MESOZOIC TRANSFORMATION OF WESTERN AUSTRALIA: rifting and breakup of Gondwana

compiled by

Arthur J Mory

Government of Western Australia
Department of Mines, Industry Regulation and Safety

Geological Survey of Western Australia

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Cover image: Rippled and cross-bedded coastal-plain facies of the Lower Cretaceous Broome Sandstone, northern Roebuck Bay. Disturbed and lenticular beds in the lower part of the image are attributed to dinosaurian activity

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About this organization

The Geological Survey of Western Australia (GSWA) was the first part of the Department of Mines, Industry Regulation and Safety to be established, in 1888 with the appointment of Harry Page Woodward as the first permanent Government Geologist to the then Colony of Western Australia. GSWA became the first scientific organization in the State and now provides objective and authoritative geoscientific data, information and knowledge to support the responsible use of the State's natural resources

GSWA research includes regional geological mapping, terrane and basin analysis, and geochronology and mineralization studies. Systematic bedrock geology mapping at 1:250 000 since the 1950s has covered all of Western Australia, of which about 28% has been mapped at 1:100 000 — all of this mapping is incorporated into the latest State geological map. In addition, regolith, geochemistry, hydrogeology and urban geology maps are available at various scales for selected areas.

GSWA's activities aim to meet a variety of society's needs, including stimulating exploration, particularly in underexplored areas — thereby sustaining the resources sector to help grow the economy — and aiding resource-area decisions at all levels of government. In conjunction with universities, industry, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Geoscience Australia, GSWA documents the State's geology, and develops robust interpretations of tectonic setting, crustal architecture, geological evolution and metallogenesis to underpin regional prospectivity analyses. Recent projects have included deep crustal seismic reflection profiling, aeromagnetic surveys, 3D-architectural modelling, prospectivity assessments of underexplored regions and surface geochemical sampling.

