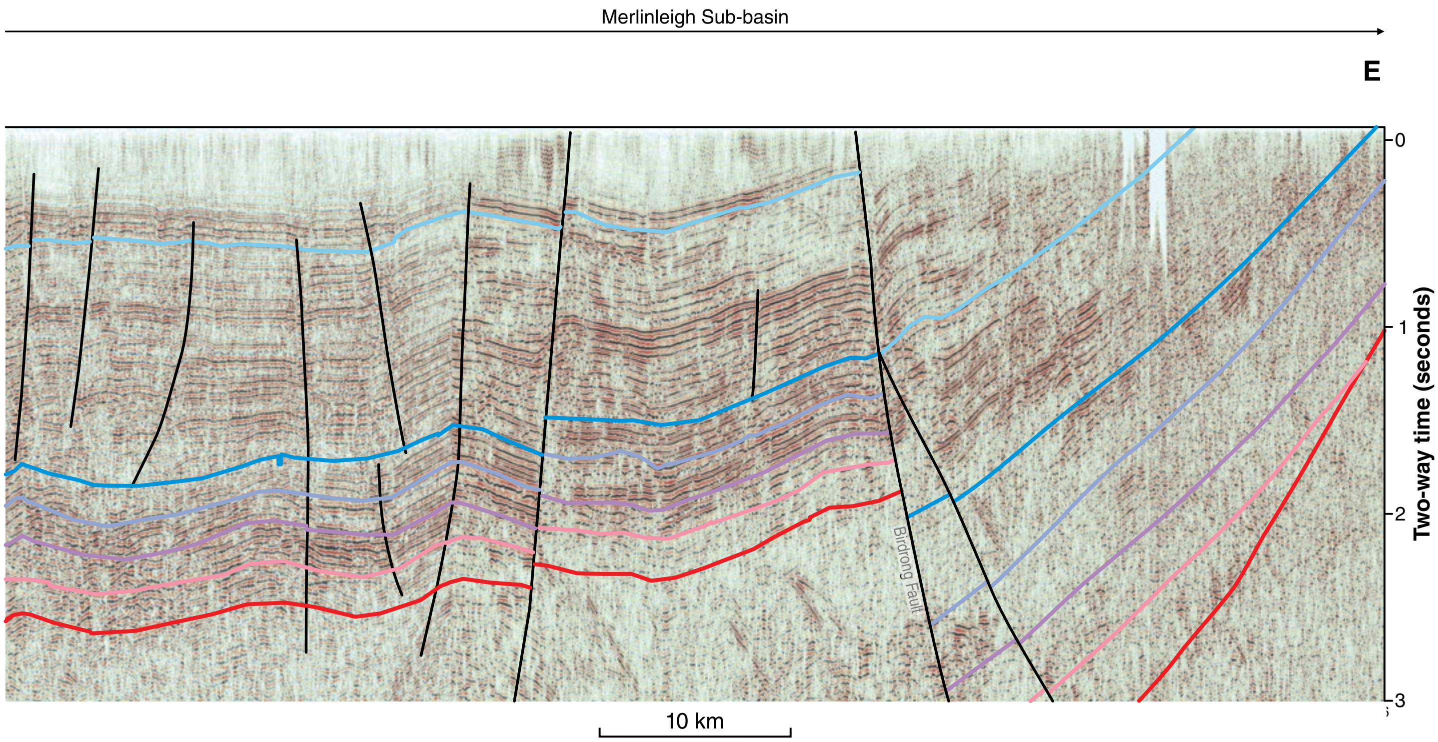


Figure 9. ***Southern Carnarvon Basin composite seismic reflection traverse across the northern Gascoyne Platform and Merlinleigh Sub-basin; see Figure 2 for location***

section in the adjacent Fitzroy Trough indicating significant depositional segregation between these sub-basins. In addition, strata in the Fitzroy Trough appear to be more strongly deformed than in sub-basins to the south, but this cannot be entirely attributed to mid-Mesozoic compression in the northern depocentre. Permian strata that extend as a sheet up to 900 km south from the Kidson Sub-basin to about latitude 29°S on the edge of the Nullarbor Plain, and as discontinuous remnants to about 31°S onto the Yilgarn Craton, are now regarded as an extension and outliers of the Canning Basin (see *Frontispiece* and Fig. 2).

Depocentres along the eastern edges of the north-northwesterly to north-trending Southern Carnarvon and Perth Basins form contiguous half grabens — in the former (Merlinleigh–Byro Sub-basins) strata mostly dip west toward the Wandagee Fault System (Fig. 9) along the western margin, whereas in the latter (Coolcalalaya Sub-basin – Irwin Terrace) strata typically dip east toward the Darling Fault along the eastern margin. Poor outcrop and insufficient subsurface data between these depocentres hinders the differentiation of the two basins near this transition. In all likelihood displacement of at least the Permian succession in the two basins by the Darling and Kennedy Range Fault Systems was at much the same time.

In the Merlinleigh Sub-basin of the Southern Carnarvon Basin, Permian rocks onlap older Paleozoic rocks and Precambrian basement to the east, and are faulted against lower Paleozoic strata over the Gascoyne Platform to the west (Fig. 9). As with the Canning Basin there is a similar separation of the Upper Devonian – Permian section, which is up to 8 km thick in the Merlinleigh Sub-basin compared to up to 5 km of Upper Ordovician to mid-Devonian strata across the Gascoyne–Bernier Platform (Fig. 6a). The only record of Permian deposition across this platform is in the northernmost part but thermal maturity data from Silurian mudstone



and dolomite indicate either the Permian did not reach a great thickness or was never deposited across most of the platform. The Byro Sub-basin at the southeastern end of the Southern Carnarvon Basin has a similar structure to that of the Coolcalalaya Sub-basin of the Perth Basin in that it is faulted against the Yilgarn Craton on its eastern margin, but it is also faulted against the Precambrian Carrandibby Inlier along part of its northwestern margin. Its relationship with the Perth Basin to the southwest is unclear as there is little subsurface data or outcrop in the adjoining part of the Coolcalalaya Sub-basin.

The eastern margin of the Perth Basin against the Precambrian West Australian Craton (Fig. 2) is the 940 km-long Darling Fault System. The thickest known Paleozoic sections in this basin are within the northernmost Coolcalalaya Sub-basin where the Ordovician–Permian section is up to 7 km thick compared with less than 2 km on the adjoining Irwin Terrace where only Middle–Upper Mississippian to Permian sedimentary rocks are known (Fig. 6a). In both structural and stratigraphic respects the Coolcalalaya Sub-basin, and the Abrolhos Sub-basin west of the Northampton Inlier, can be considered transitional areas between the Southern Carnarvon and Perth Basins. Just south of the Northampton Inlier Permian strata thin both to the south and west. Another half graben lies offshore along the Turtle Dove Ridge. Although Permian strata have not been intersected in many offshore wells, seismic reflection profiles indicate a Permian succession beneath the thick Mesozoic succession (Fig. 10). The adjoining Dandaragan and Bunbury Troughs of the central Perth Basin likely are a southern extension of the Permian depocentre along the eastern margin of the Southern Carnarvon Basin and the northern Perth Basin. In the Perth Basin the Permian is obscured by a thick Mesozoic section that is more than 10 km thick below the Perth metropolitan area. At the southern end of the Perth Basin, Permian strata directly overlie basement rocks on the Vasse Shelf and in the outliers around Collie (Collie, Wilga, and Boyup Sub-basins). On the Vasse Shelf the Permian section as a whole reaches a thickness similar to that in the Irwin Terrace, less than two km, but the Lower Permian section is considerably thinner (Fig. 6b).
To the east, near the town of Collie, the entire Permian succession is no more than one km thick.

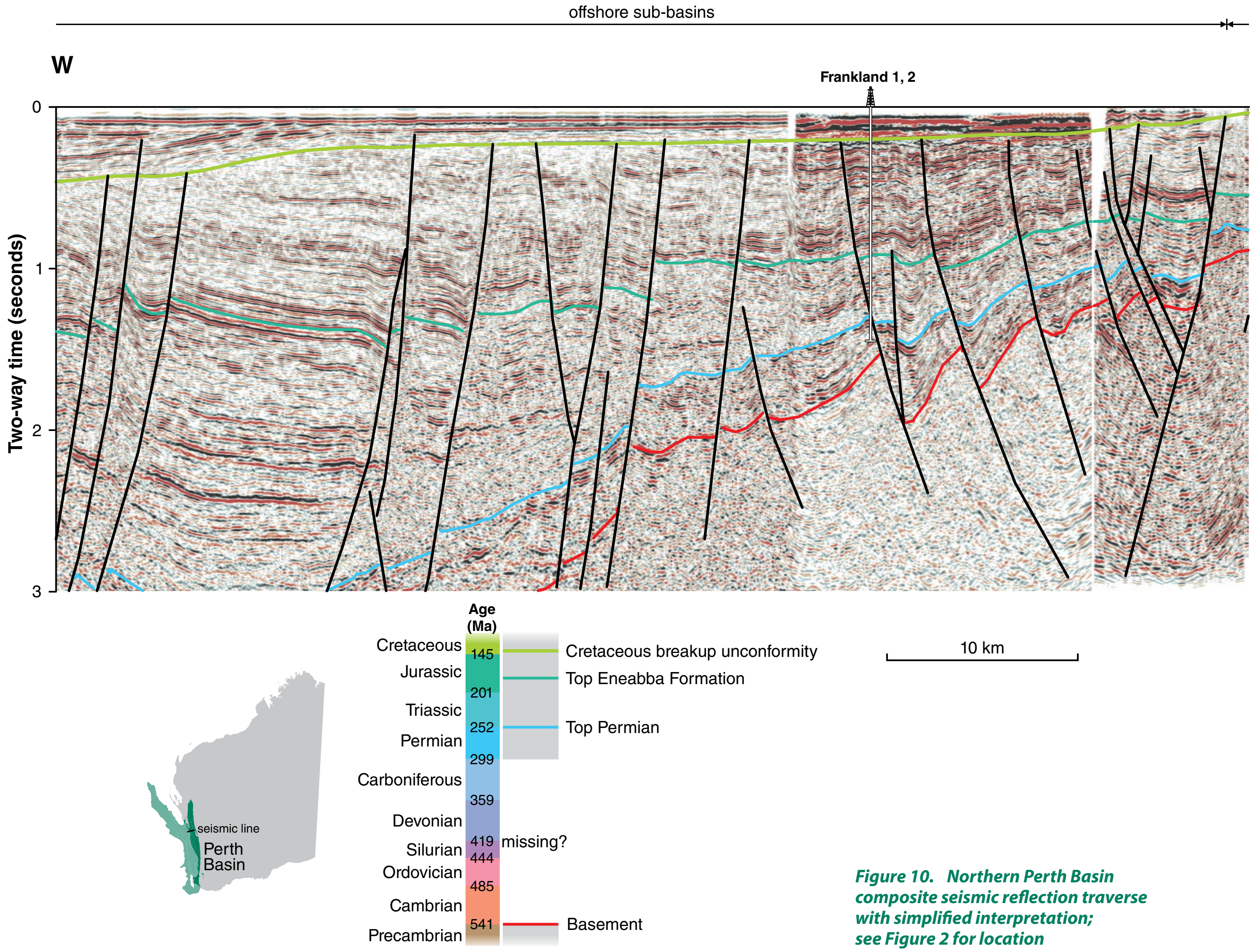
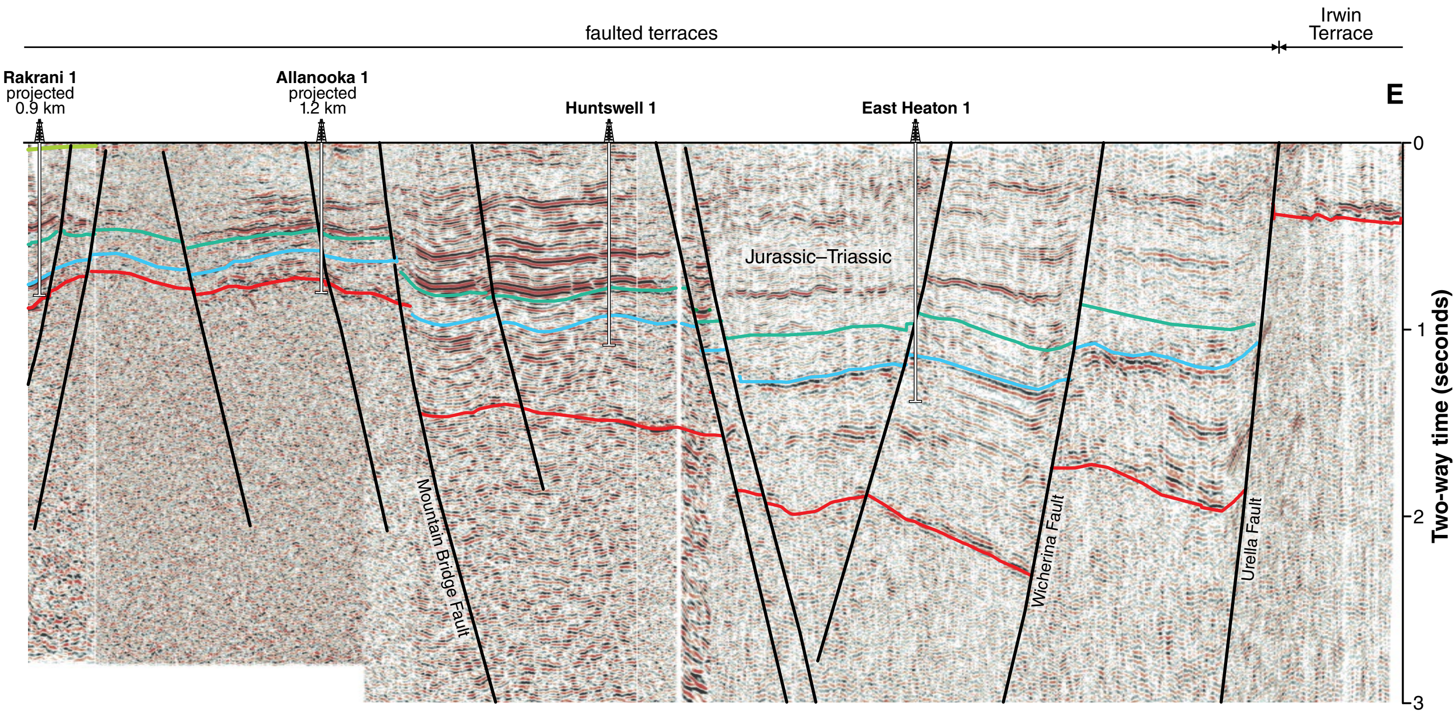


Figure 10. Northern Perth Basin composite seismic reflection traverse with simplified interpretation; see Figure 2 for location

The Permian succession may be up to 6.5 km thick next to the Darling Fault near Donnybrook and Harvey, but such estimates are imprecise as they are based on poor-quality seismic reflection data that is largely unconstrained by drilling, and even possibly incorporates a Precambrian sedimentary succession (the Cardup, Moora, Yandanooka, and Badgeradda Groups of the Pinjarra Orogen). The unconformable contact between the Permian and Precambrian basement along the margins of the Perth Basin and on the Beagle Ridge, plus the rarity of reworked pre-Permian palynomorphs throughout the entire Perth Basin succession, suggest that earlier Paleozoic sedimentation was not widespread within the southern and central parts of this basin, if it occurred at all. South of Geraldton the only evidence for older Paleozoic strata comes from reworked Late Devonian miospores (produced by vascular plants) from Upper Jurassic mudstone next to the Urella Fault. Their likely source is from the Coolcalalaya Sub-basin or farther north, transported east of the Urella Fault within Permian sediment that possibly once extended onto the Yilgarn Craton.



Controls on climate

In Western Australia, climatic variations during the Paleozoic are not always obvious because faunal and facies changes may be equally attributed to oceanic circulation patterns or the nature of barriers created by the continental blocks that once lay between Australia and Paleo-Tethys (Figs 11, 16, 17, and 24). For example, extensive Upper Ordovician evaporitic facies in the Canning Basin (initially considered Devonian) imply sub-equatorial conditions; although consistent with paleogeographic reconstructions, this does not give a clear explanation of why Silurian evaporites are present in the Southern Carnarvon Basin but absent in the Canning Basin. To explain this apparent anomaly, it is necessary to invoke barriers to oceanic circulation into the Canning Basin, or more continental conditions than in the Southern Carnarvon Basin during the Silurian, or to seek a local tectonic explanation. Such interpretations are not mutually exclusive and illustrate how ambiguous the geological record can be, and the limitations to inter-basinal correlations. A clearer example of a climatic difference is the abundance of hummocky cross-stratification in the Artinskian–Kungurian (late Early Permian) of the Southern Carnarvon Basin and the seeming absence of this facies in the Canning Basin. The difference can be interpreted as a latitudinally restricted storm belt akin to the present-day 'roaring forties' — even allowing for possible differences in continental topography windward of these basins.

Paleolatitude in the Paleozoic

Gondwana had already formed at the start of the Paleozoic, with Australia straddling the equator for most of the Cambrian–Silurian (Figs 11, 16) and then moving southward during the Devonian – Early Carboniferous (Figs 17, 24) to cool–temperate latitudes for most of the Late Carboniferous – Permian (Figs 27, 29). Redbed and evaporitic facies, including thick salt beds (see *Evaporites* box), accumulated in the Southern Carnarvon to Northern Bonaparte Basins during the mid-Ordovician to Early Devonian and indicate relatively high temperatures consistent with low paleolatitudes (see *Evaporites* box). Thick carbonate reef facies in the Givetian–Famennian (Middle to Late Devonian) in the Canning Basin, and to a lesser extent in the Southern Bonaparte Basin, vs cooler shelf and ramp, mixed carbonate–clastic conditions in the Southern Carnarvon Basin, point to warm-temperate marine waters at that time. Relatively warm-water conditions persisted into the Early Carboniferous but by the late Visean Gondwana had moved into sub-polar latitudes. Gondwana's high southerly paleolatitude and continent–ocean configurations during the Carboniferous–Permian appear to have strongly influenced the onset of glacial conditions and subsequent climatic amelioration in the Sakmarian (see *Ice ages and climate cyclicity* box). The persistence of cool conditions in eastern Australia has been attributed to either upwelling of cold abyssal waters or strong polar Panthalassan currents, whereas in the west the climate throughout much of the Permian was moderated by proximity to Tethys. This appears to counter some claims that the primary control on continental-scale glaciations in the Paleozoic was atmospheric CO_2 levels, and that continent–ocean configurations and insolation (the amount of solar radiation received per unit area) were of secondary importance.

Paleozoic evolution of Western Australia

Four main phases of basin evolution are apparent:

a) Cambrian intracratonic synorogenesis and sag probably associated with the Centralian Superbasin;

b) Ordovician to Early Devonian intracratonic rifting–sag coeval with the early phases of the Alice Springs Orogeny in central Australia;

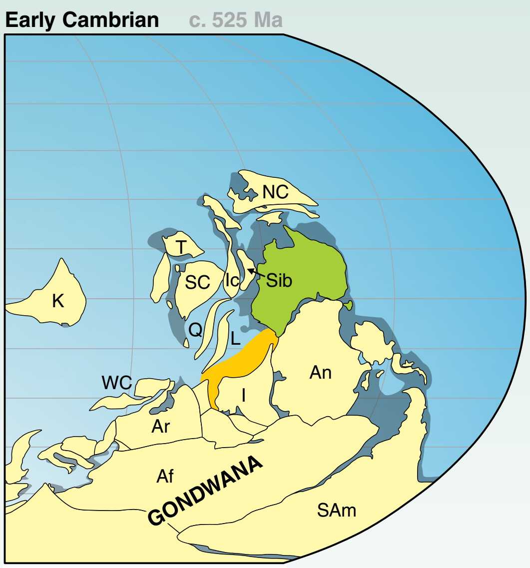
c) Middle Devonian to mid-Carboniferous renewed rifting coeval with compression in central Australia during the late part of the Alice Springs Orogeny, possibly associated with tectonic events north of Gondwana; and

d) Latest Carboniferous to Permian rifting and sag with an east–west component of extension associated with the rifting and separation of the Cimmerian continent and associated blocks from northern Gondwana.

The first two phases of intracratonic deposition were probably due to convective down-welling in the upper mantle whereas the succeeding rift–sag phases, although intracratonic, seem related to events along the northern margin of the supercontinent. The Middle Devonian to mid-Carboniferous phase was possibly associated with subduction within the Panthalassan Ocean (see pull-out box, *Panthalassa and Pangea*, page 5) north of Gondwana, whereas Late Carboniferous to Permian deposition was probably associated with rifting and separation of the Cimmerian continent and other blocks from the Australian Craton.

Selection of intervals to depict the Paleozoic evolution of Western Australia is primarily based on biostratigraphic resolution (Fig. 4), but other considerations such as regional stratigraphic and climatic events (e.g. the end of glacial conditions in the late Sakmarian, Fig. 3; and see pull-out boxes, *Dating the Paleozoic*, page 9, *Controls on climate*, page 17, and *Ice ages and climate cyclicity*, page 36) and interval duration were also given some weight. Apart from the mid-Cambrian interval covering the Kalkarindji Large Igneous Province (LIP; which includes the Antrim Plateau and Table Hill Volcanics, and Milliwindi Dykes) that lasted about 5 Ma, the duration of the intervals is between 10 and 30 Ma each and averages 22 Ma. The maximum thickness of strata preserved within each interval ranges from 1 km to 3.5 km, with an average of 2.1 km. Depocentre shifts through time are such that the maximum thickness of the Paleozoic in any basin is less than 15 km (Fig. 6a).

The paleogeographic maps and isopach images are considerably idealized as they each cover a long interval, approximating second-order sequences, which are likely controlled by regional tectonic events. Although the edge of depositional environments identified in these maps generally coincides with the preserved edge on the isopach images, there is little to indicate the original extent of various environments, especially shorelines and shallow-marine facies, across areas with limited or no



	Present continent	L	Lhasa
	Continental shelf	La	Laurentia
	Destroyed terrane	NC	North China
	Australia	Q	Qiantang
Af	Africa	S	Siberia
An	Antarctica	SAm	South America
Ar	Arabia	SC	South China
B	Baltica	Sib	Sibumasu
EE	East Europe	SMG	Southern Mongolia – Gobi
G	Greenland	T	Tarim
I	India	WC	Western Cimmerian continent
Ic	Indochina		
K	Kazakhstan		

Figure 11. Early Cambrian tectonic reconstruction (after http://portal.gplates.org/); key to various blocks is for all tectonic reconstructions

remaining sedimentary record. The isopach images have been generated from well data with some input from outcrop and seismic reflection sections. The maximum thickness in any isopach interval is 3500 m, for both the upper Ordovician interval in the Southern Carnarvon Basin and the Middle–Upper Devonian of the Fitzroy Trough, and possibly the Petrel Sub-basin. The section in the centre of the Petrel Sub-basin attributed to the Carboniferous–Permian is about 7.5 seconds two-way-time (i.e. about 15 km thick) but has minimal constraints on its age (Fig. 7). Deposition was on a rapidly subsiding continental margin, but the thickness of the succession is anomalous compared with other Paleozoic basins in Western Australia —whether or not all of the implied thickness is Paleozoic is questionable.

Biostratigraphic resolution also indicates a measure of marine influence — albeit affected by paleoecological and paleoenvironmental controls, including currents and latitudinal changes — and connectivity to typical Tethyan faunas. Such faunas are usually mid-latitude to equatorial in aspect, but Tethyan elements are uncommon in west Australian Paleozoic assemblages, indicating restricted access to open-marine circulation. This reflects the dominantly intracratonic position of most west Australian basins and their distance from the open ocean (e.g. Fig. 11; see pull-out box, *Controls on climate*, page 17).

Cambrian intracratonic synorogenesis and sag

The late Ediacaran to early Cambrian was a time of orogenesis in central and northwestern Australia, with the locus of uplift in the Musgrave Province that separates the Amadeus and Officer Basins.

The Petermann Orogeny (580–520 Ma) in this area was probably at least partly coeval with the Paterson Orogeny along the northern margin of the West Australian Craton and the King Leopold Orogeny just north of the Canning Basin. Orogenesis may have extended through the intervening area now covered by the Canning Basin, although basement events have not been dated there. These events all fall within the last phases of the assembly of Gondwana (Fig. 11) but provide little insight into the apparent lack of Cambrian deposition along the western margin of Australia. Mild deformation, possibly associated with the Delamarian Orogeny of South Australia – eastern Australia, immediately

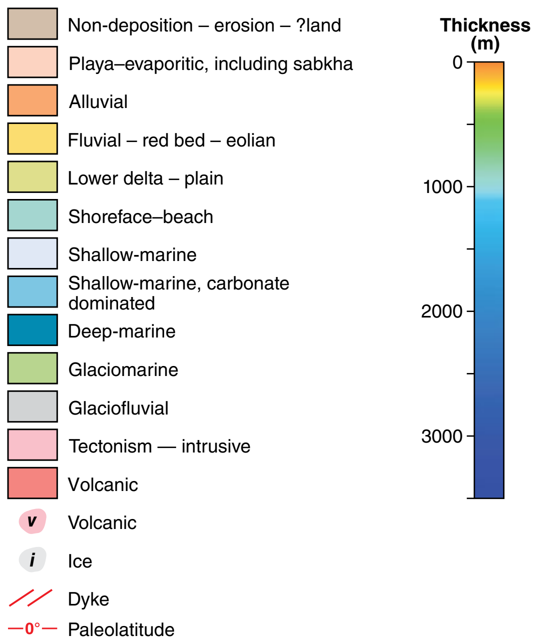


Figure 12. Key to all paleogeographic maps and isopach images. Note that blank areas on the maps have no data, and were not necessarily hinterland

predates extrusion of the Kalkarindji LIP based on gently folded, apparently Lower Cambrian, sedimentary rocks in the southern Officer Basin. The pre-Kalkarindji succession appears to be synorogenic whereas post-Kalkarindji deposition is more sag-like — in the eastern Officer Basin of South Australia the former succession is up to three km thick compared to just over one km for the latter.

Depositional history

Uplift associated with the Petermann Orogeny was accompanied by clastic sedimentation in deltaic, fluvial, alluvial, and eolian settings in the adjacent Amadeus and Officer Basins (Figs 12, 13a–c), but the general lack of fossils or volcanic facies that can be dated precludes differentiating the upper Ediacaran from lower Cambrian components, except in the more marine central and eastern Amadeus Basin in the Northern Territory. The thickest syn-Petermann strata in Western Australia are deltaic to alluvial facies, locally at least 4 km thick, preserved in the Amadeus Basin as a series of foreland basin depocentres immediately north of the Petermann thrust zones (Fig. 13a). Eolian deposition in the northwestern and southern Officer Basin (McFadden and Lungkarta Formations respectively; Fig. 3) implies that the uplifted mountain range generated a climatic divide with a rain shadow to the southwest.

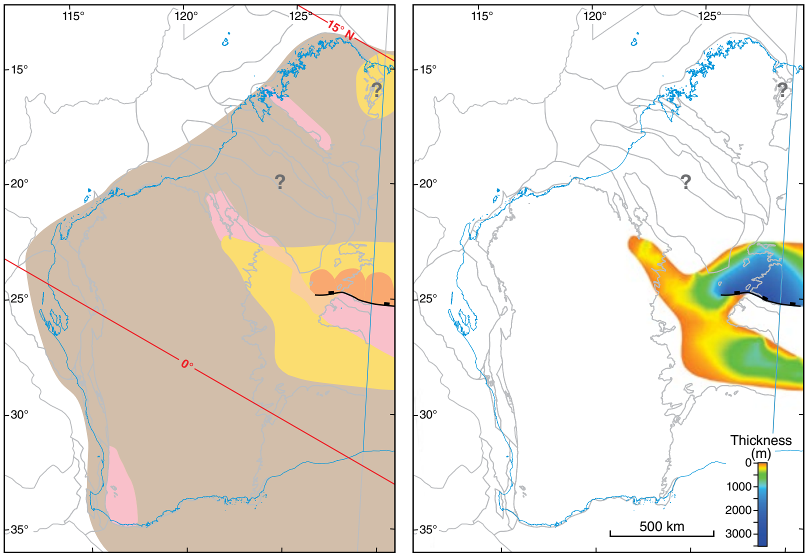


Figure 13a. Early Cambrian, 541–514 Ma, paleogeographic map (left) and isopach image (right); key in Figure 12; paleolatitude from http://portal.gplates.org/

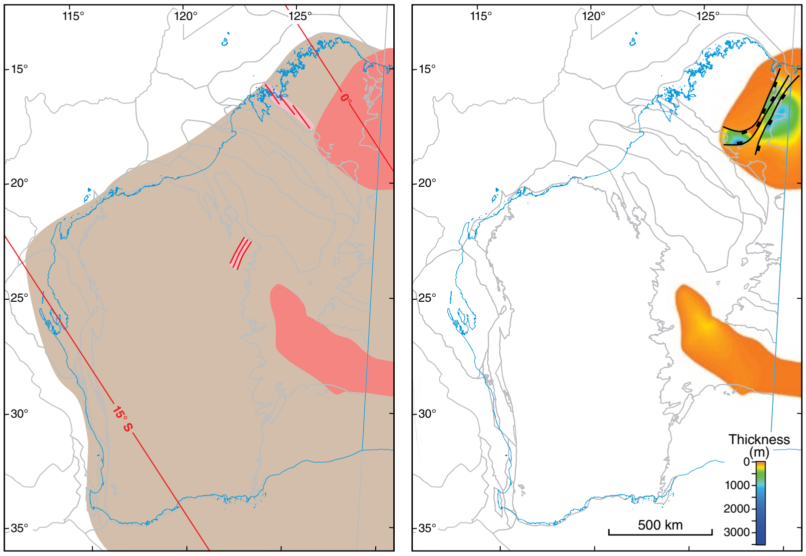


Figure 13b. Mid-Cambrian, 514–509 Ma, paleogeographic map (left) and isopach image (right); key in Figure 12; paleolatitude from http://portal.gplates.org/

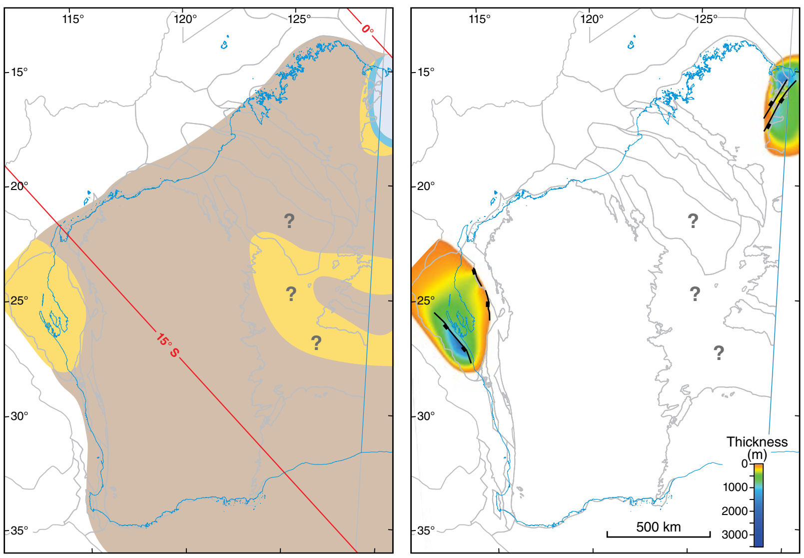


Figure 13c. Late Cambrian, 509–485 Ma, paleogeographic map (left) and isopach image (right); key in Figure 12; paleolatitude from http://portal.gplates.org/

In the East Kimberley, the uppermost part of the ~3.7 km-thick Louisa Downs Group above the mid-Ediacaran Egan Formation, and ~1.6 km of the Albert Edward Group above the Boonall Dolomite (partially equivalent to the Egan Formation), are possibly lower Cambrian (Fig. 3, queried in Fig. 13a) in spite of the lack of obvious trace or body fossils. The distribution of inferred lower Cambrian sections and Petermann Orogeny events on the margins of the Canning Basin indicates that Cambrian strata should be present especially within the Gregory Sub-basin – Crossland Platform – Kidson Sub-basins in the eastern half of the basin. In this area just two wells (Wilson Cliffs 1 and Patience 2) have penetrated beneath Ordovician strata but, given the high thermal maturity and intense silicification of these strata, they are more likely to be Precambrian than Cambro-Ordovician. Alternatively, it is possible that the Canning Basin region was a topographic high that shed sediment eastward for much of the Cambrian.

In the Officer Basin south of the Musgrave Province, an extensive but little-known succession (the 'Wirrildar beds') extends westward from South Australia. In South Australia, it consists of possibly up to 2.7 km of gently folded silty sandstone and sandy dolomite deposited in a marine to coastal setting, which appears to post-date the Petermann Orogeny and (because it is folded) pre-date the Table Hill Volcanics. In Western Australia this succession is evident only as photo-lineaments in an area covered by calcrete ridges south of the Musgrave Province. Nonetheless, this indicates an extensive early Cambrian depocentre that was at least partly marine.

The Kalkarindji LIP erupted in a brief but widespread event at about 511 Ma, approximately at the mid-Cambrian Series 2–3 boundary. Basalt flows in the Ord Basin (Antrim Plateau Volcanics, Fig. 14) and Officer Basin (Table Hill Volcanics) reach a maximum thickness of about 1500 m in the former suggesting its proximity to a major eruptive centre (Fig. 13b). Geochemically related dykes are present well to the west of preserved flows and the event can be traced as far east as western Queensland, attesting to its continental significance. Flows were channeled along dune corridors in the southern Officer Basin (Fig. 15) and in the western Northern Territory, implying an arid climate during extrusion.

The Kalkarindji LIP erupted in a brief but widespread event at about 511 Ma.

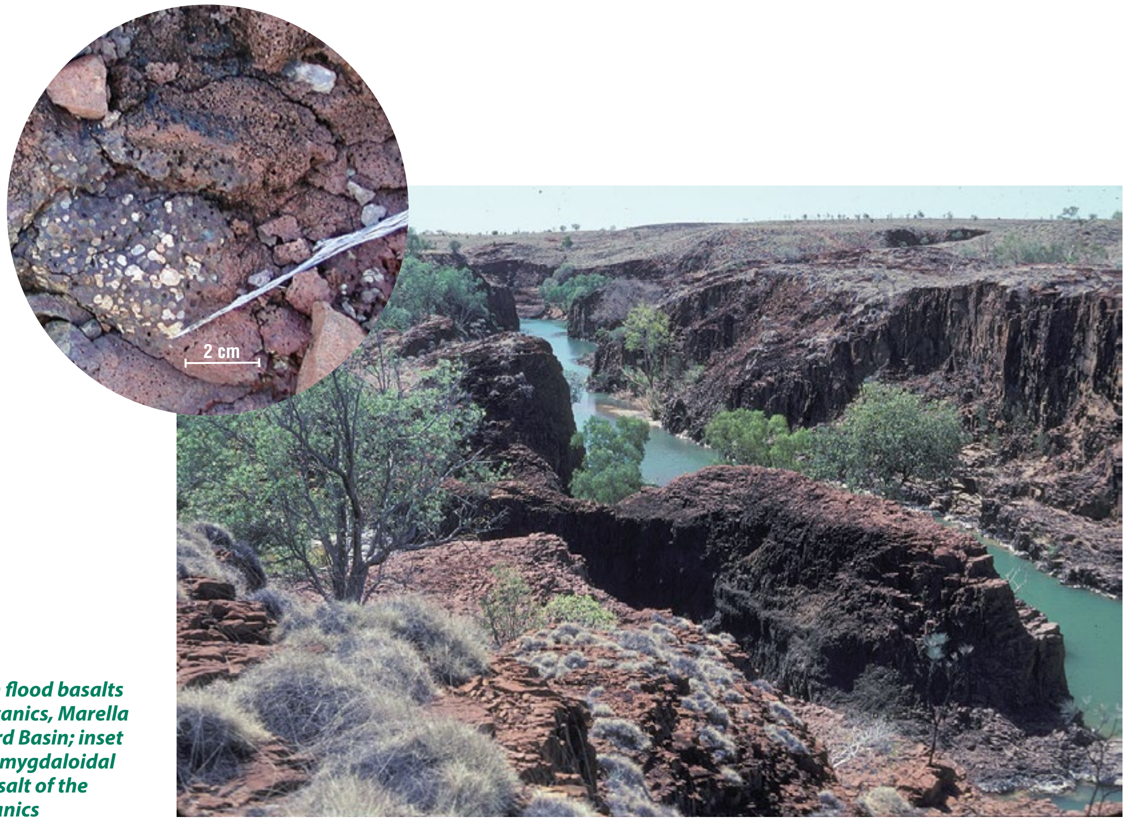


***Figure 14.** Mid-Cambrian flood basalts of the Antrim Plateau Volcanics, Marella Gorge, Nicholson River, Ord Basin; inset shows highly weathered amygdaloidal and vesicular tholeiitic basalt of the equivalent Table Hill Volcanics*

Subsidence following the eruption of the Antrim Plateau Volcanics led to shallow-marine to tidal inundation in the Southern Bonaparte and Ord Basins, with deposition of mostly marine siliciclastic sediment continuing to the end of the Cambrian in the north (Fig. 13c). The faunas imply a link to the Wiso and Georgina Basins to the southeast, although a more northerly marine connection to Paleo-Tethys is also possible. A similar, though intermittently marine, succession was deposited in the eastern Amadeus Basin in the Northern Territory, but a lack of fossil assemblages and identifiable time markers such as the Kalkarindji LIP make tracing this succession to the western Amadeus Basin equivocal, especially in Western Australia where apparently coeval sections are entirely non-marine. In the Southern Carnarvon Basin the presence of a possible offshore Cambrian sedimentary succession, up to 1500 m thick, is interpreted solely from seismic reflection data.

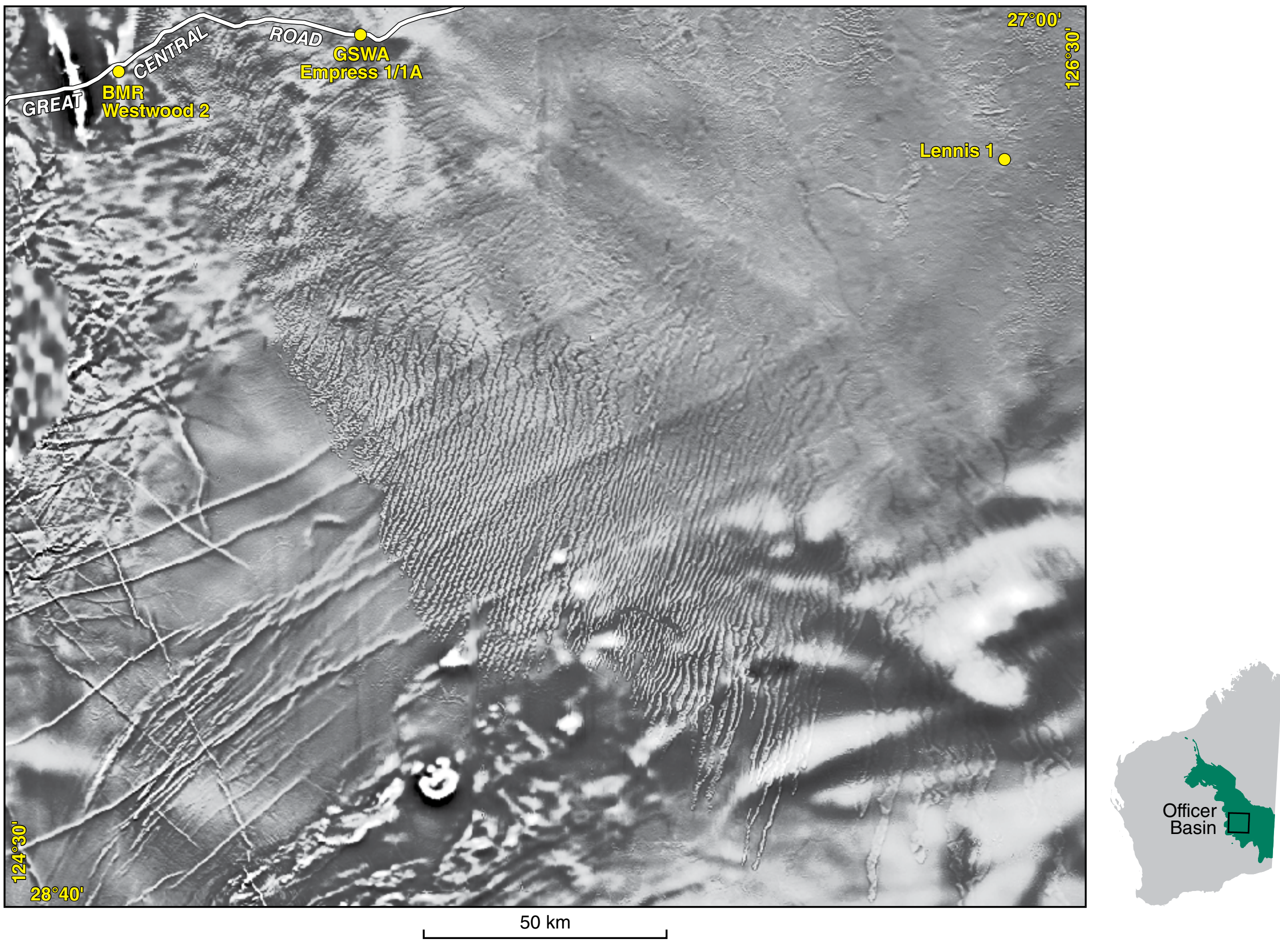


Figure 15. North-northeasterly basalt flows of the mid-Cambrian Table Hill Volcanics channelled along dune corridors, southern Officer Basin shown by aeromagnetic image (1st vertical derivative). Deeper burial to the north has obscured the magnetic character of the basalt in this image. Labelled wells intersect the Table Hill Volcanics

Ordovician to Early Devonian intracratonic rifting–sag

Northerly extension is indicated in northwestern Australia throughout this part of the Paleozoic, based on the west-northwesterly orientation of major depocentres within the Canning, Southern Bonaparte, and Arafura Basins, in contrast to the successive major compressional events in central Australia at this time. The central Australian events are grouped together as the Ordovician–Carboniferous Alice Springs Orogeny (Fig. 4) with its age based on an amalgamation of many disparate ages. How such events relate to those in northwestern Australia is unclear. In particular, the uncertainties in ages obtained from basement rocks in central Australia, and the lack of post-Devonian strata in many Centralian basins hinders differentiating shorter term events within the Alice Springs Orogeny.

Explanations for compression in central Australia vs extension to the northwest have invoked compartmentalization along a long-lived north-northeasterly striking structure extending south of the Halls Creek Orogen, variations in upper mantle flow beneath the continent, and rheological differences in basement along a northwesterly striking suture zone along the northern margin of the Broome–Crossland Platforms in the Canning Basin (the likely boundary between the North Australian and West Australian Cratons). The latter two explanations are not necessarily mutually exclusive in that they could explain the different responses to north-northeast–south-southwest compression that segregated the Canning Basin. This is especially manifested in the thick salt and restricted marine deposits that accumulated in the Late Ordovician – Silurian in the southern half of that basin (see pull-out box, *Evaporites*, page 45). Farther north salt-bearing deposits in the Petrel Sub-basin and Goulburn Graben of the Northern Bonaparte and Arafura Basins, respectively, may have had a similar origin but their age is unclear as these facies are only known indirectly from salt diapirs and seismic reflection data (Fig. 7).

Existing tectonic reconstructions imply the compartmentalization of stresses across Australia during the Alice Springs Orogeny was entirely intracratonic as they show little change in the relative positions of Gondwanan continental

Northerly extension is indicated in northwestern Australia from Ordovician to Early Devonian.

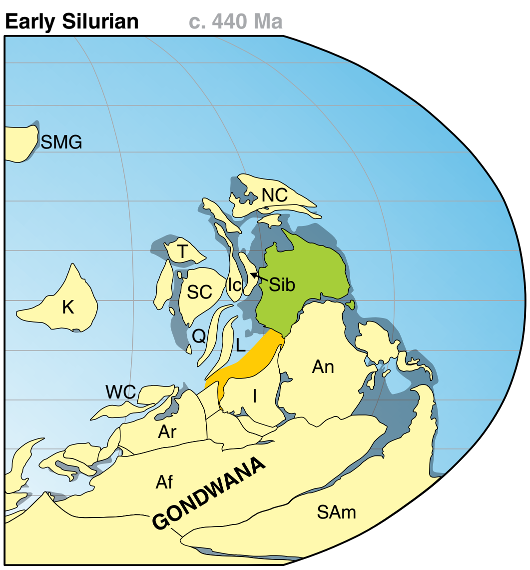


Figure 16. Early Silurian tectonic reconstruction (after http://portal.gplates.org/); key to various blocks in Figure 11

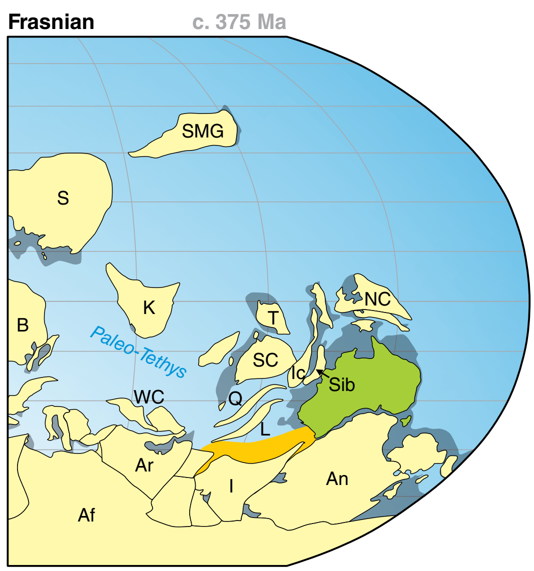
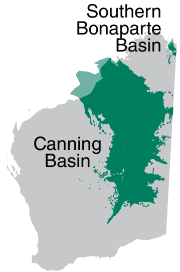


Figure 17. Frasnian (Late Devonian) tectonic reconstruction (after http://portal.gplates.org/); key to various blocks in Figure 11

blocks (compare Figs 11, 16, 17). Earlier extension and subduction along the eastern margin of Australia was orthogonal to this direction. However, this change is not obvious in northwestern Australia, where the west-northwesterly strike of major depocentres within the Canning, Southern Bonaparte, and Arafura Basins indicates northerly extension throughout the Paleozoic. In addition there was some fault control along the northeastern and southwestern margins of the West Australian Craton between the Ordovician and the Early Devonian (Figs 18a,b and 19a,b). In the Southern Carnarvon Basin, the inferred movement down-to-the-west along the eastern margin of the Gascoyne Platform is opposite to that in the Permian.