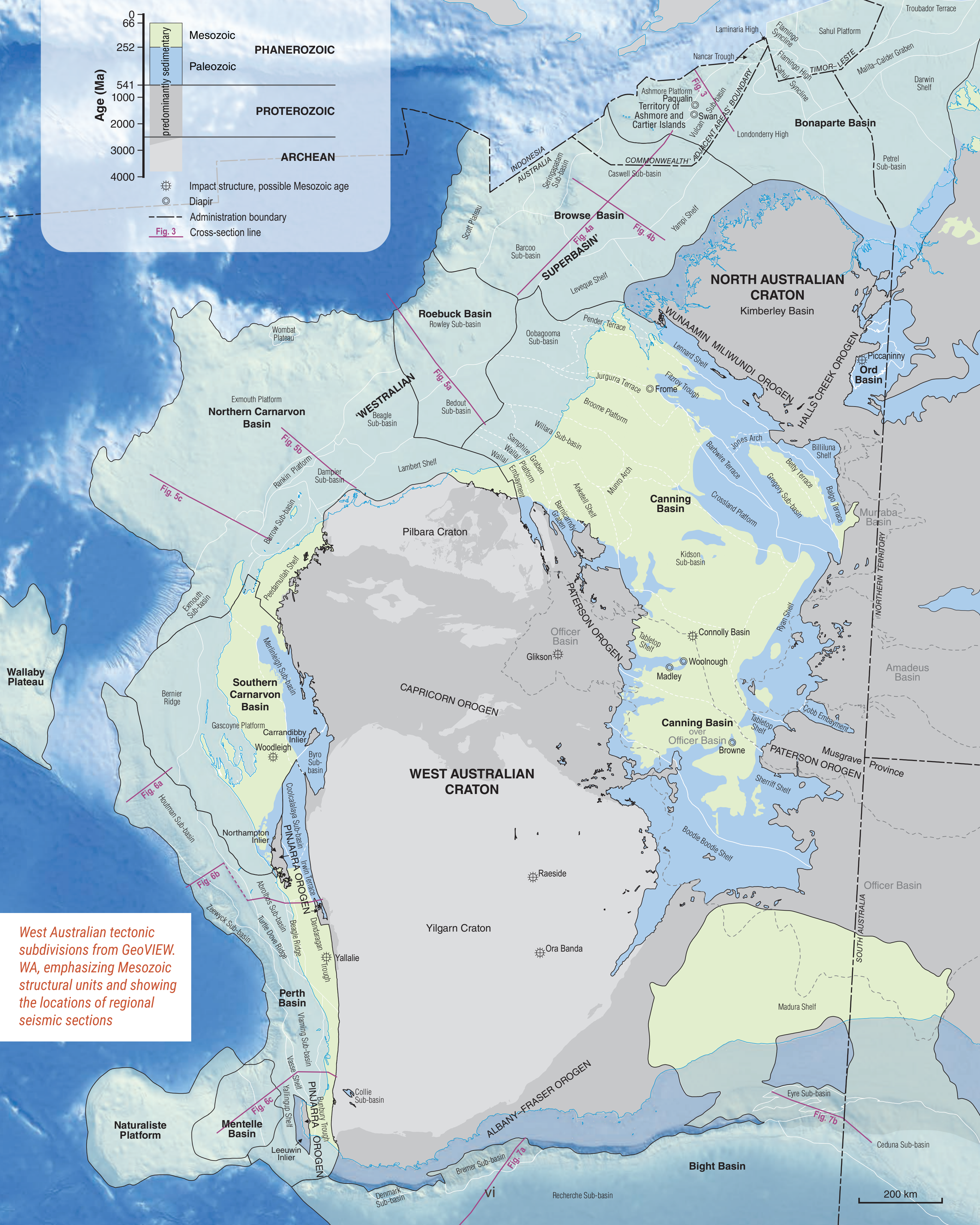
Preface

This volume — part of the Geological Survey of Western Australia's 'unearthed' series — aims to provide an introduction to the State's Mesozoic geology and mineral potential for trainee and professional geologists, particularly newcomers to the State. Previous volumes in this series cover the Proterozoic (*The birth of supercontinents and the Proterozoic assembly of Western Australia*), Paleozoic (*A Paleozoic perspective of Western Australia*) and Upper Cretaceous – Cenozoic (*Australia goes it alone — the emerging island continent 100 Ma to present*). Each volume describes part of the geological history of Western Australia, with a list of recommended references for follow-up reading.

In this volume, the Mesozoic evolution of the State is illustrated via a series of paired paleogeographic reconstructions and isopach images based on regional well correlations. Much of the narrative concerns the offshore North West Shelf, Australia's premier hydrocarbon province. Onshore, Mesozoic mineral deposits and petroleum accumulations are relatively rare or minor, and few are (or were) economic, as the State's tectonic history was not conducive to generating the diverse styles of mineralization typical of older (especially Precambrian) rocks. Whereas the main text is largely concerned with geological evolution, there is also a series of boxes detailing other aspects such as mineralization, other resources, fossils, impact features and provenance.

Information regarding the onshore geology and resources has been summarized from open-file data and GSWA reports, whereas much of the offshore information comes from Geoscience Australia and the National Offshore Petroleum Information Management System. Published sources include proceedings of symposia and conferences sponsored by the Australian Petroleum Production and Exploration Association and the Petroleum Exploration Society of Australia, especially the West Australian Basins Symposia.

Upper Cretaceous calcilutite in Giralia Range looking south to Cenozoic strata near Remarkable Hill on the horizon, Merlinleigh Sub-basin, Southern Carnarvon Basin



West Australian tectonic subdivisions from GeoVIEW. WA, emphasizing Mesozoic structural units and showing the locations of regional seismic sections

Setting the scene

Towards the end of the Paleozoic, Australia was part of Gondwana, a supercontinent that also encompassed modern-day Africa, Antarctica, Arabia, Greater India, South America and Zealandia (Fig. 1), plus smaller terranes now mostly dispersed throughout Southeast Asia. Gondwana first assembled during about 650–520 Ma (late Neoproterozoic to Early Cambrian), merged with Euramerica in the Carboniferous to form Pangea, from which it eventually began to separate in the Middle Jurassic (at ~175 Ma). Terranes adjacent to northwestern Australia broke off in the Permian during the development of the great Tethyan Ocean. Shortly afterwards, Gondwana separated from Pangea and split into smaller continental plates, with the final departure of Greater India from Australia in the Valanginian (Early Cretaceous). Antarctica and Zealandia, which were the last parts of Gondwana to separate from Australia, started to detach in the latest Santonian to early Campanian (Late Cretaceous, ~83 Ma). Antarctica separated completely from Australia in the Eocene (at ~40 Ma), with Zealandia separating in the early Miocene (~20 Ma).

Our knowledge of the State's Mesozoic geology, especially offshore, is greatly reliant on exploration for hydrocarbons — the foremost natural resource within sedimentary basins of this age — primarily along the North West Shelf, which extends about 2500 km from Exmouth northeast to Melville Island in the Northern Territory. By comparison, the onshore Mesozoic record in Western Australia is relatively incomplete, due to long periods of erosion, weathering or non-deposition, and is complicated by difficulties in reliably dating rocks of this age in many places. Mesozoic sedimentary successions along the North West Shelf host over 350 significant hydrocarbon accumulations, including giant gasfields and large oilfields. In comparison, onshore fields with reservoirs of this age are typically smaller (many are now depleted) and, apart from some heavy mineral sands, the majority of onshore Mesozoic mineral deposits are either relatively minor or sub-economic at present.