Depositional history

In the Canning Basin the onset of deposition in the Early Ordovician contrasts with the Southern Bonaparte and Arafura Basins where deposition seemingly continued without an obvious break from the Cambrian (Figs 2–3). Whether the Nambeet Formation and Wilson Cliffs Sandstone of the Canning Basin (with thicknesses exceeding 775 m in Samphire Marsh 1, and 731 m in Wilson Cliffs 1, respectively) are partly late Cambrian in age is uncertain; however, that is unlikely for the Nambeet Formation, based on intraformational divisions showing significant thickness changes. Furthermore, the Kudata Dolomite (lower Prices Creek Group) on the Lennard Shelf contains an



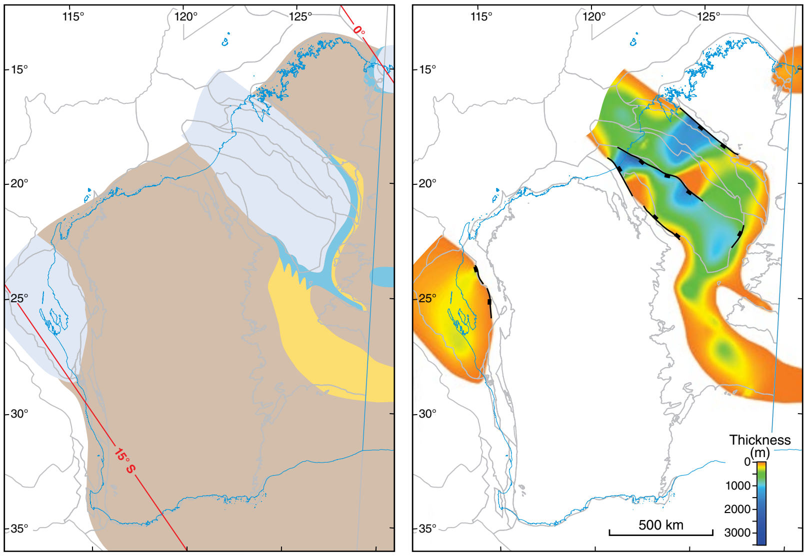


Figure 18a. Early Ordovician, 485–458 Ma, paleogeographic map (left) and isopach image (right); key in Figure 12; paleolatitude from http://portal.gplates.org/

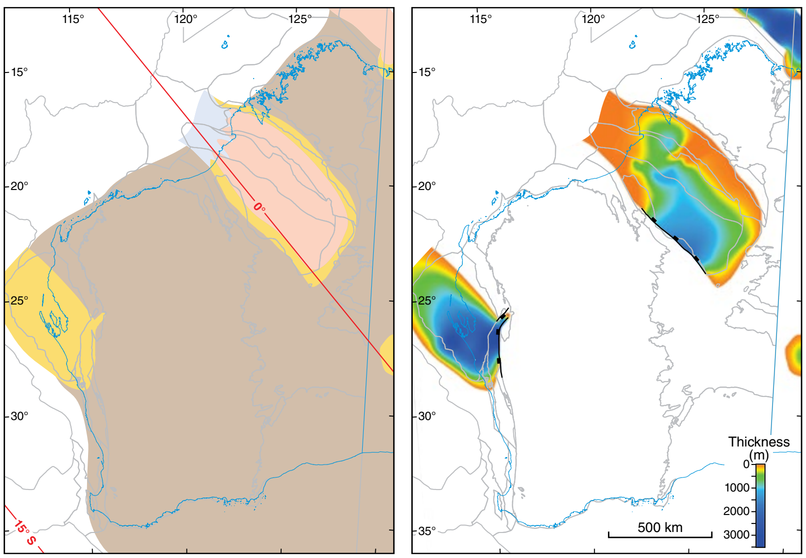


Figure 18b. Middle–Late Ordovician, 458–438 Ma, paleogeographic map (left) and isopach image (right); key in Figure 12; paleolatitude from http://portal.gplates.org/

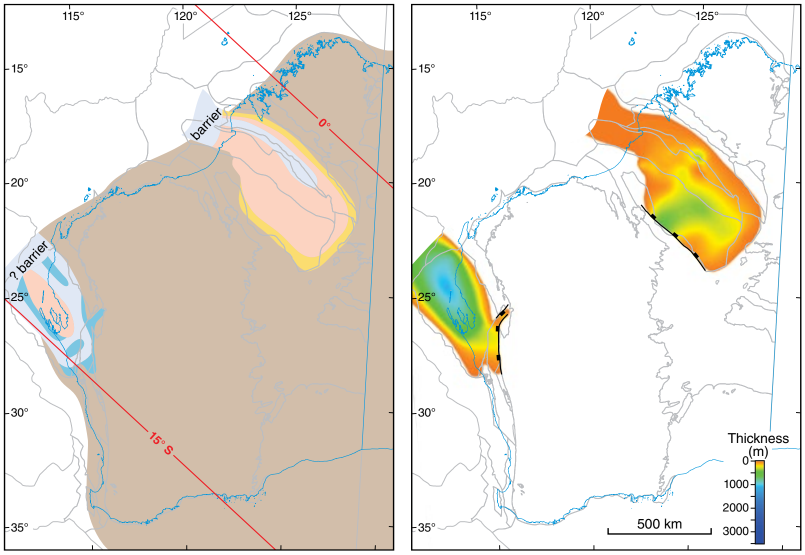


Figure 19a. Silurian, 438–419 Ma, paleogeographic map (left) and isopach image (right); key in Figure 12; paleolatitude from http://portal.gplates.org/

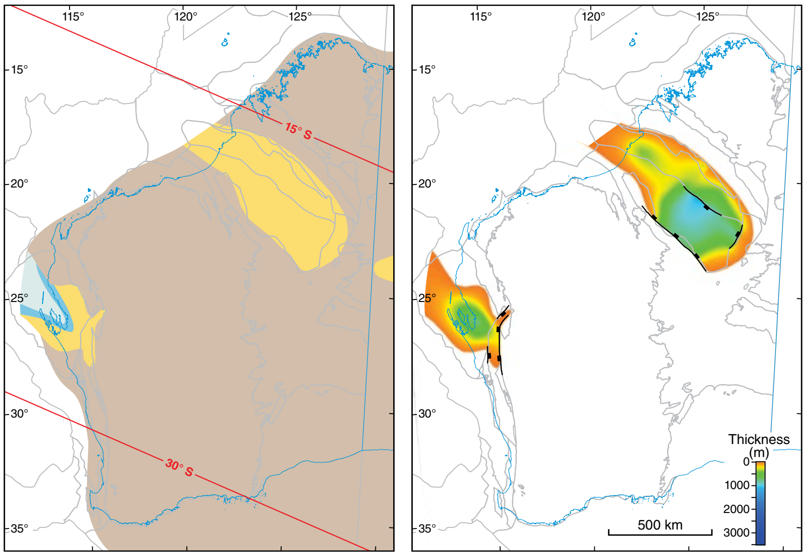


Figure 19b. Early Devonian, 419–388 Ma, paleogeographic map (left) and isopach image (right); key in Figure 12; paleolatitude from http://portal.gplates.org/

Angular unconformity between Ordovician Gap Creek Formation (below) and late Givetian Cadjebut Formation, Emanuel Range, Canning Basin

Figure 20. Lower Ordovician limestone and shale outcrop, Prices Creek, northern Canning Basin

earliest Ordovician conodont fauna indicating it correlates with the Nambeet Formation; by comparison the Kunian Sandstone (basal Prices Creek Group) remains undated and so may extend into the Cambrian.

The best-known Ordovician sections in the State are from the Canning Basin and include outcrops of the Prices Creek Group along its northern margin (Fig. 20). The interval showing the greatest marine influence is of Tremadocian–Darriwilian (Lower–Middle Ordovician) age culminating with warm water mud–carbonate deposition (Goldwyer and Nita Formations, Fig. 3). Algal mounds developed along the Admiral Bay Fault Zone in the Middle Ordovician became the loci of mineralization during Late Ordovician – Early Silurian and Devonian burial, probably combining metal-rich basinal fluids and sulfate from Ordovician–Silurian anhydrite (see pull-out box, *Lead and zinc mineralization,* p. 27; Fig. 21). Although these Middle Ordovician sections have clear correlatives in the Amadeus, Wiso, and Georgina Basins to the east, a connection via the supposed Larapintine Seaway is uncertain as existing paleontological evidence for such a connection is weak — the hypothesis requires a more-detailed assessment of non-pelagic shelly fossils from both the Amadeus and Canning Basins than is currently available.

By comparison, an early Ordovician non-marine connection, via the Officer Basin into South Australia, seems more likely (Fig. 18a) but assumes the Lennis Sandstone in Western Australia is of this age.

By the Late Ordovician, marine influence waned and paralic deposition became widespread in the Canning Basin, and extended into the Southern Carnarvon Basin and probably much of the Petrel Sub-basin of the Northern Bonaparte Basin (Fig. 18b). Evaporitic conditions were periodically established in the Canning Basin, possibly at the same time as thick halite accumulations formed in the Petrel Sub-basin, Northern Bonaparte Basin (Fig. 18b, see pullout box, *Evaporites*, page 45). Barriers allowing intermittent ingress of seawater presumably developed near the northwestern ends of these basins, or across the blocks that later formed the Cimmerian continent. The sandy redbeds in the Southern Carnarvon Basin (Tumblagooda Sandstone, Fig. 22) had oceanic connections based on a rich ichnofauna (see pull-out box, *Early life on land at Kalbarri*, page 28) and abundant tidal structures but, as with the other basins, connections to Paleo-Tethys could only have been indirect at this time.

Significant Mississippi Valley-type (MVT) zinc–lead mineralization is known from the Canning and Bonaparte Basins.

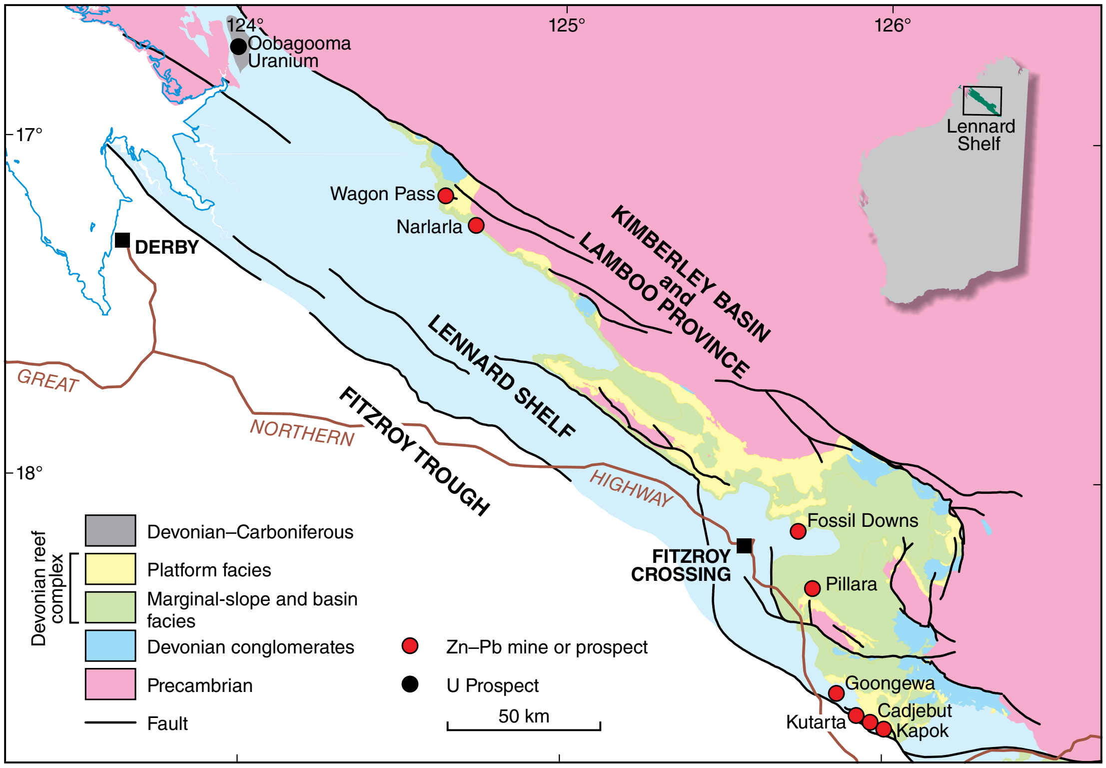


Figure 21. The Lennard Shelf MVT district, northern Canning Basin

Zinc and lead mineralization

Significant Mississippi Valley-type (MVT) zinc–lead mineralization is known from the Canning and Bonaparte Basins, hosted within Paleozoic ramp- and reef-carbonates. In the Canning Basin two mineralizing events are recognized: i) Late Silurian to Early Devonian (Admiral Bay deposit); and ii) Late Devonian to earliest Carboniferous (Lennard Shelf MVT district). In the Bonaparte Basin mineralization is hosted in both Upper Devonian and Lower Carboniferous reef and platform carbonate facies.

The giant Admiral Bay sulfide deposit, discovered in 1981 by Meridian Oil's petroleum exploration well Great Sandy 1, is hosted in ramp carbonates of the Lower Ordovician Nita and Goldwyer Formations in the Willara Sub-basin of the Canning Basin. Metalicity Limited reports inferred resources of 170 Mt at 4.1% Zn, 2.7% Pb, and 25 g/t Ag, and in November 2016 advised that it had commenced a pre-feasibility study. The stratabound deposit extends over a strike length of 19 km at depths of between 1200 and 1600 m. The mineralization was sourced by metalliferous brines, probably from Precambrian and Ordovician rocks, and migrated along the transpressional Admiral Bay Fault Zone into an anticlinal trap probably during the Late Silurian.

The Lennard Shelf MVT sulfide deposits (Fig. 21) consist of eight established relatively small and isolated zinc–lead bodies with minor silver. The deposits are hosted in platform and marginal-slope carbonate facies of the Middle to Upper Devonian reef complexes. The Narlarla deposit was mined briefly in 1906, and mined out in the 1950s and 1960s. Exploration of the Lennard Shelf in the 1970s discovered the Cadjebut and Pillara deposits (in 1978), followed by Goongewa (1985), and Kapok (1989). Cadjebut, Goongewa, and Kapok have been mined out and Pillara is now classified as on care-and-maintenance. Other small deposits such as Kutarta are currently uneconomic, and the Fossil Downs and Napier Range (Wagon Pass) prospects require further resource assessment. Production from the region yielded 977 000 t Zn, 412 000 t Pb and 17 t Ag. Remaining resources estimated by Meridian Minerals, now Northwest Nonferrous Australia Mining Pty Ltd, under the JORC Code (Joint Ore Reserves Committee) are 17.7 Mt at 5.4% Zn and 4.1% Pb for 960 000 t Zn and 725 000 t Pb.

Mineralization across the Lennard Shelf was controlled by a combination of dolomitization, extensional faults, basement highs, brecciation, and facies contacts. Fluids probably migrated during the latest Famennian to earliest Carboniferous, soon after the deposition of the reef complexes. For deposits on the faulted margin of the shelf the metal source was probably from deep within the adjoining Fitzroy Trough, possibly from both Precambrian and Paleozoic rocks. Basinal brines migrated along regional aquifers and up northeasterly trending faults and fractures into platform carbonates and evaporitic carbonates along the leading edge of the Lennard Shelf, where dolomitization of the host rocks helped trap the hydrothermal fluids. For other deposits and prospects farther from the Fitzroy Trough mineral-bearing fluids probably came from local sources. The small size of deposits discovered so far means that the district is not perceived as highly prospective on a global scale.

Several small MVT deposits are hosted in Upper Devonian and Lower Carboniferous carbonate rocks in the Southern Bonaparte Basin. At Sorby Hills, 46 km north-northeast of Kununurra, 13 irregular mineralized bodies are present along an 8 km trend hosted in Lower Carboniferous carbonate and siliciclastic rocks of the Burt Range Formation. According to KBL Mining Ltd the indicated and inferred resources for these bodies are 16.5 Mt at 4.7% Pb, 53 g/t Ag and 0.7% Zn. The lead–zinc mineralization is breccia-hosted and controlled by a combination of dolomitization, faulting, collapse features, paleohighs, paleochannels, and minor unconformities. The metal source was probably from more deeply buried Devonian–Carboniferous basinal facies.

Other lead–zinc prospects, presently sub-economic, are present along the Ningbing Range in the Southern Bonaparte Basin within platform and marginal-slope carbonate facies of an Upper Devonian reef complex similar to that hosting the Lennard Shelf MVT district, and also in the Southern Carnarvon Basin within shallow-marine carbonate-bank facies of the Devonian Gneudna Formation and Lower Carboniferous Moogooree Limestone.

Figure 22. Upper Ordovician – Lower Silurian coastal-channel and bay facies, Tumblagooda Sandstone; Red Bluff, Southern Carnarvon Basin

Early life on land at Kalbarri

The Upper Ordovician – Lower Silurian Tumblagooda Sandstone is exposed along the Murchison River gorge and in coastal cliffs in Kalbarri National Park, 600 km north of Perth. The sandstone contains diverse trace-fossil assemblages, possibly showing evidence of invertebrate animals' first steps onto land. The traces include burrows, trails, scratch marks, tunnels, and trackways probably created by over 30 animal species, including several types of arthropods. Most of the traces were produced by animals living under water in coastal–deltaic environments, but the preservation and degree of detail of some seems to indicate that they were formed on damp but emergent sand and silt suggesting an amphibious life style for at least the larger arthropods. Based on their morphology and width, the large trackways at the Z Bend and The Loop in the National Park were probably made by eurypterids (an extinct group akin to scorpions but related to arachnids, a class of eight-legged invertebrates) up to one metre long. Intensely burrowed, churned-up beds can be seen at all lookouts, and were formed by systematic mining of sediment for food by worms and other animals. Similar trace fossils are found in the Devonian Taylor Group in Antarctica and the Ordovician–Silurian Mereenie Sandstone at Kings Canyon in central Australia.

Criss-crossing arthropod trackways of possible *Eurypterid* origin on a rippled surface of the Tumblagooda Sandstone, Kalbarri

Silurian deposition appears to have been restricted to the Southern Carnarvon and Canning Basins (Fig. 19a). Low-diversity conodont assemblages from the Dirk Hartog Group in the Southern Carnarvon Basin indicate periods of isolation from Paleo-Tethys at this time (Fig. 16). Although few ages are available from the apparently coeval Worral Formation in the Canning Basin, this does not necessarily mean the basin was more isolated from Paleo-Tethys than the Southern Carnarvon Basin. The similarity in lithology (apart from the lack of salt in the Canning Basin), the inferred restricted-marine conditions for both basins, and slow deposition (<50 m/Ma), indicates comparable intracratonic controls, in many ways similar to those for the Early Devonian.

In the Early Devonian, deposition fluctuated between very shallow-marine and sabkha, and fluvial–eolian conditions in the Southern Carnarvon Basin, whereas fluvial–eolian conditions dominate in the Canning Basin (Fig. 19b). In both basins, the Lower Devonian succession is known only from subsurface intersections. Both regions probably lay in the same global climate cells, but were not directly connected.

Middle Devonian to mid-Carboniferous rifting–sag

This phase of rifting marks a major change in the style of basin development across the State and the highest rates of deposition for the Paleozoic (Fig. 6b). In addition, the positions of depocentres relocated eastward in the Southern Carnarvon Basin and northward in the Canning Basin. The phase coincides with the most rapid southerly movement of the part of Gondwana that eventually became Australia. However, how that influenced tectonic events within this region, or along its periphery, is poorly understood.

A phase of marked extension that commenced during the Givetian – middle Famennian (mid- and Late Devonian) is implied by at least 3.5 km of strata that accumulated in the main depocentres (Fitzroy Trough and Petrel Sub-basin; Fig. 23a) at an overall rate of about 150 m/Ma (Fig. 6b). Rapid deposition continued in the late Famennian to near the end of the Carboniferous in these depocentres at up to ~200 m/Ma (Figs 6b, 23b) denoting continued tectonic control on subsidence.

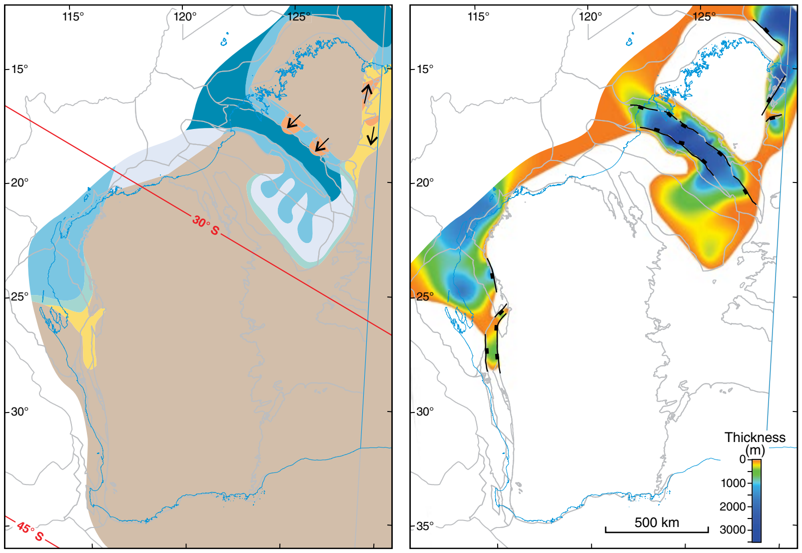


Figure 23a. Givetian – mid-Famennian (Middle–Late Devonian; 388–363 Ma) paleogeographic map (left) and isopach image (right); key in Fig. 12; paleolatitude from http://portal.gplates.org/

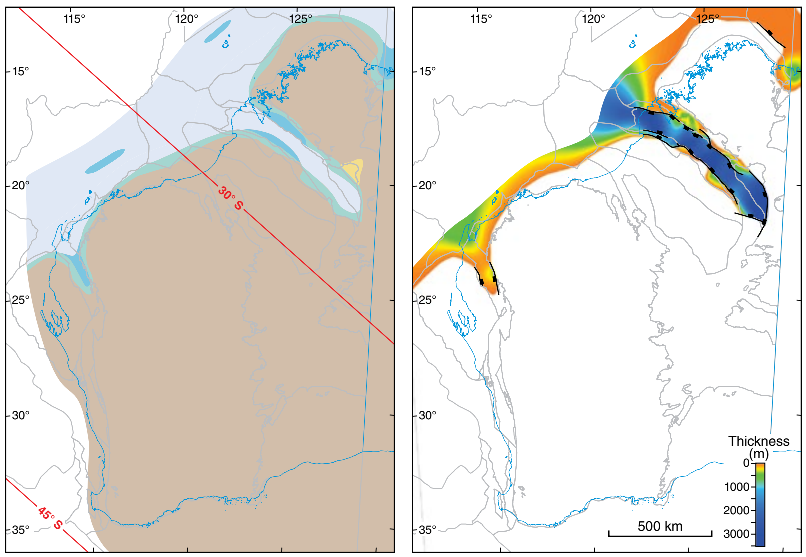


Figure 23b. Late Famennian – Tournaisian (363–350 Ma) paleogeographic map (left) and isopach image (right); key in Figure 12; paleolatitude from http://portal.gplates.org/

These deposits are inferred as having a synorogenic origin, presumably related to rifting of various continental blocks along the northern margin of Gondwana (compare Figs 17 and 24) and possibly the later phases of the Alice Springs Orogeny in central Australia (Pertnjara–Brewer Movement in central Australia, Pillara Extension in the northern Canning Basin). In the Southern Bonaparte and Ord Basins, reactivated strike-slip movements along the Halls Creek Fault Zone on the edge of the Halls Creek Orogen in the Frasnian (Late Devonian) were probably related to north–south shortening associated with the Alice Springs Orogeny in central Australia. This uplift may have been the origin of siliciclastic sediment dispensed west-southwest into the northern Canning Basin, and probably also controlled the development and infill of the Bonaparte and Ord Basins.