This volume explores the changing landscape and geology of the State and its surrounding terranes during the Mesozoic (252–66 Ma), and discusses the fragmentation of Gondwana and its still-evident effects, including resources formed during the era such as oil and gas, minerals and water. Of these resources, near-surface rocks and minerals have helped build our industries, roads and buildings; groundwater supplies water for human, animal, agricultural, mining and industrial uses, and also can be utilized for cooling or heating; and subsurface oil and gas underpins electricity generation, transportation, agriculture and the manufacture of products including fertilizers, fabrics, lubricants, plastics and many pharmaceuticals. Other important resources hosted within Mesozoic rocks include heat and pore space in which CO_2, H_2 or other gases may be stored.

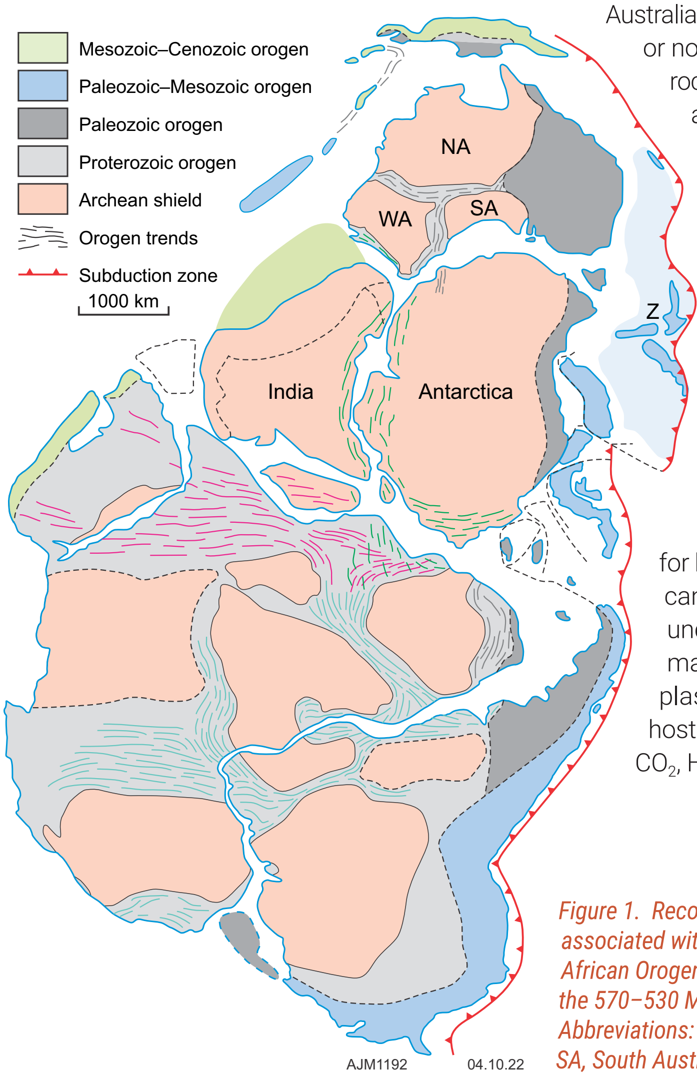


Figure 1. Reconstruction of Gondwana showing the main cratons and orogens associated with its final amalgamation. Red lines show trends in the 750–620 Ma East African Orogen; pale blue lines, the 630–520 Ma Brasiliano–Damara Orogen; and green, the 570–530 Ma Kuunga Orogen, which is partly equivalent to the Pinjarra Orogen. Abbreviations: WA, West Australian Craton; NA, North Australian Craton; SA, South Australian Craton; Z, Zealandia (after Meert, 2011 and Gray et al., 2008)

Overview of the Mesozoic of Western Australia

During the Mesozoic, the west of the Australian continent underwent subsidence and rifting leading up to the Late Jurassic – Early Cretaceous separation of Greater India (much of which is now assumed to underlie the Himalayas) and the dispersal of smaller terranes (now distributed throughout Southeast Asia). Following breakup, Western Australia was subjected to trailing-edge rifting and marginal sag with relatively minor structuring.

This summary of Western Australia's Mesozoic depositional and structural history incorporates a series of tectonic reconstructions, and isopach images generated from gridded borehole and petroleum well information paired with paleogeographic maps. Offshore Mesozoic successions, which were deposited within the eastern Gondwana interior rift, are emphasized given they are more complete than onshore sections as, except in much of the Perth Basin, they are typically thinner and with numerous stratigraphic breaks. Although the onshore basins are intracratonic offshoots of the offshore basins (Fig. 2), there are many features in common, largely because of a shared history of rifting and post-rift oceanic separation since the Carboniferous. However, there are also considerable differences in depositional development with fewer marine intervals onshore, at least prior to the breakup of Gondwana.