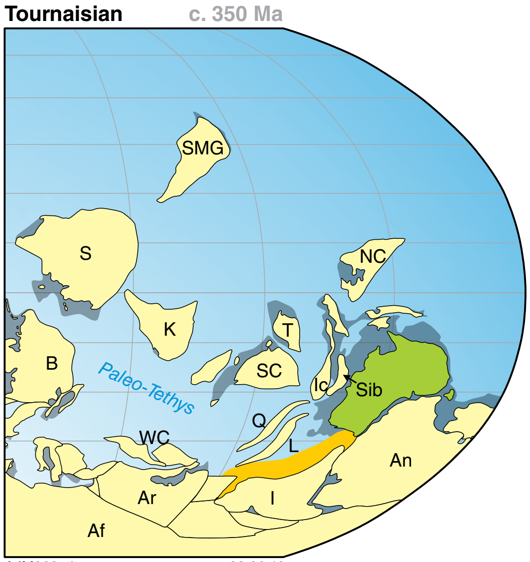


Figure 24. Tournaisian (Early Carboniferous) tectonic reconstruction (after http://portal.gplates.org/); key to various blocks in Figure 11

Apparent gaps in sedimentation from about the Givetian to near the end of the Carboniferous across the southern Canning Basin, and late Emsian to Permian across the Gascoyne Platform (Southern Carnarvon Basin), suggest local uplift across those sub-basins. The relatively low thermal maturity of strata from those areas indicates they more likely became relative highs compared to adjacent younger depocentres. Such relative elevation hints at local compression, perhaps due to heterogeneities in basement rheology within the West Australian Craton beneath the southern Canning Basin and the Pinjarra Orogen beneath the eastern part of the Southern Carnarvon Basin.

Depositional history

The Middle–Late Devonian saw the widespread development of carbonate platforms and reefs (see pull-out boxes, *Devonian reefs*, page 31 and *Life in Devonian and Permian seas*, page 32), albeit locally interrupted by thick clastic deposits along the faulted margins of the Southern Carnarvon, Canning, and Bonaparte Basins (Fig. 23a). Evidence for interbasin connection is clear for the first time in the Paleozoic. Paleocurrents from alluvial and fluvial clastic facies in Purnululu National Park or the Bungle Bungles of the Ord Basin indicate a link to deltaic facies across the Billiluna Shelf in the northeastern Canning Basin. In addition, the similarity of carbonate facies in the Canning and Southern Bonaparte Basins indicates some sort of connection around the North Australian Craton. In the Canning Basin, the Late Devonian probably had the most direct connection to oceanic circulation of any part of the Paleozoic, based on faunal similarity with that of Upper Devonian sections in present-day Europe (see pull-out box, *Dating the Paleozoic*, page 9). Although terranes such as Sibumasu, and other blocks within the Cimmerian continent, lay adjacent to northwest Australia, they presumably did not hinder oceanic circulation into the Canning Basin at this time (Fig. 17, c. 375 Ma).

Well-exposed Upper Devonian carbonate rocks along the northern margin of the Canning Basin are amongst the world's best examples of exhumed reef complexes (Fig. 25) and host several small MVT deposits and oil fields (see pull-out boxes, *Lead and zinc mineralization*, page 27, and *Oil and gas*, page 44). These carbonates are coeval in part with similar facies in the Southern Bonaparte Basin, with bank–shelf facies along the southern margin of the Fitzroy Trough (now strongly dolomitized), and with bank–shelf facies in the Southern Carnarvon Basin. Whether these carbonates flanked the entire Kimberley region in the Late Devonian is uncertain. Disparities between these carbonates on the Lennard and Carlton Shelves (see *Frontispiece* for locations), including later onset of carbonate deposition near the Frasnian–Famennian boundary and an early Famennian backstep of the reef in the Carlton Shelf, indicate localized tectonic events. Basinal shale and mudstone seaward of the reef complexes are rich hydrocarbon source rocks,

Devonian reef complexes of the Canning Basin may be the world's best example of an exposed ancient barrier reef system.

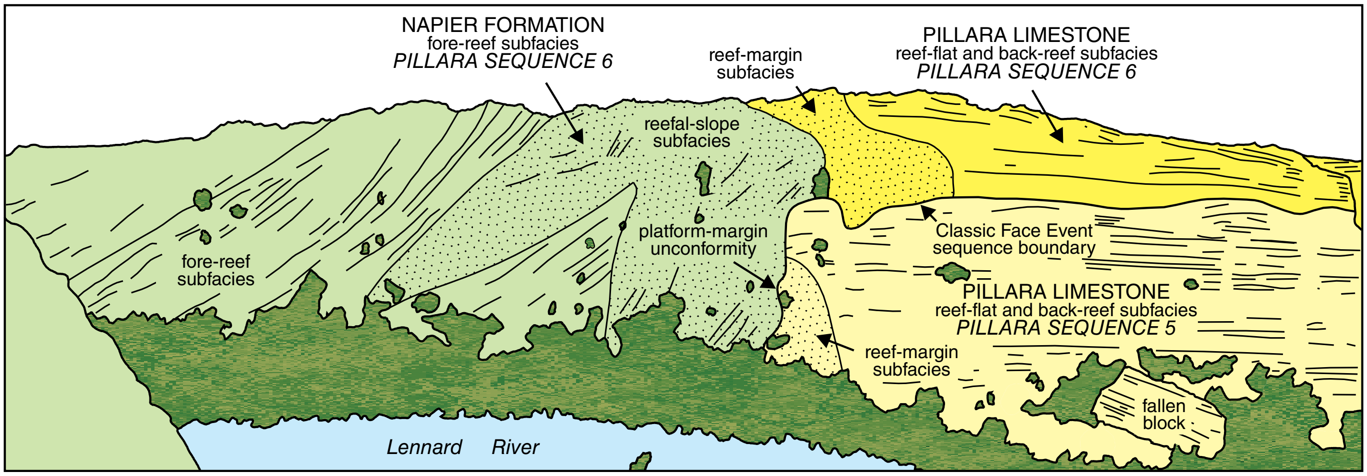


Figure 25. Top: Panoramic view, looking southwest, of the classic face of the Upper Devonian reef complex at Windjana Gorge, northern Canning Basin; the cliff is about 60 m high; bottom: Distribution of facies (after Playford, et al., 2009, fig. 486)

Devonian carbonate reefs

Devonian reef complexes form rugged limestone ranges along the northern edge of the Canning Basin (Fig. 25), and may be the world's best example of an exposed ancient barrier reef system comparable to the modern Great Barrier Reef along Australia's northeast coastline. The reef system formed as fringing barrier reefs, atolls, and banks that grew on and abutted Proterozoic sedimentary, igneous, and metamorphic rock for 350 km along strike (Fig. 23a). The rocks are prospective for both zinc and lead deposits and petroleum (see boxes, *Lead and zinc mineralization* and *Oil and gas*), and are used as a comparative exploration and depositional model for reefs that host prolific oilfields elsewhere in the world from Canada to Kazakhstan.

Platform, marginal slope, and basin deposits are all spectacularly exposed in the reef complexes, especially in Windjana Gorge. The platforms were constructed by shallow-water organisms in shallow subtidal to intertidal and lagoonal environments forming horizontal beds protected by fringing, rigid, wave-resistant reefs. The reefs built over the flanking marginal-slope down which mostly platform-derived debris accumulated on steep slopes extending to water depths of several hundred metres. The slope deposits grade into basin facies consisting of gently sloping to horizontal calcareous mudstone and sandstone beds. The platforms grew vertically and periodically back-stepped during a long-term Givetian–Frasnian global transgression. As the transgression peaked and sea level fell during the latest Frasnian and Famennian the platforms advanced and grew rapidly seawards, but not enough to offset subsidence or to allow prolonged emergence. The Frasnian–Famennian boundary marks a major global mass extinction of metazoan organisms, and in the reef complexes is reflected by a distinct demise of the stromatoporoids and corals as reef builders across a relatively brief sea-level fall of about 100 to 200 m. The Kellwaser anoxic events that are recognized at this boundary in Europe have been found in the reef complexes but without marked anoxia; possibly the age of the events in Australia varies slightly from that in Europe. The demise of the reefs late in the Famennian is associated with subaerial exposure indicating a drop in sea level of at least 100 m, possibly due to a sudden decrease in seawater temperatures following an onset of glaciation in the southern polar region.

Recently, a paleomagnetic record for the Late Devonian has been established from the reef complexes, fleshing out a previously unknown part of the Earth's paleomagnetic history and paleomagnetic path. The new data indicate Australia lay about seven degrees closer to the equator in the Late Devonian and was oriented somewhat more counter-clockwise compared with its present position.

and may be terrigenous material that bypassed the reef areas via large channels which, in the Canning Basin, are filled with conglomerate.

The Frasnian/Famennian extinction, at c. 372 Ma, is one of the major global extinction events, and coincides with the peak of a long-term Frasnian–Famennian transgressive–regressive couplet in Western Australia. In the Canning Basin reef complexes depositional rates were much slower by a factor of 3 or 4 in the Famennian due to long-term regressive conditions vs the Frasnian transgressive setting, except in areas subject to active tectonic subsidence. The global extinction is marked by a major faunal overturn in Western Australia when shallow water fauna such as stromatoporoids became extinct, and deeper water organisms moved into vacant ecological niches. There was also a marked sea-level fall across the boundary, estimated from outcrop in the Canning Basin at between 100 and 200 m, which lasted perhaps a million years. There are distinct anoxic events near or at the boundary in Europe, whereas those recognized in the Canning Basin reef complexes have minimal associated anoxic effects and slightly pre-date the Frasnian/Famennian boundary, raising the possibility that they are not synchronous with the European events.

Siliciclastic sediment influx was locally dominant in the Southern Bonaparte Basin throughout the Frasnian, but intermittent for the entire Late Devonian in the Canning Basin. The source of this sediment was largely a product of uplift associated with contemporaneous strike-slip movements along the Halls Creek Fault System in the east Kimberley. In the Ord Basin alluvial

Life in Devonian and Permian seas

Upper Devonian and Lower Permian rocks of Western Australia contain some exceptional marine fossil assemblages that have captured global attention.

The Gogo Formation, a basin facies of the Devonian reef complex in the Canning Basin (see box, *Devonian reefs*), has nodules containing exquisitely preserved armored fish and sharks (more than 50 species) including fragile soft-tissue, such as nerves and embryos with umbilical cords. Arthropods, nautiloids, ammonoids, and other invertebrates have also been extracted from the nodules, but no signs of soft-tissue preservation have been found for these. The assemblage is from a facies deposited in subtropical waters perhaps approaching 500 m deep; this, and other similar Upper Devonian facies in the reef complexes, is amongst the deepest water Paleozoic facies preserved in mainland Western Australia and, given the prevalence of cosmopolitan species, arguably shows the best connection to Tethys.

Since the discovery of Permian fossils in Western Australia in 1861 several hundred species of marine invertebrate fossils from diverse shallow-water assemblages have been described, mostly from the Sakmarian–Kungurian. These assemblages include foraminifers, brachiopods, bivalves, bryozoans, excellently preserved crinoids (illustrated at right), corals, blastoids, nautiloids, and others. Also present are abundant trace fossils indicating invertebrate and crustacean feeding and other activities, but few of these have been described (unlike for the Ordovician – Lower Silurian, see box, *Early life on land at Kalbarri*). The immediate post-glacial Lower Permian successions show the greatest marine influence, and indicate a general warming in climate, but connections to the open ocean (Meso-Tethys, Fig. 29) must have been indirect judging from the largely endemic species present (see box, *Dating the Paleozoic*). By comparison, eastern Australian Permian faunas are far less diverse indicating the influence of strong polar Panthalassan currents. The inference from the Permian fossil assemblages above the Lower Permian glacial facies in Western Australia is that temperate–warm, shallow, interior seas, likely no deeper than 30 m, extended into the Canning and Southern Bonaparte Basin, and along the narrow depocentres on the estern margin of the Southern Carnarvon Basin into the northern Perth Basin (Fig. 28b). However, these seas could not have been well connected to Tethys as the macrofaunas, although diverse, comprise dominantly endemic species.

Jimbacrinus bostocki in Cundlego Formation, 3.2 km east of Jimba Jimba Homestead, Gascoyne region. Image courtesy Didier Descouens from https://commons.wikimedia.org./wiki/File:jimbacrinus_bostocki_MHNT_Gascoyne_Junction_Western_Australia.jpg fans shed southward off an east–west striking fault (in present-day Osmand Range); these facies are limited to the northern part of Bungle Bungle Range in Purnululu National Park and grade into sandy fluvial–eolian facies farther south within which karstic towers developed in the Cenozoic (see panorama below). Frasnian sandstones of the Southern Bonaparte Basin also have a similar origin, but were largely produced by northerly directed sediment transport — they show comparable landforms to those in the Ord Basin, but are not as well developed. In the Canning Basin there were separate Frasnian and Famennian phases of such sedimentation that cut through, and were syndepositional with, carbonate reef facies. In the Southern Carnarvon Basin Frasnian marine carbonate–mud facies were supplanted by siliciclastic facies in the Famennian. The Upper Devonian siliciclastic deposits are inferred to have a synorogenic origin, and are possibly related to the coeval Alice Springs Orogeny in central Australia. However, the coarse-grained clastic facies in the Southern Carnarvon Basin are too remote from central Australia to be explained so simply.

Reefal extinction in the late Famennian coincided with another brief but significant regression and the cessation of microbial deposition. It was sufficiently long for caves and drainage notches to develop in the exposed faces of reef scarps thereby confirming a drop in sea level of at least 100 m. The uppermost reef-flat surfaces locally show large desiccation polygons, preserving the start of emergence, directly overlain by low-energy silty carbonates. The regression was followed by mixed siliciclastic and carbonate bank–shelf deposition that continued into the earliest Carboniferous.

Carbonate deposition declined at the end of the Devonian, even though carbonate banks were still present locally especially in the Canning

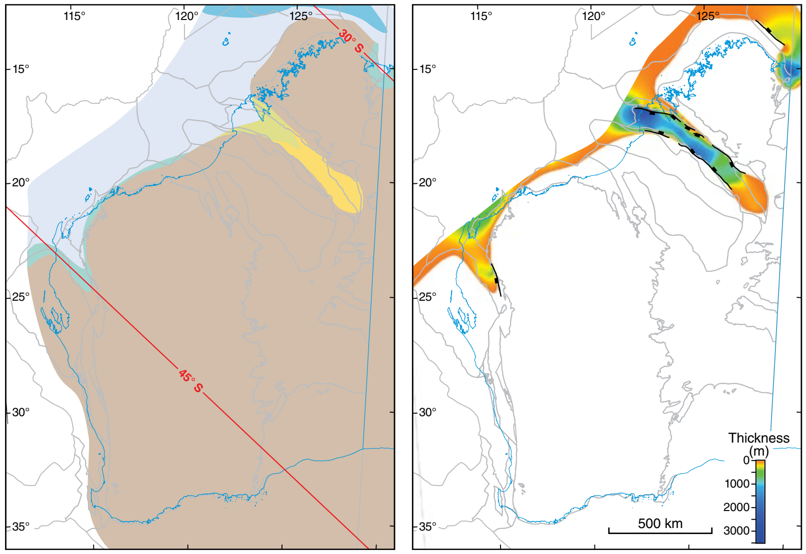


Figure 26a. Visean (350–330 Ma) paleogeographic map (left) and isopach image (right); key in Figure 12; paleolatitude from http://portal.gplates.org/

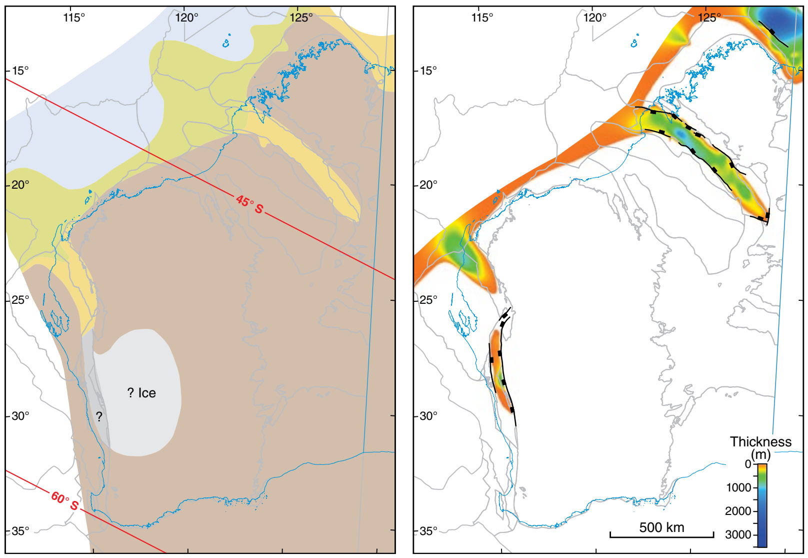
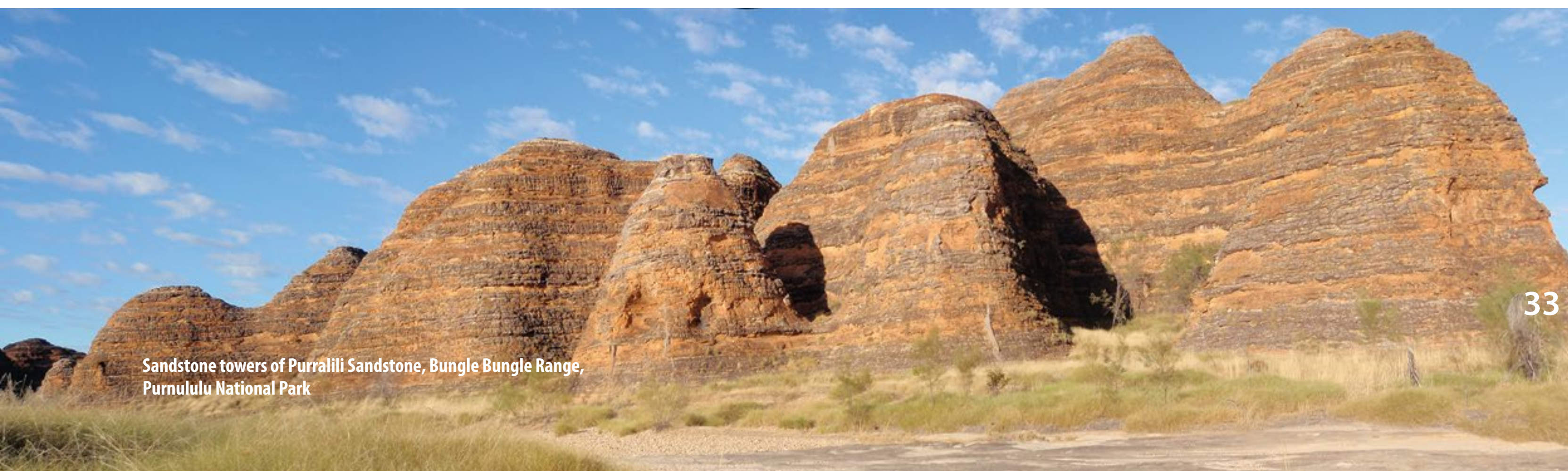


Figure 26b. Late Visean – Bashkirian (330–315 Ma) paleogeographic map (left) and isopach image (right); key in Figure 12; paleolatitude from http://portal.gplates.org/



Sandstone towers of Purralili Sandstone, Bungle Bungle Range, Purnululu National Park

Basin, and sedimentation contracted markedly into the Petrel, Fitzroy–Gregory, and northern Merlinleigh Sub-basins (Figs 23b, 26a). This period was also characterized by relatively rapid deposition (up to ~200 m/Ma in the latest Devonian to Tournaisian, Figs 6b, 23b), implying continued tectonic control on subsidence, perhaps associated with some movement of the continental blocks outboard of the Australian continent (Fig. 24). Although a disconformity can be demonstrated between the mid-Tournaisian and Visean (Early Carboniferous) in the Southern Bonaparte and Canning Basins the presence of this break in the Southern Carnarvon Basin is uncertain. The relevant section, the Williambury Formation, has only been dated from its stratigraphic position below the mid-Visean Yindagindy Formation, but is presumed to be at least partially equivalent to the Anderson Formation and Weaber Group in the Canning and Southern Bonaparte Basins, respectively (Figs 2, 23b, 26a).

Upper Visean to Bashkirian (mid-Mississippian – Lower Pennsylvanian) deposits range from possible fluvioglacial facies north of Mullewa in the northern Perth Basin to entirely fluvial facies in the Canning Basin (Fig. 26b). In eastern Australia (and other parts of Gondwana) coeval deposits show clear glacial features, but this part of the succession appears to be entirely fluvial in Western Australia with the possible exception of some outcrops close to the Darling Fault in the northern Perth Basin. These facies are best dated in the Canning Basin from spore–pollen assemblages, although the age of such assemblages is poorly constrained. Well correlations indicate a major mid-Pennsylvanian break in deposition of about 15 Ma (Fig. 6b), especially in the Canning Basin, a break not obvious in seismic reflection profiles. Additionally, it is unclear whether units of apparently similar age within the Southern Carnarvon Basin (Harris Sandstone and Quail Formation) are older, younger, or synchronous with this break. Regional correlations indicate that about half of the Pennsylvanian is missing (approximately Moscovian to mid-Gzhelian) across Western Australia and in the continental fragments Sibumasu and west China, which at the time lay outboard of the Canning Basin (Fig. 27). Possible reasons for the Pennsylvanian break in the sedimentary record must incorporate environmental factors, such as the presence of a large ice sheet preventing sediment reaching west Australian basins (see

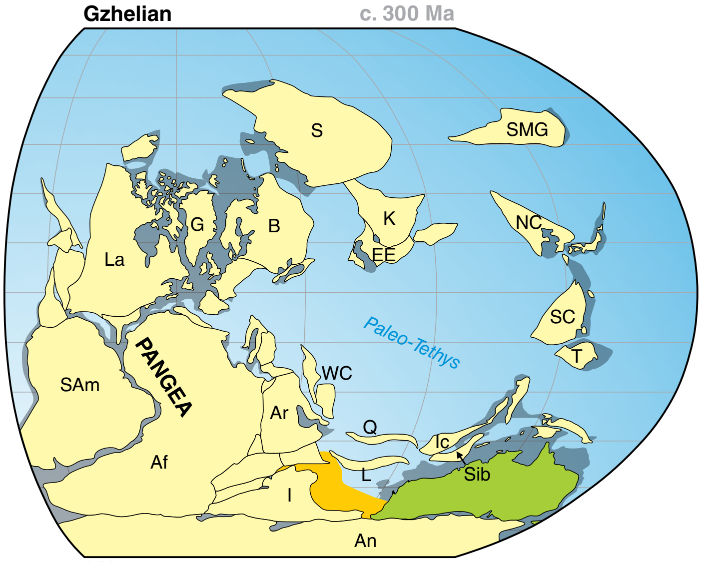
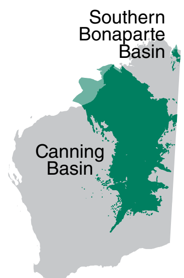


***Figure 27.* Gzhelian (latest Carboniferous) tectonic reconstruction (after http://portal.gplates.org/); key to various blocks in Figure 11**

pull-out boxes, *Controls on climate*, page 17; *Ice ages and climate cyclicity*, page 36), and tectonic effects to explain the similar break in parts of Gondwana beyond the direct influence of such an ice sheet.



Late Carboniferous to Permian rifting and sag

The coincidence of the onset of deglacial deposition in the Gzhelian to early Sakmarian (latest Pennsylvanian to early Cisuralian) with the highest rates of deposition deduced for the Paleozoic (up to ~430 m/Ma in the Petrel Sub-basin, Fitzroy Trough, and Merlinleigh–Byro–Coolcalalaya–Irwin Sub-basins, possibly extending to the southern end of the Perth Basin; Fig. 6b) suggests deglaciation across Western Australia (see pull-out box, *Ice ages and climate cyclicity*, page 36) was coincident with a regional tectonic event. Apart from the inference of increased east–west extension, neither the nature of that event nor its coincidence with deglaciation is well understood. Although this coincidence has been explained as a by-product of the merging of Gondwana and Laurentia (Fig. 27), and uplift along the present position of the subglacial Gamburtsev Mountains in East Antarctica, synrift activity along the margin of the Cimmerian blocks prior to their mid-Permian departure from Gondwana must also have played a role.

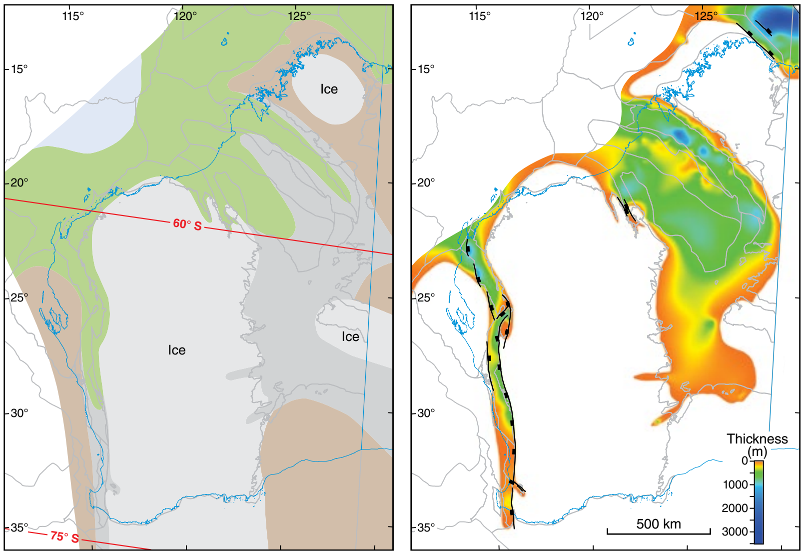


Figure 28a. Late Gzhelian – mid-Sakmarian (300–293 Ma) paleogeographic map (left) and isopach image (right); key in Figure 12; paleolatitude from http://portal.gplates.org/

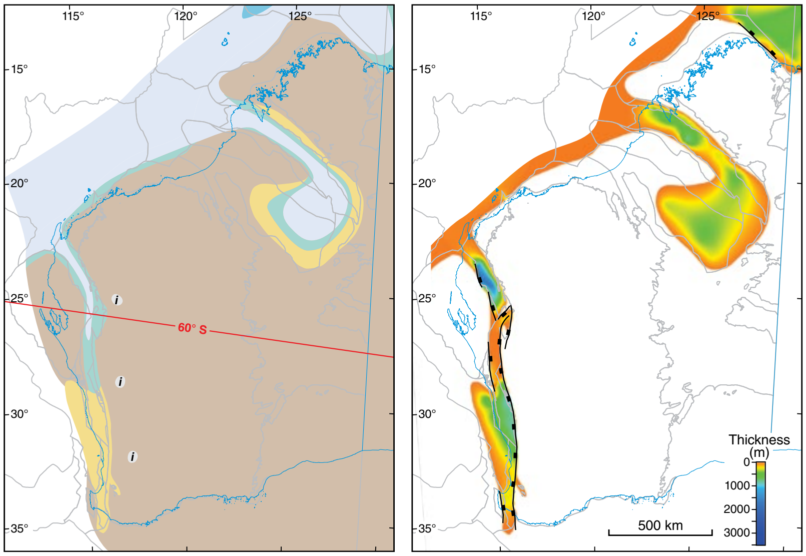


Figure 28b. Late Sakmarian – Roadian (293–269 Ma) paleogeographic map (left) and isopach image (right); key in Figure 12; paleolatitude from http://portal.gplates.org/

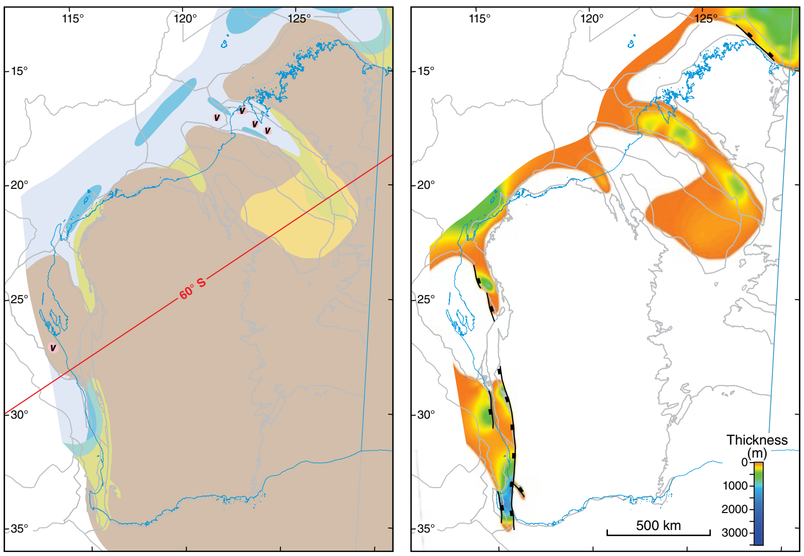


Figure 28c. Wordian–Changhsingian (269–252 Ma) paleogeographic map (left) and isopach image (right); key in Figure 12; paleolatitude from http://portal.gplates.org/

The most rapid sedimentation was in half-grabens along the western margin of the West Australian Craton, and farther north in the Fitzroy Trough and the Petrel Sub-basin (Fig. 6b), all of which are seemingly extensional features. The deglacial facies extend far into the southeastern part of the State (the southernmost Canning Basin, Fig. 2), where they are relatively thin and their preservation is probably due to intracratonic sag. In contrast, strata of late Visean – Bashkirian (middle Mississippian to early Pennsylvanian) age are far more restricted (compare Figs 26b and 28a).

In the Peedamullah Shelf on the southern margin of the Northern Carnarvon Basin a break between the Callytharra and Chinty Formations spans approximately the mid-Artinskian – Wordian (mid-Cisuralian – mid-Guadalupian), and probably is related to shorter breaks between the Caryngina and Dongara or Beekeeper Formations in the northern Perth Basin, and also

Figure 29. Capitanian (latest Guadalupian) tectonic reconstruction (after http://portal.gplates.org/); key to various blocks in Figure 11

Ice ages and climate cyclicity

An ice age is a period when the temperature of Earth's surface and atmosphere is reduced for long enough to allow expansion of ice sheets and glaciers, generally in several episodes. Within the ice age, individual colder episodes are termed glacial periods, or just 'glacials', and intervening warm periods are interglacials. The transition from an ice age with marked glacial conditions to a warmer period, typically accompanied by sea-level rise, is referred to as deglaciation.

Ice ages have been recognized or inferred through much of the Earth's geological record. Major continent-scale ice ages are rarer — the Late Carboniferous – Early Permian glaciation (commonly called the Gondwanan glaciation) is the largest recognized in the Phanerozoic. At its height kilometres of ice moving slowly northward may have covered much of the Australian continent, and effectively trapped sediment until interglacials and final deglaciation. At present, the Earth could be considered to be in a deglacial phase following Pleistocene glacial periods that saw both a mini-ice age in the Middle Ages (~1645 – 1715 AD) when the Thames River regularly froze over, and an interglacial phase when Greenland was settled and grapes were cultivated (the Medieval Warm Period of ~950 – 1250 AD). Several major glaciations have been recognized in the Neoproterozoic, giving rise to the Cryogenian System and a proposal for a Snowball Earth when the entire globe froze over. By comparison, there are few periods when the Earth was considered to be essentially ice-free — the mid-Cretaceous is perhaps the most notable, when relative sea level was thought to be 50–250 m higher than now.

The cause of glaciations and their transitions into climatically warmer periods has been related to several continent- to global-scale simultaneous events, such as astronomical cycles, plate tectonics, changes to oceanic circulation, atmospheric composition, and variations in solar intensity. Plate tectonics can determine the position and elevation of the continents and influence both oceanic and global atmospheric circulation. Supervolcanoes and asteroid impacts also can introduce enough gas or particulate matter into the atmosphere to influence climate.

Astronomical cycles result from regular variations in the Earth's movement and orbit that affect the amount of solar radiation striking Earth, and produce regular oscillations in global sea level. These are Milankovitch cycles, named after the first person to explain their cause. They have three distinct periodicities:

- wobbles in the Earth's axis in ~22 000 year cycles (*precession*);
- variations in tilt of the Earth's axis between 22° and 24.5° (*obliquity*, 41 000 year cycles); and
- *eccentricity* of the Earth's orbit around the sun in cycles up to 400 000 years.

Milankovitch cycles are the commonly hypothesized cause of metre-scale cyclicity in carbonate platforms (as in the Devonian reef complexes of the Canning Basin) and have existed since early in Earth's history.

Recognizing past ice ages

Ancient ice ages are identified or inferred from a variety of criteria including sediment types (most commonly diamictite and tillite, including exotic pebbles to boulders that may be glacial erratics), geomorphological features such as glacial scouring on basement rocks, isotopic studies, and paleoclimatic assessment of fossil assemblages.

At present, the Earth could be considered to be in a deglacial phase.

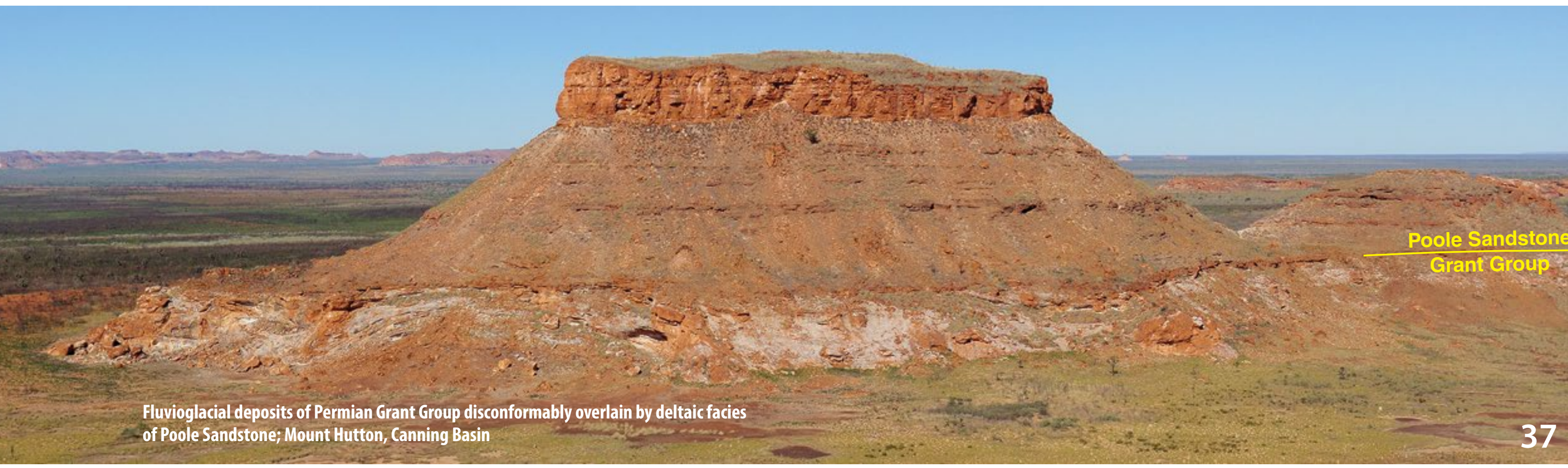
between the Grant and Liveringa Groups in the southwestern Canning Basin. It is possible that this mid-Permian break, which is coeval with rapid deposition in the Merlinleigh Sub-basin, is rift-margin uplift related to the separation of the Cimmerian continent from Gondwana (compare Figs 27 and 29). Inactivity farther north at this time suggests the rifting was relatively localized or that pre-existing structures somehow isolated those basins from this event.

In the western basins east–west extension continued to dominate throughout the remainder of the Permian, whereas sedimentation in the northern basins contracted, at much reduced rates, into older long-lasting depocentres (Figs 28a–c). Sedimentation rates from the Artinskian to the end of the Permian were around 40 m/Ma apart from for the Artinskian–Kungurian (Early Permian) in the Merlinleigh Sub-basin and the mid-Guadalupian – Lopingian (Middle–Late Permian) in the southern Perth Basin where rates were higher (~120 m/Ma and 60 m/Ma, respectively, Fig. 6b).

Depositional history

In the latest Carboniferous to Early Permian, widespread glacial deposits encroached onto the West Australian and North Australian Cratons; the majority of such deposits are thin compared to the adjoining basins in which a series of transgressive cycles accumulated, possibly better termed 'deglacial' (see pull-out box, *Ice ages and climate cyclicity*, page 36). These deposits (Fig. 30 and panorama below showing Grant Group) are equivalent to the oldest Permian (P1) glacial facies in eastern Australia and are amongst the most widespread facies associations within Gondwana. This phase of deposition extended into the mid-Sakmarian, based on overlying warmer water marine faunas, but is difficult to subdivide or correlate in detail across the State due to the dominance of channelized facies.

The Lower Permian shows the most distinctive glacial features in the State including diamictite, soft-sediment deformation/slumping, erratic boulders (Fig. 30a), and discontinuous polymictic boulder beds and boulder lags (Fig. 30b). The wide distribution of such facies across the State suggests they are best explained by glacially related processes, rather than just rapid sedimentation involving re-deposition and mass flow. Nevertheless, a strong fluvial component is indicated by the dominance of well-rounded clasts in the majority of boulder beds. Striae within lowermost Permian strata also indicate dominantly north-northwesterly sediment movement across the State but the origin of such features is not well understood; they may have been produced by drift ice or by bed-load drag in a fluvioglacial setting. Striated basement surfaces outcrop east of the Lyons River in the Southern Carnarvon Basin, at the abandoned Goongewa mine on the northern margin of the Canning Basin, near Dovers Hills east of the Canning Basin, and along the southern margin of the Canning Basin (e.g. Fig. 30c). In the latter region remnants of tunnel valleys extend up to 70 km into the adjacent West Australian Craton, and in the central Earaheedy Basin in central



Fluvioglacial deposits of Permian Grant Group disconformably overlain by deltaic facies of Poole Sandstone; Mount Hutton, Canning Basin

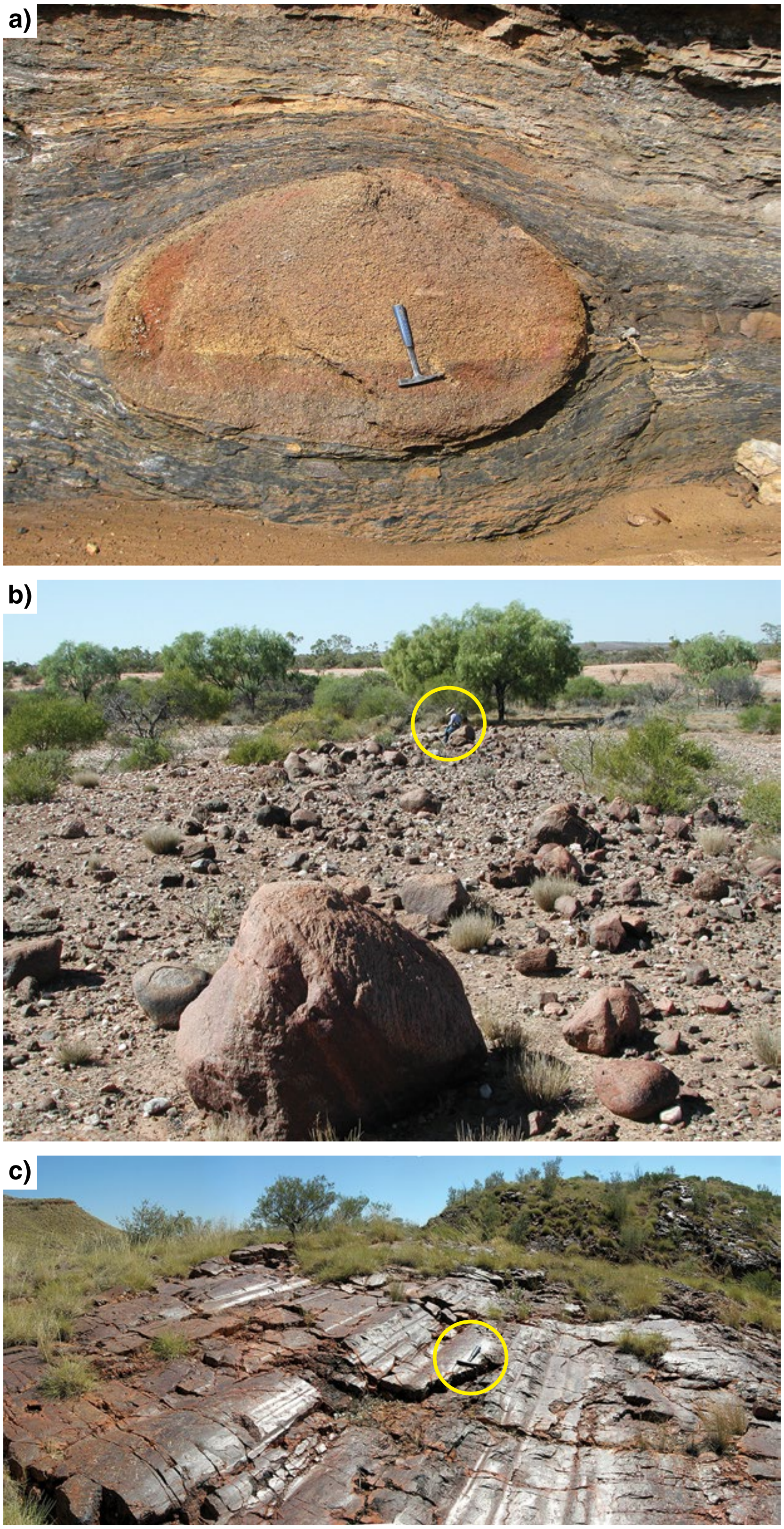
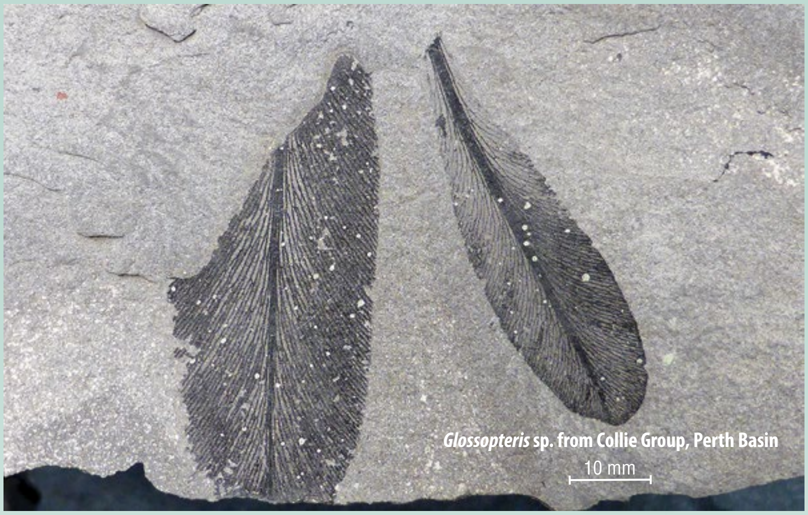


Figure 30. Lower Permian glacial features: a) large glacial erratic granite boulder in the Carynginia Formation, Irwin River South Branch, northern Perth Basin; b) boulder bed in the Lyons Group east of Kennedy Range, Southern Carnarvon Basin (circled figure is for scale); c) striated surface at base of Paterson Formation near the Oakover River, southwestern Canning Basin (circled hammer is for scale)

Coal

Coal accumulated in many Australian basins during the cool to temperate conditions that followed the retreat of the latest Carboniferous – Early Permian Gondwanan ice sheet. Of the Permian coal deposits in the Perth, Canning, Southern Carnarvon, and Southern Bonaparte Basins only those in the Collie Sub-basin (an outlier of the Perth Basin) are economic. Commercial mining commenced there in 1898, and has continued to the present (Fig. 31), yielding over 220 Mt of low-ash, low-sulfur, sub-bituminous coal, chiefly for electricity generation to the southwest grid. The connection of gas fields in the northern Perth Basin and Northern Carnarvon Basin to Perth by the Parmelia Pipeline in 1971 and the Dampier to Bunbury Natural Gas Pipeline in 1984 has eroded the contribution of coal to electricity generation. Since then, the contribution of coal has declined to about 49%. In 2015 Yancoal (previously Premier Coal) and Lanco (previously Griffin Coal), mined 6.95 Mt of coal from Collie. About 90% of this was used for thermal electricity generation. The remainder was mostly utilized in the manufacture of cement, with minor metallurgical applications such as a reductant in the mineral sands and silicon metal industries.

The Collie coalfield contains 60 seams, up to 13 m thick, of sub-bituminous thermal coal, within the Collie Group — a 900 m-thick glaciodeltaic succession of Sakmarian–Wordian age. Of these seams, 30 have been exploited. In 2014 the Economic Demonstrated Resources for this coalfield were estimated at 930 Mt. Permian seams elsewhere in the Perth Basin (Rosabrook Coal Measures, Vasse Shelf; Irwin River Coal Measures, Irwin Terrace) and in the Canning Basin (Lightjack Formation, Fitzroy Trough) are thinner and currently subeconomic. All seams discovered so far in the Southern Carnarvon and Southern Bonaparte Basins are thin and generally at depths greater than 200 m rendering them unlikely to be exploited in the near future. The potential for coalbed methane is minimal throughout Western Australia due to the prevalence of thin, low rank, inertinite-rich seams, whereas alternative energy sources, primarily solar and wind, are gaining momentum and supply up to 15% of the electricity to the southwest grid under favourable conditions.



Glossopteris sp. from Collie Group, Perth Basin

Figure 31. Multiple seam mining of the Muja Coal Measures, Collie Coalfield (from Millar et al., 2011, fig. 6); excavators are 7 m high. The Collie Sub-basin is an outlier of the southern Perth Basin

Western Australia. A polished basal pavement was exhumed at the now-abandoned Goongewa mine in the northern Canning Basin — now buried again after rehabilitation of the minesite*. All are likely to have been formed in the earliest Permian given the age of overlying strata and indicate ice movement to the north-northwest — apart from Dovers Hills, where the ice moved to the west. In the subsurface, similar channels have been mapped in the Canning Basin indicating sediment was transported into the Fitzroy Trough from both the northern and southern margins, and in the southern edge of the Northern Bonaparte Basin where the channels run northeast into the Petrel Sub-basin and then turn abruptly to the northwest. In the latter case, the northern extent of an ice sheet is inferred to have reached a paleolatitude as far north as about 50°S (currently 13°10′S; Fig. 28a).

The end of the deglacial phase is marked by a period of warmer water mud–carbonate deposition from the mid-Sakmarian into the Artinskian (Early Permian) when sedimentation rates slowed to about 10 m/ Ma (Fig. 6b). This warm phase is not evident in the southern Perth Basin where the Permian succession is entirely non-marine with coal seams (best seen at Collie; see pull-out box, *Coal*, page 39, and Fig. 31). Farther north, fewer and thinner coal seams are preserved in the Irwin River Coal Measures, northern Perth Basin, with an early Artinskian temporary return to cooler conditions. In the Artinskian–Kungurian, deposition of shallow marine muds extended from the Northern Bonaparte Basin southward to the northern Perth Basin with an unseen transition to non-marine facies at the southern end of the latter basin (presumably beneath the thick Mesozoic succession in the central Perth Basin). Large-scale hummocky and swaley cross-stratified facies of this age in the Merlinleigh Sub-basin (Southern Carnarvon Basin) are best interpreted as shallow-water storm deposits, because foraminiferal assemblages from intercalated fine-grained facies indicate a shallow interior sea akin to the present Baltic Sea (see pull-out box, *Controls on climate*, page 17).

Guadalupian–Lopingian (middle–late Permian) deposition across Western Australia was dominantly deltaic with minor marine incursions in the Wordian (mid-Guadalupian) in the northern Perth Basin, along the southeast margin of the Northern Carnarvon Basin, and in the Fitzroy Trough in the Canning Basin. In the outboard part of the Australian Plate from the Exmouth Sub-basin to the Northern Bonaparte Basin deposition appears to have been more marine. A carbonate-dominated outer shelf setting probably extended from the northwestern Browse Basin to Timor-Leste. In the Southern Carnarvon Basin deposition within an interior seaway continued into the Wordian — the preserved section finishes at this level (see adjacent panorama). Farther south, Roadian–Wordian (lower – mid-Guadalupian) carbonates are present in the northern Perth Basin, and the Tethyan aspect of foraminifera from this region imply a marine connection west of the Gascoyne Platform (Fig. 29) that bypassed the earlier interior seaway through the Merlinleigh Sub-basin (Figs 28b–c). Poorly dated Permian volcanic rocks in the Canning and Southern Carnarvon Basins were probably emplaced during rifting along the western margin of the continent in the middle to late Permian, prior to the creation of Meso-Tethys (Figs 28c, 29).

Summary

Biostratigraphic studies underpin inter-basinal stratigraphic correlations and explanations of the Paleozoic evolution of Western Australia — volcanic facies that can be dated using radiometric techniques are rare. However, biostratigraphic resolution is low, possibly due to the Cimmerian continent and other blocks along the northern margin of Gondwana selectively hindering the spread of Tethyan biotas into Western Australian basins for much of the Paleozoic. In spite of some notable exceptions, such as parts of the Ordovician and deeper water facies of the Upper Devonian reef complexes in the Canning Basin, the majority of Cambrian to Carboniferous successions are more poorly age constrained than those of the Permian. Other difficulties with inter-basinal correlations are that few of the tectonic events preserved in the stratigraphic record as unconformities can be correlated between basins, probably due to the distance between them and their separation by intervening Precambrian terranes. Nevertheless an integrated approach, incorporating regional climatic events and without over-interpreting the available biostratigraphy, allows at least broad correlations between basins. The correlations across west Australia (summarized in Fig. 4), presented as a series of time intervals

* A portion of this pavement is on display in the Timewalk at Geoscience Australia (Canberra).

of 10–30 Ma duration, approximate second-order sequences and so should reflect broad supracrustal processes.

Paleozoic deposition in Western Australia was largely intracratonic — especially during the Cambrian when it appears to have been strongly linked to Centralian basins, and likely controlled by structural events in central Australia. The remainder of the Paleozoic, by comparison, was influenced by roughly north–south extension probably driven by events along the margins of the Australian Plate. However, explanations for tectonic events are not well understood prior to the Permian when the rifting and separation of continental blocks from the northern edge of Gondwana (the early position of the Australian continent) become obvious. In particular, there is no simple explanation for the extension apparent in the west Australian basins and its approximate coincidence with compression in central Australia during the Ordovician–Carboniferous Alice Springs Orogeny.

Explanations for this segregation include stress decoupling and partitioning along a shear zone extending along the Halls Creek Orogen (including strike-slip movement along the Halls Creek Fault) and the eastern edge of the Canning Basin. Alternatively, this partitioning may be due to the interplay between various blocks within Cimmeria versus subduction along the northeastern Panthalassan margin of what became the Australian continent. More substantial connections between the Paleozoic tectonic history of Western Australia and the Neoproterozoic to Paleozoic assembly and dispersal of continental blocks within Gondwana await more-detailed paleomagnetic data from the numerous Gondwanan blocks, especially those now distributed throughout Southeast Asia.

Although there are many similarities between west Australian basins, there are also significant differences in their Paleozoic evolution that possibly reflect poorly understood deep-basement structure. Gravity modelling of the Petrel Sub-basin hints at the central gravity high being due to Proterozoic – early Paleozoic crustal thinning, whereas the succeeding, thick, relatively little-deformed ?mid-Devonian to Permian strata indicate rift–sag phases (Fig. 7). By comparison, the more-deformed Canning Basin has a marked asymmetry with an abrupt northward shift in the main depocentre in the mid-Devonian (Fig. 8). This may be due to reactivation of a thick-skinned intracratonic Precambrian thrust belt along the likely North Australian and West Australian cratonic margin near the southern margin of the Fitzroy Trough. Farther south, the Southern Carnarvon Basin also shows a marked depocentre shift in the mid-Devonian, but to the east and with relatively little deformation (Fig. 9). The influence of basement structure in this region is possibly due to reactivation along the edge of the West Australian Craton and Proterozoic Pinjarra Orogen or an as-yet unknown basement terrane below the Gascoyne Platform. To the south, the apparent absence of pre-Permian Paleozoic strata below most of the Perth Basin could be due to non-deposition or major erosion — if such older strata are preserved it would most likely be only in the deepest parts of the basin (Fig. 10).

Paleozoic deposition in Western Australia was largely intracratonic – especially during the Cambrian.

Upper Permian shoreface to shallow-marine siliciclastic deposits, Kennedy Group, Kennedy Range, Southern Carnarvon Basin; the outcrop is about 110 m high

Resources

Western Australia's mineral wealth is overwhelmingly associated with three billion years of pre-Gondwanan orogenesis, metamorphism, and magmatism, and Mesozoic hydrocarbon-bearing basins within the Westralian Superbasin along the North West Shelf (see pull-out box, *Oil and gas*, page 44, Table 1, and Figs 32, 33). Although many ore bodies are in regolith of Cenozoic age, most have been reworked and concentrated from underlying Precambrian bedrock. Western Australia's comparatively short and simple Paleozoic history is in marked contrast — 290 million years of basin development with little igneous activity and gentle extensional tectonic events produced sedimentary rocks that are with very few exceptions little deformed. Consequently, Paleozoic mineralization is largely controlled by specific depositional and basin settings, and includes sediment-hosted and stratabound deposits of lead–zinc (see pull-out box, *Lead and zinc mineralization,* page 27), evaporites (see pull-out box, *Evaporites,* page 45), coal (see pull-out box, *Coal,* page 39), and uranium (see pull-out box, *Uranium and copper,* page 45). These

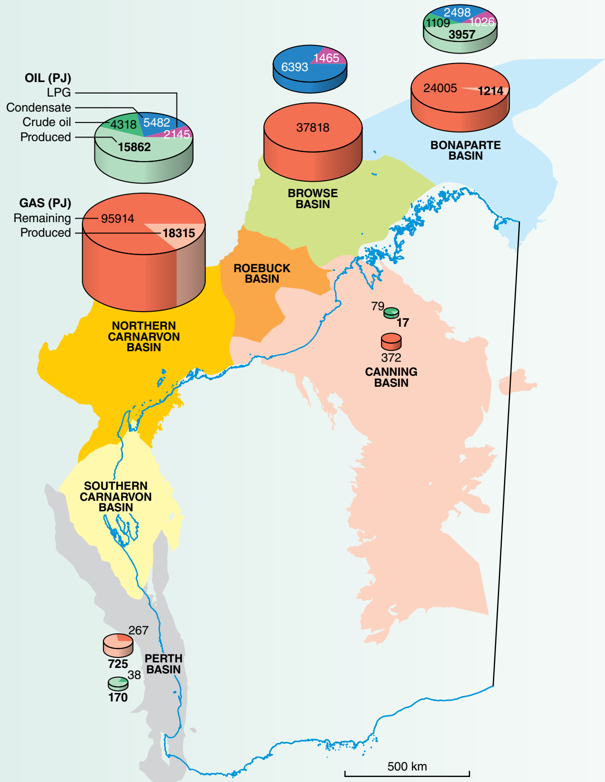


Figure 32. Distribution of oil and gas in Western Australia (after Geoscience Australia and Bureau of Resources and Energy Economics, 2014, figs 3.1 and 3.11); PJ = petajoules (1015 joules)

Table 1. Resources and production from the Mesozoic North West Shelf compared with Paleozoic basins

Basin	Resources			Production		
	GIIP total gas resources (1)	GIIP Shale gas and tight gas (2)	Oil and condensate (2)	Gas	Oil and condensate	Stratigraphy
Perth Basin	1.3 Gm^3	4750 Gm^3	2100 GL	19 Gm^3	4.7 GL oil and 0.1 Gm^3 condensate	(1) Upper Permian (2) Lower Permian (Caryngina Formation) and Lower Triassic (Kockatea Shale)
NW Shelf, Northern Carnarvon Basin (Mesozoic)	3400 Gm^3	na	na	716 Gm^3	301 GL oil and 140 Gm^3 condensate	Mesozoic
Canning Basin	5 Gm^3	34 750 Gm^3	38 700 GL	na	550 ML	(1) Devonian–Permian (2) Ordovician (Goldwyer Formation)
Southern Bonaparte Basin	na	na	na	3.6 Gm^3	na	

Notes: GIIP = Gas initially in place; na = not available; Gm^3 = Giga cubic metres; GL/ML = Giga/Million litres

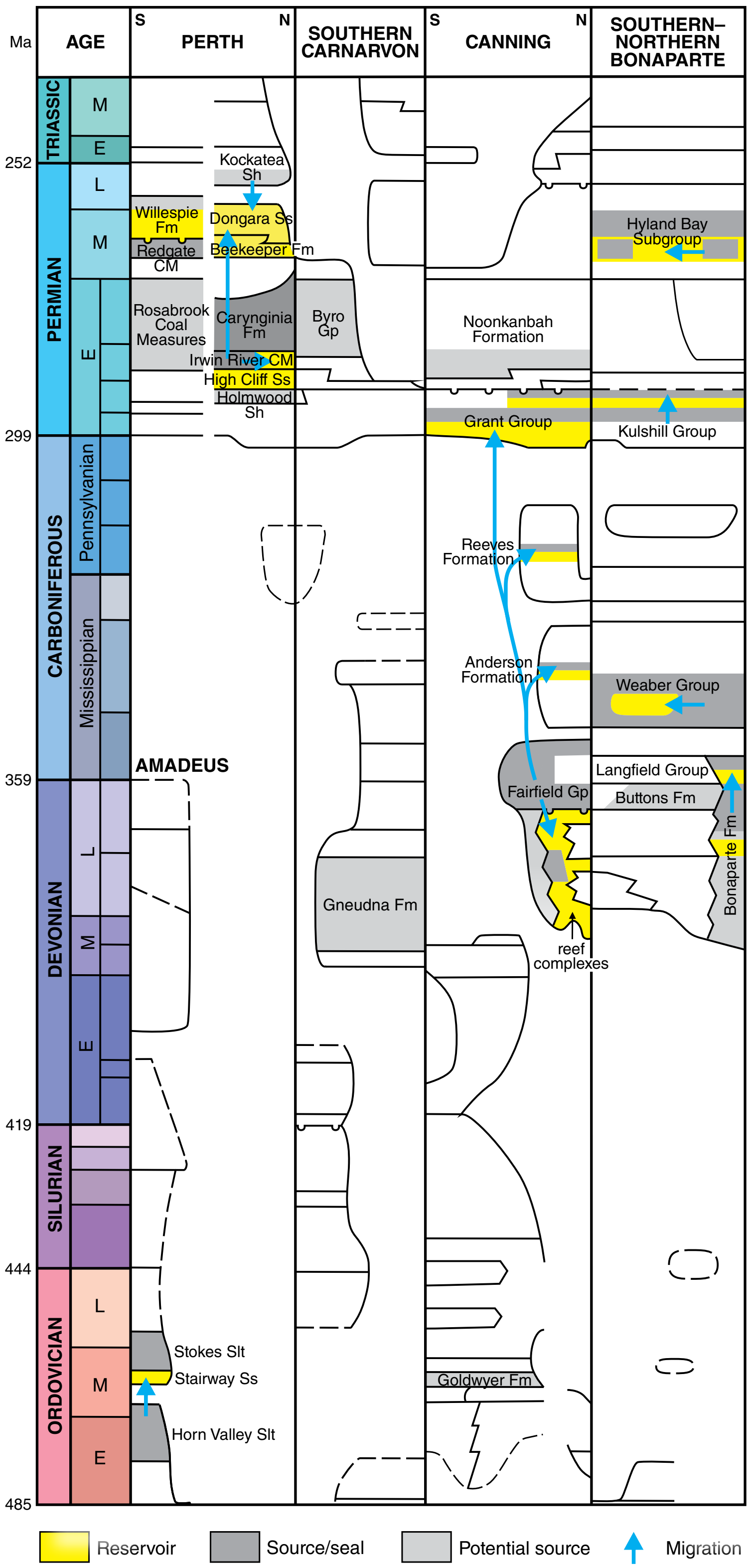


Figure 33. Stratigraphic distribution of Paleozoic hydrocarbon elements in Western Australia. Abbreviations as in Figure 3

Paleozoic mineralization includes sediment-hosted and stratabound deposits of lead–zinc, and evaporites, coal, uranium, and copper.

settings are markedly different from eastern Australia, where Phanerozoic base metal and gold mineralization was mainly controlled by extensive volcanism, magmatism, and compressional tectonics (e.g. in the Delamarian, Lachlan, and Tasman Orogens). In eastern Australia the most important metal-forming period, the 490–435 Ma Benambran cycle, produced gold, porphyry copper–gold, and epithermal copper–gold deposits. Apart from zinc–lead deposits such as the giant, but deep, Admiral Bay deposit (see pull-out box, *Lead and zinc mineralization*, page 27) and the potential for significant shale gas in the Ordovician Goldwyer Formation and Carboniferous part of the Fairfield Group in the Canning Basin, and possibly the Lower Permian Carynginia Formation in the northern Perth Basin (Fig. 33; see pull-out box, *Oil and gas*, page 44), Western Australia's Paleozoic history has not been conducive to the diverse mineralization styles developed in the Precambrian. Additionally, its basins did not develop exceptional petroleum systems as in the Mesozoic along the North West Shelf. Possibly many traps in Paleozoic strata were breached during the Mesozoic breakup of Gondwana. Future exploration for mineral and petroleum resources within Paleozoic regions is likely to focus on shale and tight gas, and stratabound mineral deposits. Additional uses of Paleozoic strata could be for the geosequestration of CO_2 or to store hazardous waste as long as there is no conflict with access to other resources, especially groundwater (see pull-out box, *Groundwater,* page 13) and geothermal energy (see pull-out box, *Geothermal energy,* page 5).

Oil and gas

Western Australia is amongst the world's least-explored regions for oil and gas — with approximately one exploration well per 3000 km^2 drilled offshore and one well per 2600 km^2 drilled onshore in sedimentary basins. Nevertheless, 80% of Australia's natural gas discovered in Western Australia is from the Mesozoic succession along the North West Shelf covering almost 900 000 km^2 (Fig. 32). Figure 33 shows the stratigraphic distribution of hydrocarbon elements within the Paleozoic, based mostly on known fields.

Oil was discovered in 1953 at Rough Range in the Southern Carnarvon Basin. Although production from it was small (total production 15.4 kL or 96 800 bbl) and intermittent, it provided the impetus for further exploration leading to the discovery of the Barrow field in 1964 on Barrow Island in the Northern Carnarvon Basin. Other early discoveries in the 1960s were in the Permian of the onshore northern Perth Basin, of which the Dongara gasfield was the largest. World-class gasfields were discovered in the offshore Northern Carnarvon Basin in Mesozoic reservoirs, for example the giant North Rankin (1971), Goodwyn (1971), and Gorgon (1980–81) fields. Since 1965, more than 1 400 000 km of 2D and 225 000 km^2 of 3D seismic reflection data have been collected, and more than 4000 wells have been drilled in the State and adjacent Commonwealth-controlled offshore waters. Approximately 800 wells, mostly onshore, have intersected Paleozoic strata in Western Australia (see map on page 57).

Fields with Paleozoic reservoirs are small, apart from Blacktip in the Southern Bonaparte Basin, which commenced production in 2009. Across the State, total production to early 2015 from Paleozoic reservoirs (Table 1) has reached 19 Gm^3 gas, 0.1 Gm^3 condensate, and 4.7 GL oil for the Perth Basin, 550 ML oil for the Canning Basin, and 3.6 Gm^3 gas for the Southern Bonaparte Basin. By comparison, there are more than 90 fields with Mesozoic reservoirs along the North West Shelf that have already yielded more than 716 Gm^3 gas, 140 Gm^3 condensate, and 301 GL oil. Paleozoic discoveries include 20 fields with Permian reservoirs in the northern Perth Basin, eight with Devonian–Permian reservoirs in the northern Canning Basin, and three with Carboniferous–Permian reservoirs in the Southern Bonaparte Basin. In the Canning Basin seven fields are currently in production; the rest have been either depleted or shut-in due to low production.

The majority of Paleozoic reservoirs in Western Australia are sandstone — the Dongara Sandstone in the northern Perth Basin, the Grant Group in the northern Canning Basin, and the Keyling and Treachery Formations (Kulshill Group) in the Southern Bonaparte Basin. Despite their growing importance internationally as hydrocarbon hosts, carbonate rocks are volumetrically minor within the Paleozoic of Western Australia. Such reservoirs are known from the Middle Permian in the now-depleted Woodada field of the northern Perth Basin, the Devonian reef succession in the now shut-in Blina field, and the Ungani Dolomite in the eponymous field, both in the northern Canning Basin. Other potential resources such as shale gas from the Laurel Formation in the Canning Basin and the Carynginia Formation in the Perth Basin are difficult to assess due to insufficient data.

Table 1 compares resources and production from the Paleozoic in Western Australia with the immense Mesozoic resources in the Northern Carnarvon Basin.

First flow of oil in Western Australia, Rough Range, 1953 (reproduced with permission of Battye Library, Perth)

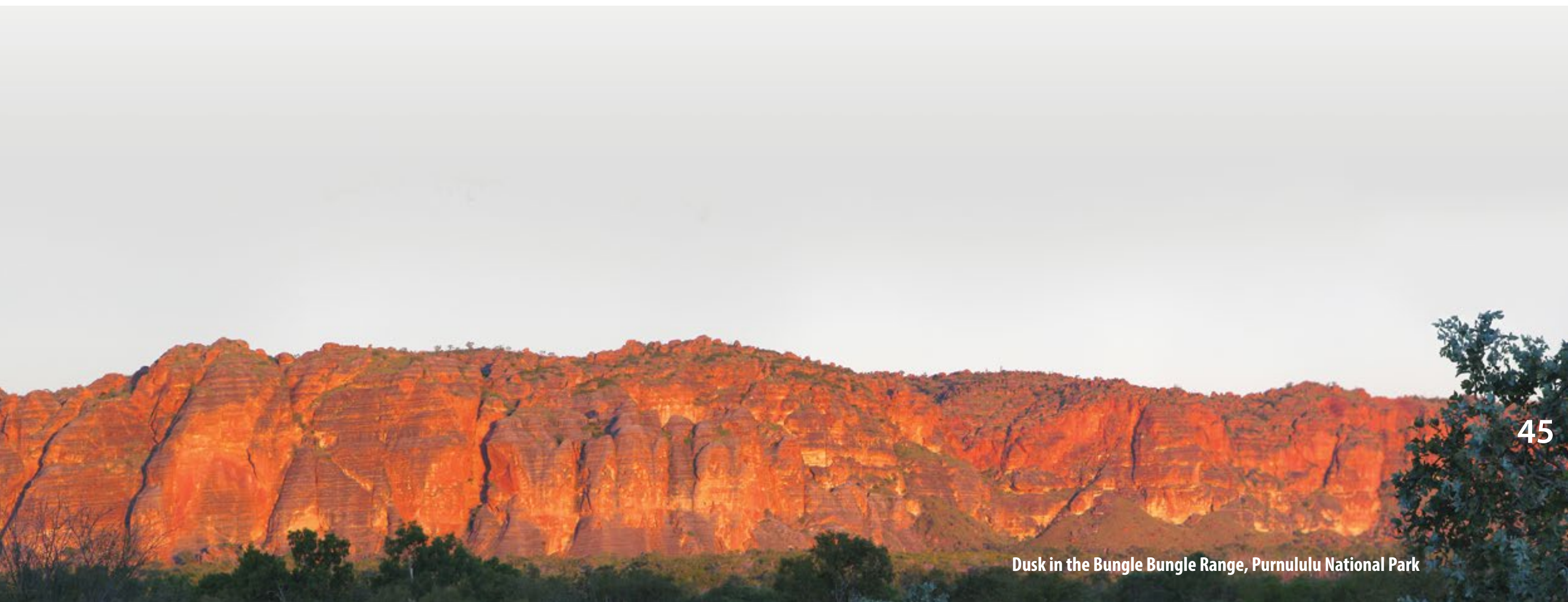
Evaporites

Thick evaporitic mineral deposits are present within redbed successions in the Carribuddy Group of the Canning Basin and in shallow-marine carbonate facies of the Dirk Hartog Group in the Southern Carnarvon Basin (Fig. 3). The evaporites formed during periods of arid conditions in the Ordovician and Silurian, and comprise bedded halite (NaCl) with lesser amounts of anhydrite ($CaSO_4$) nodules and fracture fillings. The Mallowa Salt (see photo) in the Ordovician Carribuddy Group is widespread throughout the Canning Basin, though mostly buried at depths greater than one kilometre beneath Devonian to Mesozoic rocks. Locally this unit is over 800 m thick, and is the most voluminous halite formation in Australia. Evaporites in the Southern Carnarvon Basin (Silurian Yaringa Formation) are thinner (up to 105 m) and also deeply buried. In the Northern Bonaparte Basin evaporite deposits are known only from salt structures imaged on seismic reflection profiles and in wells drilled into salt domes (e.g. Fig. 7; all in the offshore Petrel Sub-basin), and are likely older than Late Devonian. Whereas potash minerals, such as silvite (KCl) or sulfate of potash (K_2SO_4) have been targeted by several exploration programs, so far they have not been detected. These minerals are mostly used to make fertilizers and by weight are currently valued at eight to ten times that of common salt or gypsum. In the Paleozoic of Western Australia Barite ($BaSO_4$) —which is typically considered a hydrothermal mineral — is usually restricted, to small prospects associated with fault zones.

Halite in core (Mallowa Salt), Kidson 1, 3100 m deep, Canning Basin

Uranium and copper

Exploration within the Paleozoic has yielded one sediment-hosted uranium deposit in the northwestern Canning Basin and a series of copper prospects in the Cambrian Antrim Plateau Volcanics (Fig. 14). The Oobagooma uranium deposit (Fig. 21) in Devonian–Permian strata has an inferred resource of contained U_3O_8 estimated at 10 000 t averaging 0.12% U_3O_8 suitable for in-situ recovery.



Dusk in the Bungle Bungle Range, Purnululu National Park

Postscript to the Paleozoic

Toward the end of the Paleozoic the loci of deposition shifted to areas that are now offshore — in particular the North West Shelf (Westralian Superbasin). The notable exception is in the Perth Basin where the Mesozoic succession is up to 12 km thick below the Perth metropolitan area (and likely even thicker offshore). Thick Triassic to Lower Jurassic synrift deposits were followed by rifting later in the Jurassic (e.g. Fig. 34) culminating in the separation of Greater India from Australia in a northeast–southwest then north–south zipper-like motion between the Oxfordian (Late Jurassic) to the Valanginian (Early Cretaceous). This is associated with a major unconformity along the margin of Western Australia that extends onshore. Unlike the Perth Basin, the Mesozoic in the Southern Carnarvon Basin is relatively thin and predominantly of Cretaceous age. Nonetheless, breakup was still a major event that rejuvenated most fault systems across the basin. Despite some similarity in deep structural orientation between the Perth and Southern Carnarvon Basins the latter was isolated from offshore events prior to breakup, possibly because of the shallow basement of the Northampton Inlier and along the northwestern margin of Shark Bay. By comparison, the Canning Basin and the southeastern end of the Petrel Sub-basin within the Northern Bonaparte Basin were little affected by breakup. In these, the main structural grain was northwesterly, at too high an angle to the main Mesozoic stress fields to be easily rejuvenated. Instead these basins were truncated by northeast–southwest structures.

Toward the end of the Paleozoic the loci of deposition shifted to areas that are now offshore – in particular the North West Shelf (Westralian Superbasin).

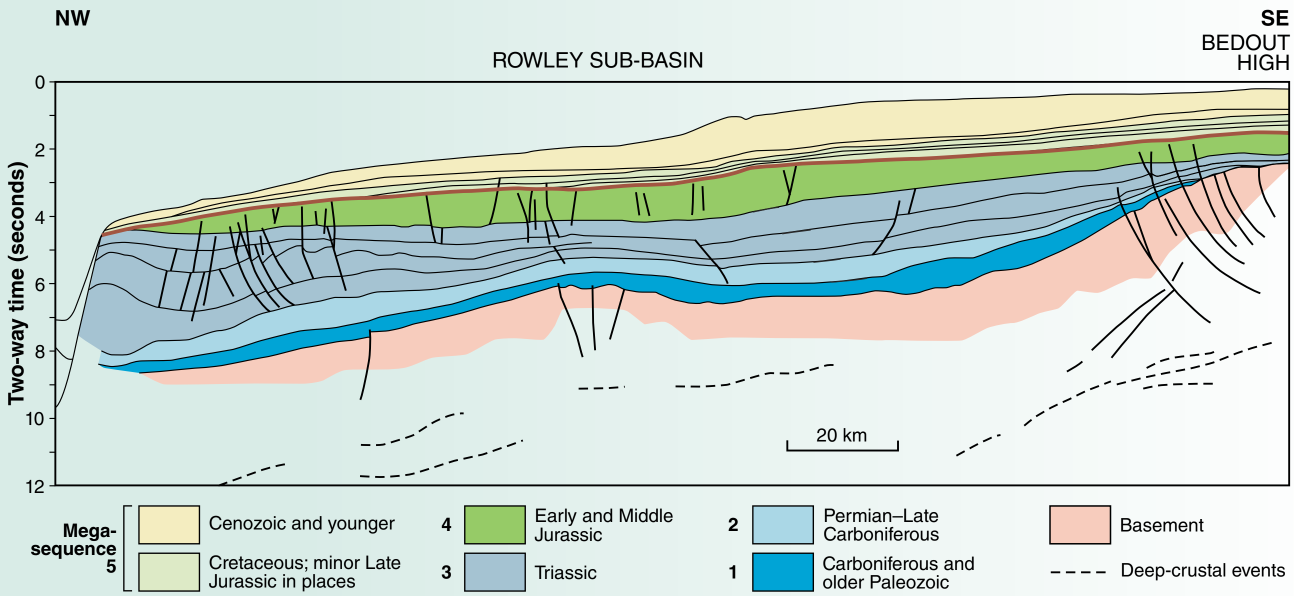


Figure 34. Cross-section from the Bedout High across the Rowley Sub-basin on the North West Shelf showing prograding post-breakup strata overlying the rifted sequence beneath the breakup unconformity marked in red (after Colwell and Stagg, 1994, fig. 7)

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Maps of Western Australia

1. Tectonic divisions of Western Australia

2. Geology of Western Australia

3. Bouguer gravity anomaly of Western Australia

4. Total magnetic intensity anomaly of Western Australia

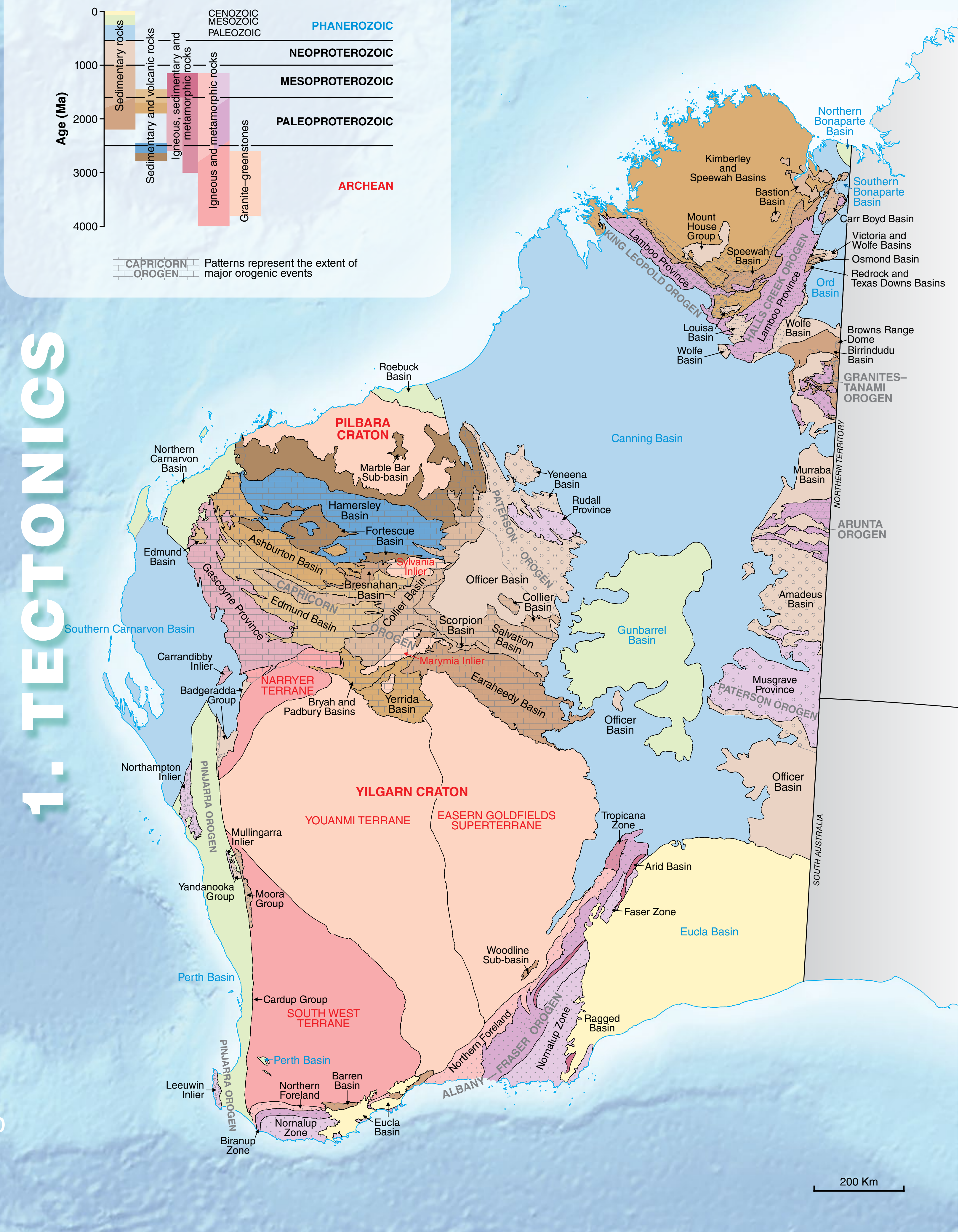
5. Localities and mineralization mentioned in text (with Index)

*6. Depth to basement model (Basin architecture)
from OZ SEEBASE (image courtesy FrogTech Geoscience)*

7. Wells drilled containing Paleozoic strata

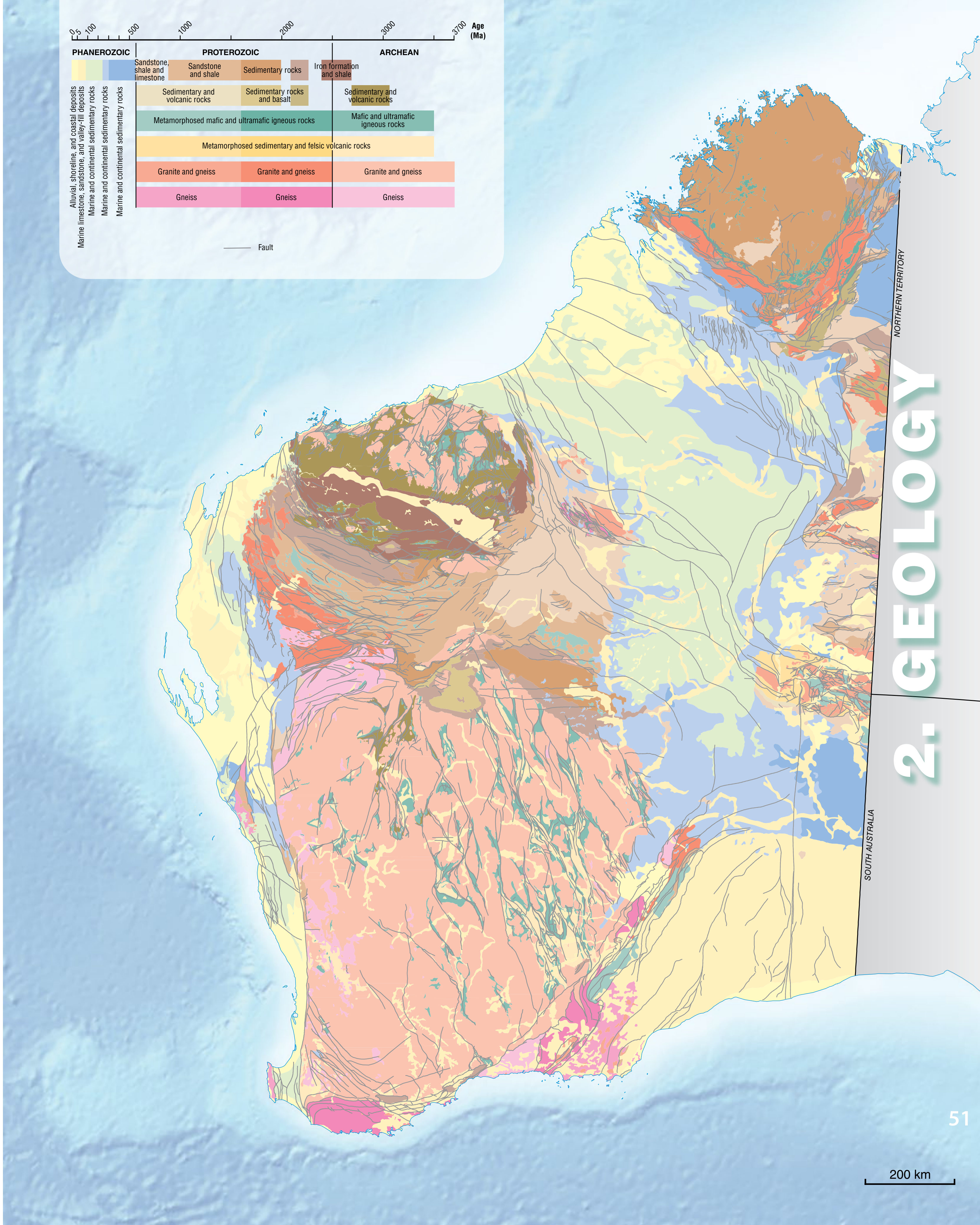
8. Paleozoic coal occurrences

1. TECTONICS



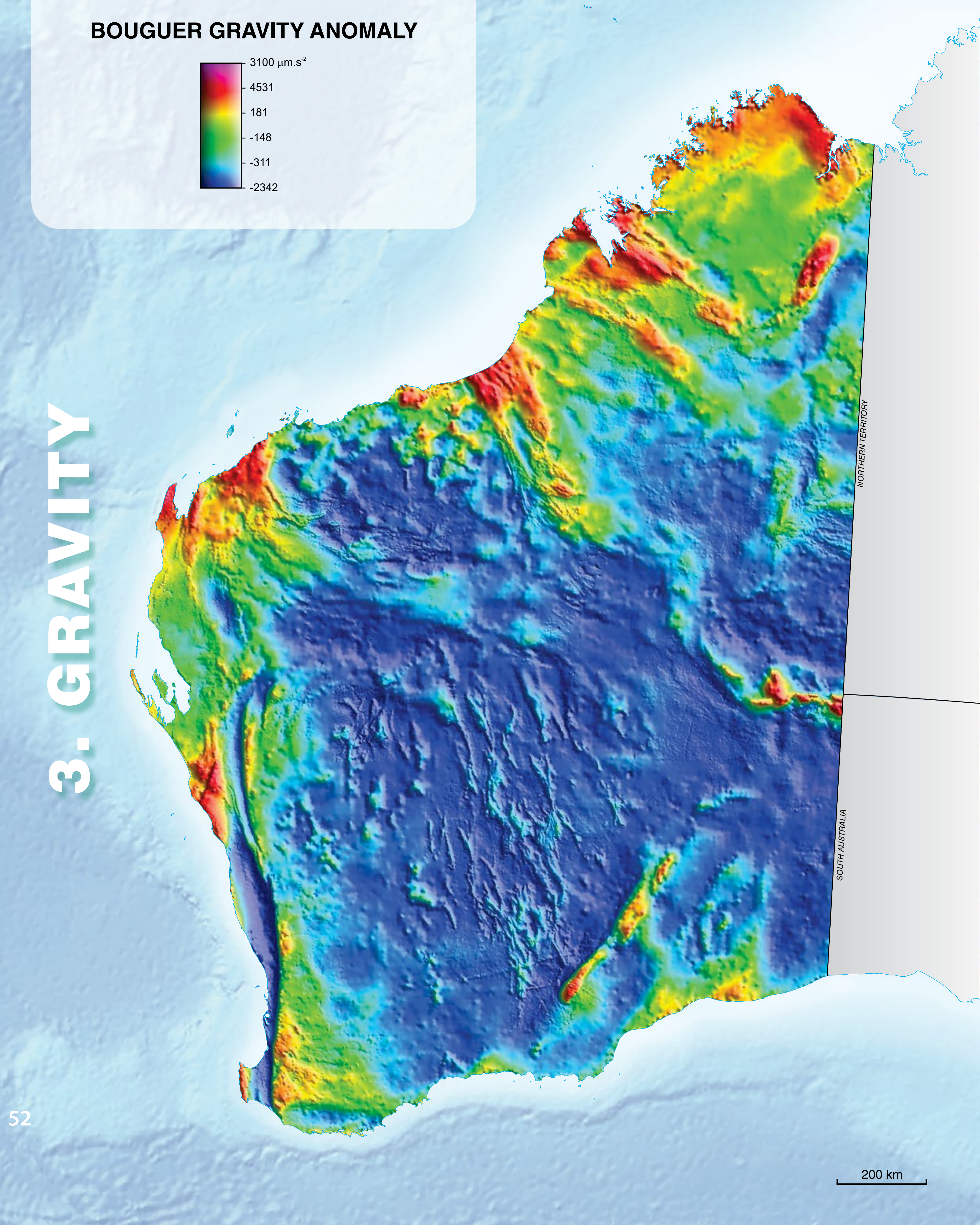
Age (Ma)
0
1000
2000
3000
4000
Sedimentary rocks
Sedimentary and volcanic rocks
Igneous, sedimentary and metamorphic rocks
Igneous and metamorphic rocks
Granite–greenstones
CENOZOIC
MESOZOIC
PALEOZOIC
PHANEROZOIC
NEOPROTEROZOIC
MESOPROTEROZOIC
PALEOPROTEROZOIC
ARCHEAN
CAPRICORN OROGEN
Patterns represent the extent of major orogenic events
Northern Bonaparte Basin
Southern Bonaparte Basin
Kimberley and Speewah Basins
Bastion Basin
Carr Boyd Basin
Mount House Group
Speewah Basin
Victoria and Wolfe Basins
Osmond Basin
Redrock and Texas Downs Basins
Ord Basin
KING LEOPOLD OROGEN
Lamboo Province
HALLS CREEK OROGEN
Lamboo Province
Wolfe Basin
Louisa Basin
Wolfe Basin
Browns Range Dome
Birrindudu Basin
GRANITES–TANAMI OROGEN
Roebuck Basin
Canning Basin
PILBARA CRATON
Marble Bar Sub-basin
Northern Carnarvon Basin
Hamersley Basin
Fortescue Basin
Yeneena Basin
Rudall Province
PATERSON OROGEN
NORTHERN TERRITORY
Murraba Basin
ARUNTA OROGEN
Edmund Basin
Ashburton Basin
Sylvania Inlier
Gascoyne Province
Bresnahan Basin
Officer Basin
CAPRICORN
Edmund Basin
Collier Basin
Collier Basin
Amadeus Basin
Southern Carnarvon Basin
Scorpion Basin
Salvation Basin
Gunbarrel Basin
OROGEN
Marymia Inlier
Musgrave Province
PATERSON OROGEN
Carrandibby Inlier
NARRYER TERRANE
Earaheedy Basin
Badgeradda Group
Yerrida Basin
Bryah and Padbury Basins
Officer Basin
Northampton Inlier
Officer Basin
PINJARRA OROGEN
YILGARN CRATON
YOUANMI TERRANE
EASERN GOLDFIELDS SUPERTERRANE
Tropicana Zone
Mullingarra Inlier
SOUTH AUSTRALIA
Arid Basin
Yandanooka Group
Moora Group
Faser Zone
Eucla Basin
Woodline Sub-basin
Perth Basin
Cardup Group
SOUTH WEST TERRANE
Ragged Basin
Nornalup Zone
FRASER OROGEN
Northern Foreland
ALBANY
Perth Basin
PINJARRA OROGEN
Barren Basin
Leeuwin Inlier
Northern Foreland
Nornalup Zone
Eucla Basin
Biranup Zone
200 Km

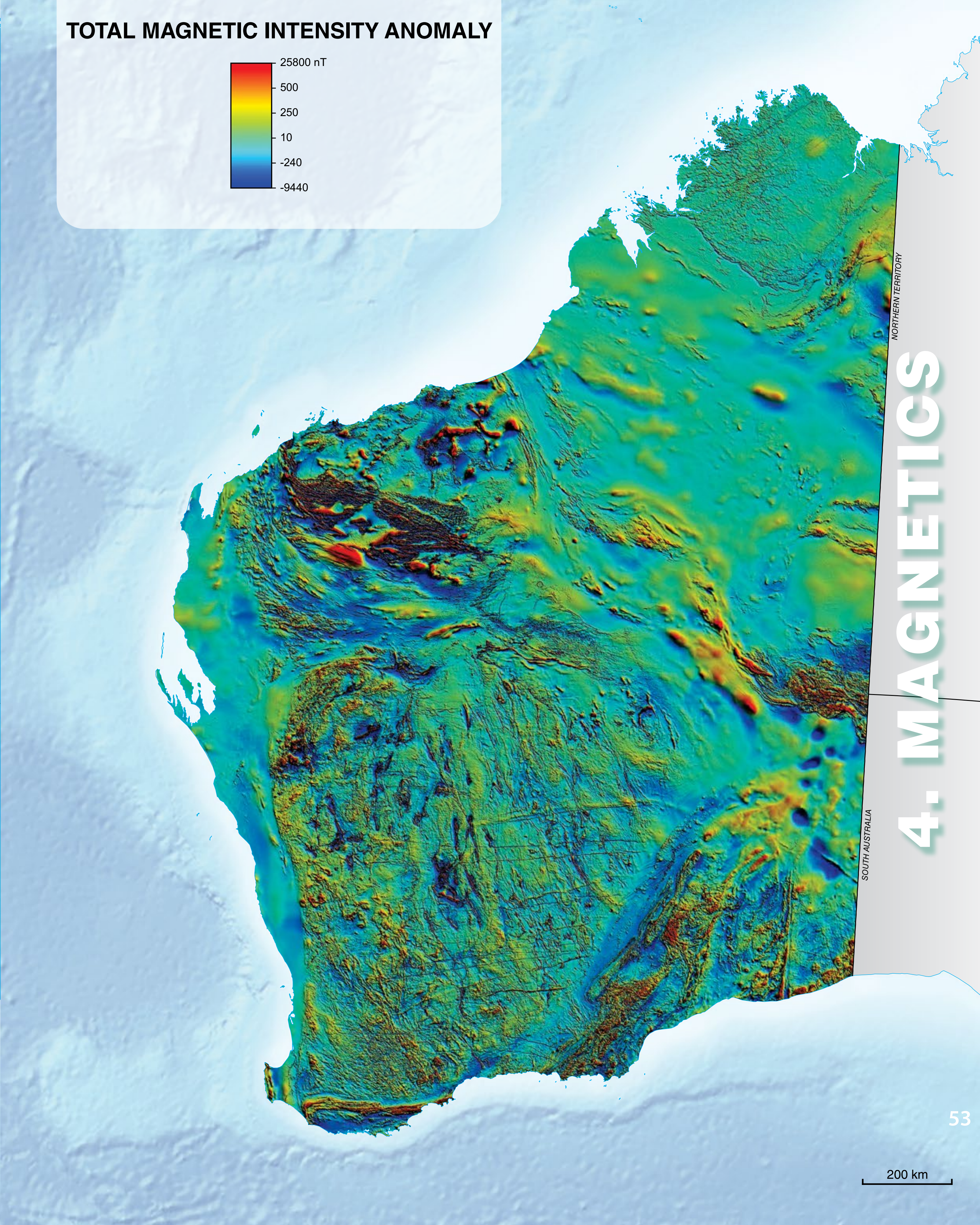
2. GEOLOGY



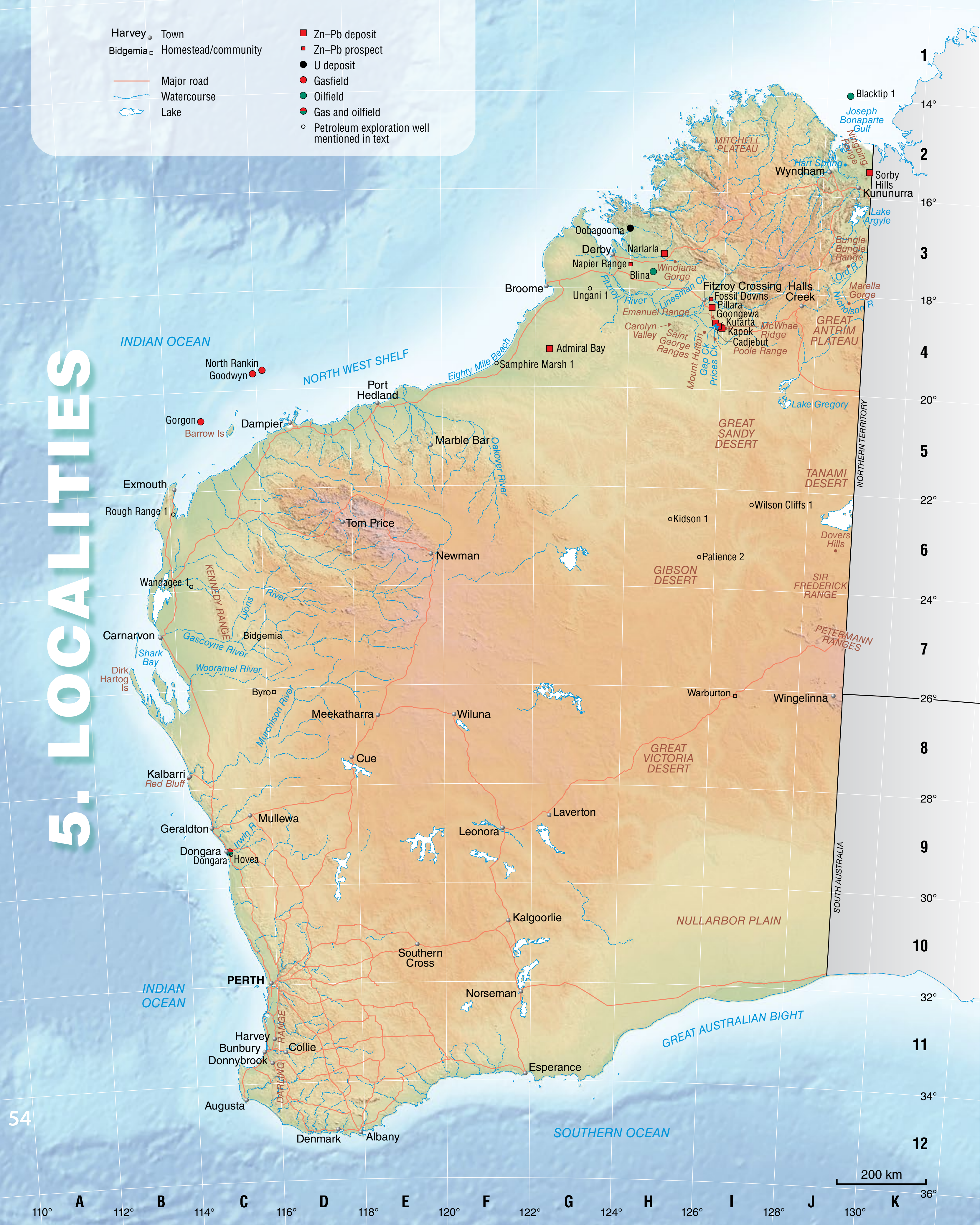
0
5
100
500
1000
2000
3000
3700
Age (Ma)
PHANEROZOIC
PROTEROZOIC
ARCHEAN
Alluvial, shoreline, and coastal deposits
Marine limestone, sandstone, and valley-fill deposits
Marine and continental sedimentary rocks
Marine and continental sedimentary rocks
Marine and continental sedimentary rocks
Sandstone, shale and limestone
Sandstone and shale
Sedimentary rocks
Iron formation and shale
Sedimentary and volcanic rocks
Sedimentary rocks and basalt
Sedimentary and volcanic rocks
Metamorphosed mafic and ultramafic igneous rocks
Mafic and ultramafic igneous rocks
Metamorphosed sedimentary and felsic volcanic rocks
Granite and gneiss
Granite and gneiss
Granite and gneiss
Gneiss
Gneiss
Gneiss
Fault
NORTHERN TERRITORY
SOUTH AUSTRALIA
200 km

3. GRAVITY


BOUGUER GRAVITY ANOMALY
3100 µm.s-2
4531
181
-148
-311
-2342
NORTHERN TERRITORY
SOUTH AUSTRALIA
200 km


TOTAL MAGNETIC INTENSITY ANOMALY
25800 nT
500
250
10
-240
-9440
NORTHERN TERRITORY
SOUTH AUSTRALIA
200 km

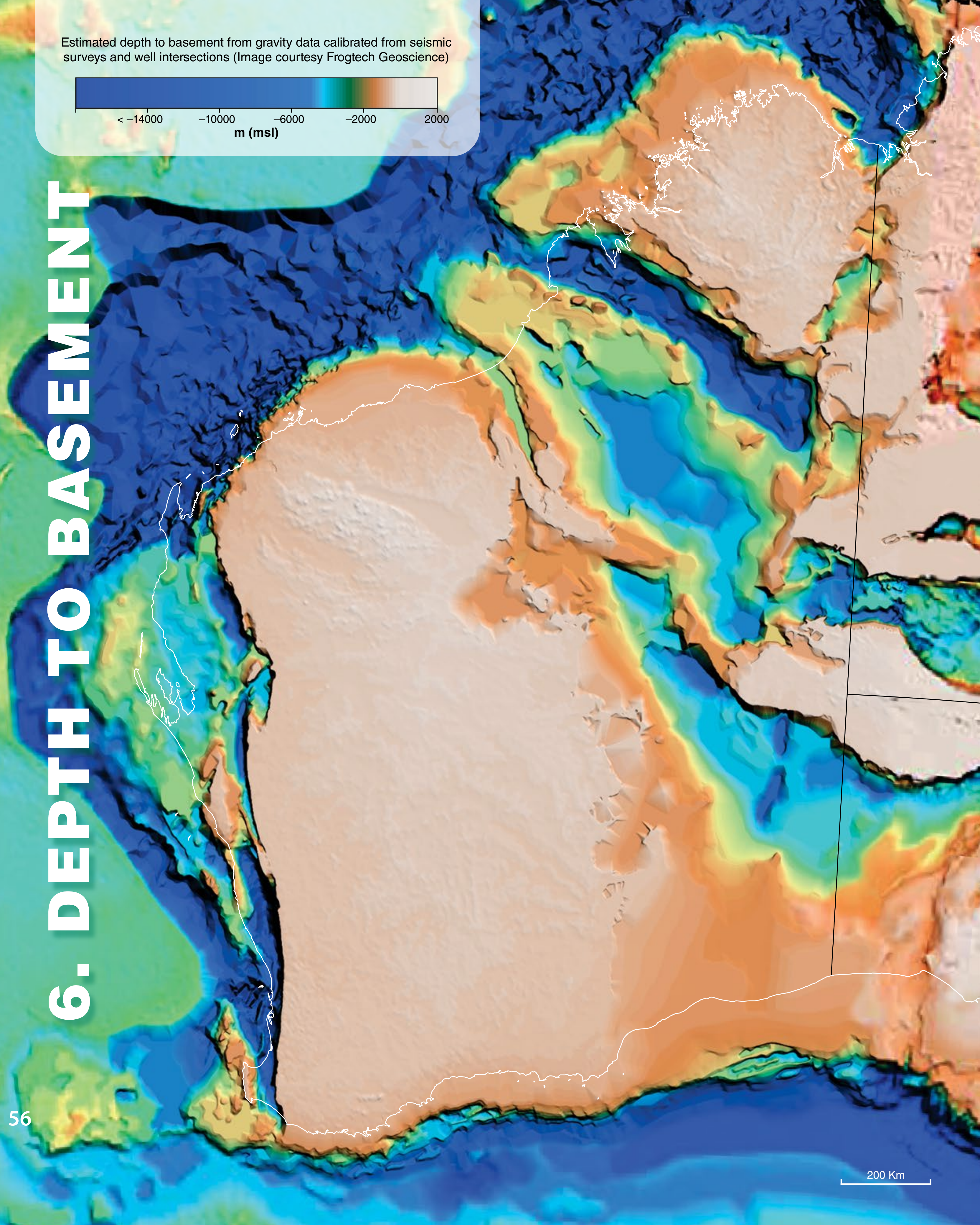
5. LOCALITIES



Index to Localities map

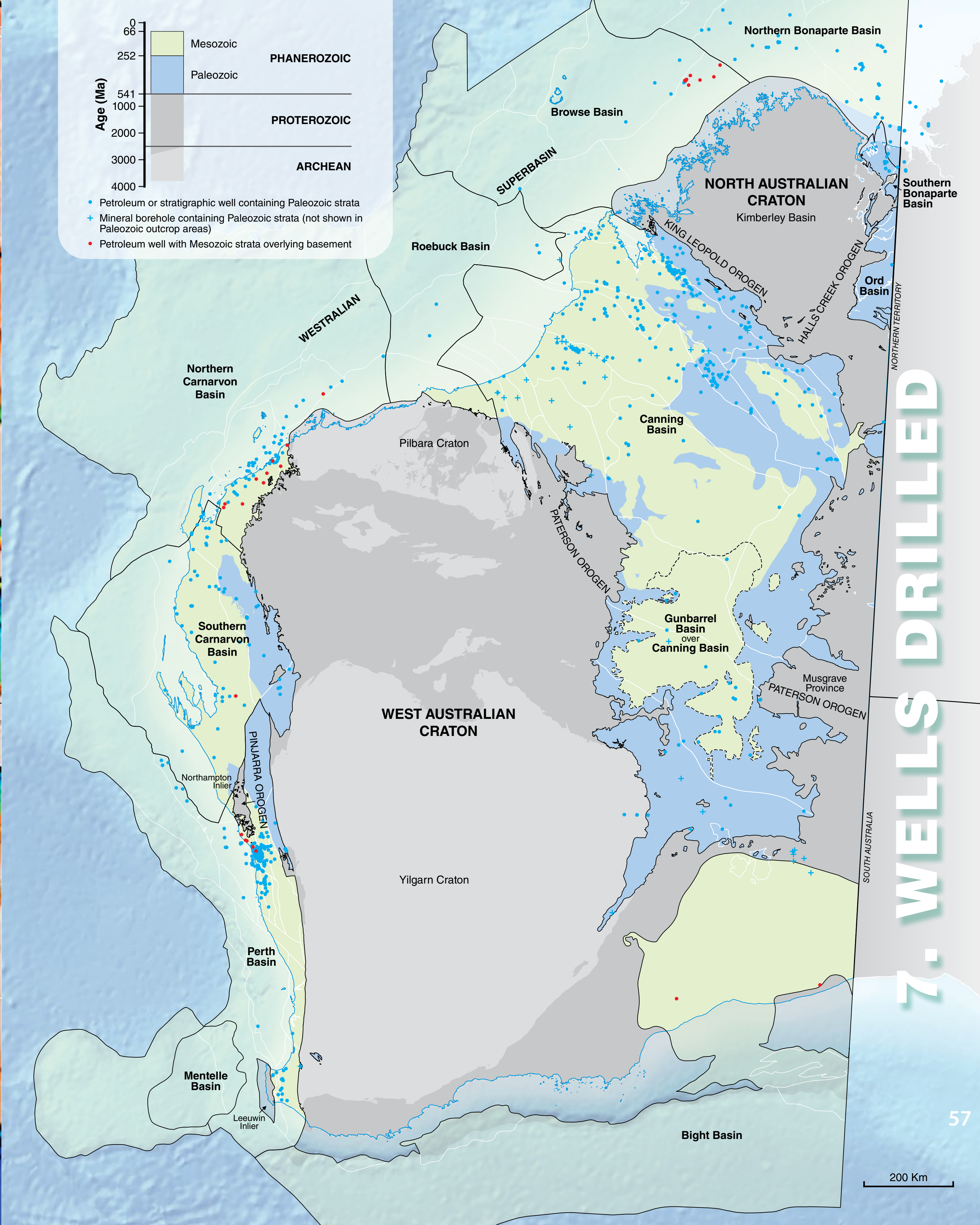
Name	Category	Ref
Admiral Bay	Zn–Pb deposit	G4
Albany	Town	D12
Barrow Island		C5
Bidgemia	Homestead	C7
Blacktip 1	Oilfield	J1
Blina	Oilfield	H3
Broome	Town	G3
Bunbury	Town	C11
Bungle Bungle Range		J3
Byro	Homestead	D8
Cadjebut	Zn–Pb deposit	H4
Carnarvon	Town	B7
Carolyn Valley		H4
Collie	Town and coal mine	D11
Cue	Town	D8
Dampier	Town	D5
Darling Range		D11
Denmark	Town	D12
Dirk Hartog Island		B7
Dongara	Town	C9
Dongara	Gas and oilfield	C9
Donnybrook	Town	C11
Dovers Hills		J6
Eighty Mile Beach		F4
Emanuel Range		H4
Esperance	Town	F11
Fitzroy Crossing	Town	H4
Fitzroy River		G4
Fossil Downs	Zn–Pb deposit	H4
Gap Creek		H4
Gascoyne River		C7
Geraldton	Town	C9
Gibson Desert		H7
Goodwyn	Gasfield	C4
Goongewa	Zn–Pb deposit	H4
Gorgon	Gasfield	C5
Great Antrim Plateau		J4
Great Australian Bight		I11
Great Sandy Desert		I5
Great Victoria Desert		H8
Hart Spring		J2
Harvey	Town	C11
Hovea	Gasfield/petroleum well	C9
Indian Ocean		C4
Irwin River		C9
Joseph Bonaparte Gulf		J2
Kalbarri	Town	C8
Kalgoorlie	Town	F10
Kapok	Pb–Zn deposit	I4
Kennedy Range		C7
Kidson 1	Petroleum well	H6
Kununurra	Town	J2
Kutarta	Zn–Pb deposit	H4
Lake Argyle		J3
Lake Gregory		I5
Laverton	Town	G9
Leonora	Town	F9
Linesman Creek		H3
Lyons River		C7
Marble Bar	Town	E5
Marella Gorge		J4
McWhae Ridge		I4
Meekatharra	Town	E8
Mitchell Plateau		H2
Mount Hutton		H4
Mullewa	Town	C9
Murchison River		D7
Napier Range	Zn–Pb deposit	H3
Narlarla	Zn–Pb deposit	H3
Newman	Town	E6
Nicholson River		J4
Ningbing Range		J2
Norseman	Town	F11
North Rankin	Gasfield	D4
North West Shelf		D4
Nullarbor Plain		I10
Oakover River		F5
Oobagooma	U deposit	G3
Ord River		J3
Patience 2	Petroleum well	H6
Perth	City	C10
Petermann Ranges		J7
Pillara	Zn–Pb deposit	H4
Poole Range		H4
Prices Creek		H4
Red Bluff		C8
Rough Range 1	Petroleum well	C6
Saint George Ranges		H4
Samphire Marsh 1	Petroleum well	F4
Shark Bay		B7
Sir Frederick Range		J6
Sorby Hills	Pb–Zn deposit	J2
Southern Cross	Town	E10
Southern Ocean		G12
Tanami Desert		J5
Tom Price	Town	D6
Ungani 1	Petroleum well	G3
Wagon Pass (Napier R.)	Zn–Pb deposit	H3
Warburton	Homestead	I8
Wilson Cliffs 1	Petroleum well	I6
Wiluna	Town	F8
Windjana Gorge		H3
Wingelinna	Town	J8
Wooramel River		C7
Wyndham	Town	J2

6. DEPTH TO BASEMENT

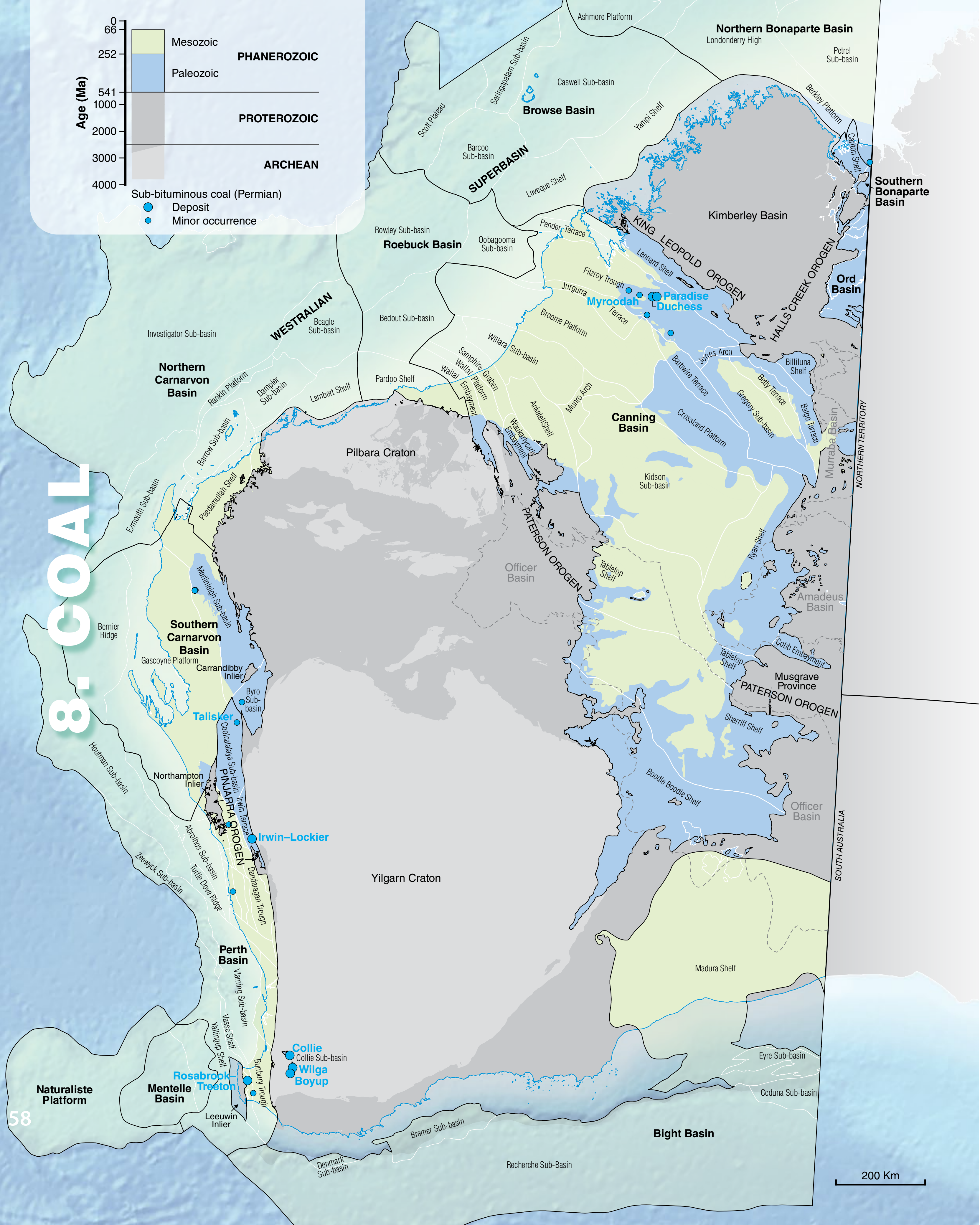


Estimated depth to basement from gravity data calibrated from seismic surveys and well intersections (Image courtesy Frogtech Geoscience)

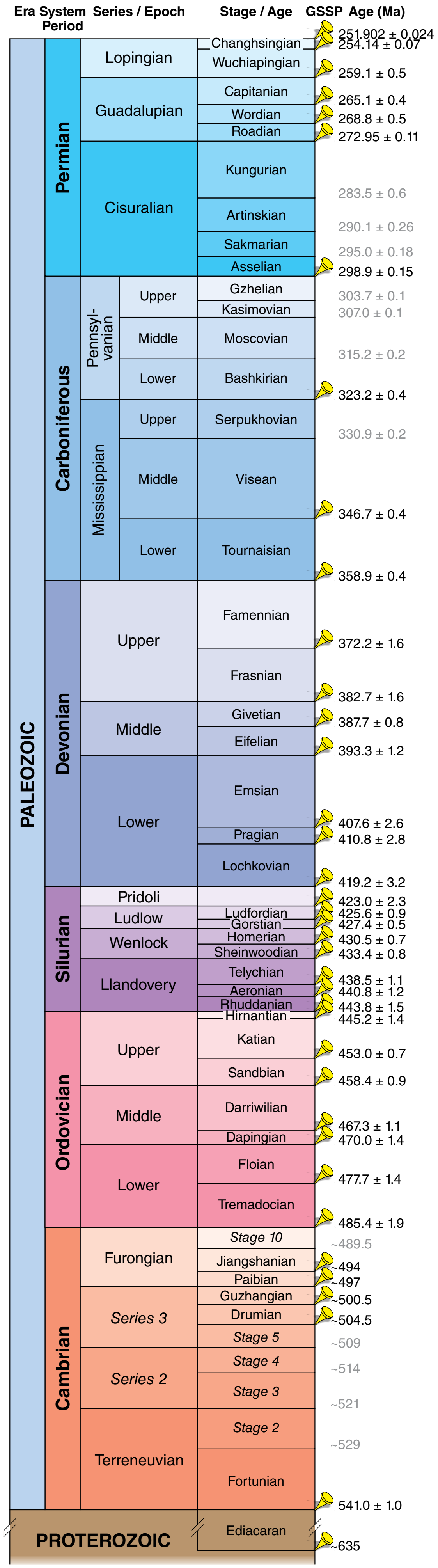
7. WELLS DRILLED



8. COAL



Age (Ma)
0
66
252
541
1000
2000
3000
4000
Mesozoic
Paleozoic
PHANEROZOIC
PROTEROZOIC
ARCHEAN
Sub-bituminous coal (Permian)
Deposit
Minor occurrence
Ashmore Platform
Northern Bonaparte Basin
Londonderry High
Petrel Sub-basin
Seringapatam Sub-basin
Caswell Sub-basin
Browse Basin
Scott Plateau
Yampi Shelf
Berkley Platform
Carlton Shelf
Barcoo Sub-basin
SUPERBASIN
Leveque Shelf
Southern Bonaparte Basin
Kimberley Basin
Rowley Sub-basin
Roebuck Basin
Oobagooma Sub-basin
Pender Terrace
KING LEOPOLD OROGEN
Lennard Shelf
Fitzroy Trough
Jurgurra Terrace
Myroodah
Paradise
Duchess
HALLS CREEK OROGEN
Ord Basin
WESTRALIAN
Beagle Sub-basin
Bedout Sub-basin
Broome Platform
Investigator Sub-basin
Northern Carnarvon Basin
Willara Sub-basin
Jones Arch
Billiluna Shelf
Rankin Platform
Dampier Sub-basin
Lambert Shelf
Pardoo Shelf
Samphire Graben
Wallal Platform
Wallal Embayment
Barbwire Terrace
Betty Terrace
Gregory Sub-basin
Munro Arch
Crossland Platform
Balgo Terrace
Canning Basin
Murraba Basin
NORTHERN TERRITORY
Barrow Sub-basin
Anketell Shelf
Waukarlycarly Embayment
Pilbara Craton
Exmouth Sub-basin
Peedamullah Shelf
Kidson Sub-basin
PATERSON OROGEN
Ryan Shelf
Officer Basin
Tabletop Shelf
Merlinleigh Sub-basin
Amadeus Basin
Bernier Ridge
Southern Carnarvon Basin
Gascoyne Platform
Carrandibby Inlier
Cobb Embayment
Tabletop Shelf
Musgrave Province
PATERSON OROGEN
Byro Sub-basin
Talisker
Sherriff Shelf
Coolcalalaya Sub-basin
Houtman Sub-basin
Northampton Inlier
PINJARRA OROGEN
Irwin Terrace
Boodie Boodie Shelf
Officer Basin
Irwin–Lockier
Abrolhos Sub-basin
Zeewyck Sub-basin
Turtle Dove Ridge
Dandaragan Trough
Yilgarn Craton
SOUTH AUSTRALIA
Perth Basin
Vlaming Sub-basin
Madura Shelf
Vasse Shelf
Yallingup Shelf
Collie
Collie Sub-basin
Wilga
Boyup
Rosabrook–Treeton
Bunbury Trough
Eyre Sub-basin
Naturaliste Platform
Mentelle Basin
Ceduna Sub-basin
Leeuwin Inlier
Bremer Sub-basin
Bight Basin
Denmark Sub-basin
Recherche Sub-Basin
200 Km



Geological time scale for Paleozoic (based on IUGS Chronostratigraphic chart v 2016/12)

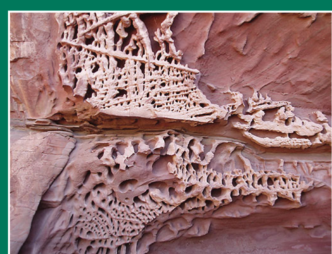
The Geological Survey of Western Australia follows the USGS colour scheme for lithostratigraphic units and this is replicated in the chronostratigraphic charts in this volume

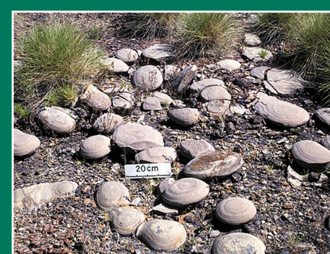
About this book

Paleozoic strata are preserved across about 30% of onshore Western Australia in both the coastal and interior basins. These sedimentary successions are largely unmetamorphosed and little deformed as igneous rocks are minimal and orogenic events were subdued.

Arthur Mory has used a series of statewide paleogeographic reconstructions paired with isopach images to detail the Paleozoic depositional and structural history of the onshore sedimentary basins — the time slices are based on regional correlations underpinned by biostratigraphical and paleontological studies. He recognizes four main phases of basin evolution commencing in the Cambrian and continuing through to the latest Permo-Carboniferous when the Gondwanan glaciation affected much of Western Australia. Exhumed Devonian carbonate reefs in the Canning and Southern Bonaparte Basins are deemed equivalent to Australia's renowned present-day Great Barrier Reef.

A Paleozoic perspective of Western Australia is the third volume to be published under the banner of 'Western Australia unearthed', a series that will progressively chronicle the geological evolution of Western Australia.





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