The main resources within the Mesozoic successions are hydrocarbons, especially in the Northern Carnarvon, Roebuck, Browse and Bonaparte Basins along the offshore North West Shelf (see frontispiece and resources map). Onshore, the most significant economic mineral deposits in, or partially in, Mesozoic sedimentary rocks are heavy mineral sands. Due to the subdued impact of orogenic events and the rarity of onshore volcanism through the Mesozoic in the State, other resources are limited; they include coal, uranium, greensands, base metals and gemstones, but these deposits are either minor or sub-commercial at present. Nevertheless, Mesozoic strata host potable groundwater and associated low-enthalpy geothermal resources; are quarried or excavated for construction materials; and have the capacity to store large volumes of greenhouse or combustible gases.

In contrast to the west, the eastern margin of the Australian continent developed from a late Carboniferous subduction complex followed by crustal addition associated with trench retreat to the Zealandia – Pacific Plate margin. There, a series of Late Triassic to mid-Late Cretaceous back-arc to foreland basins formed, with some occasional magmatism continuing into the Paleogene. This, plus difference in climatic conditions during some periods (such as the Early Cretaceous), can hinder correlation between the east and west of the continent, and explains the higher mineral prospectivity of at least some eastern Australian Mesozoic terranes.

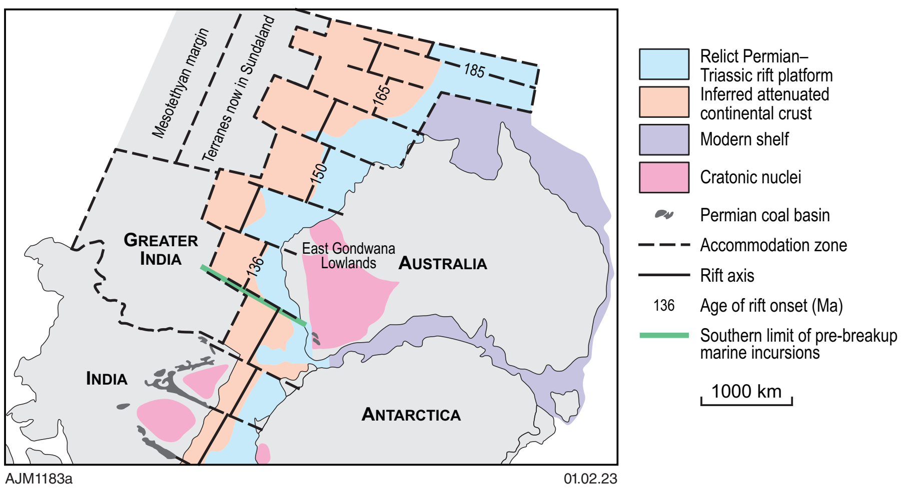


Figure 2. The east Gondwana rift with generalized breakup ages (after Harrowfield et al., 2005; Haig et al., 2017)

History of discovery

Early fossil collections dating back to 1839 by German naturalist J.A.L. Preiss included an 'encrinite', probably from the Gingin Chalk, but its significance was not recognized until over a century later. The first published mention of the Mesozoic in Western Australia followed the Gregory brothers' 1848 discovery of fossil shells and wood along the Greenough River, which Charles Moore determined in 1870 to be Jurassic (see ***Macrofaunas,*** p. 14), an interpretation that has been upheld. By comparison, it was not until 1907 that F.T. Gregory's 1861 suggestion of a Cretaceous age for the Gingin Chalk was confirmed when W. Howchin described foraminifera from the site. Other early documented finds of Jurassic fossils within the State include a pecten from Point Torment near Derby and plants described in 1910 from near Mingenew (now deemed Late rather than Early Jurassic). The relevance of early discoveries of Mesozoic fossils farther north was not appreciated until decades later when the continuity of such strata below the North West Shelf was first considered. The earliest of these discoveries were Cretaceous radiolarians from near Darwin (described by G.J. Hinde in 1893), for which an age was not determined until two years later when R. Etheridge Jnr. reported nearby ammonites and other fossils collected by H.Y.L. Brown.

Extensive drilling for artesian water during the 1890s and 1900s, largely near the coast in the Perth, Southern Carnarvon and Canning Basins, provided the first evidence of Mesozoic rocks in the subsurface (see ***Aquifers,*** p. 49). Descriptions of those sections (and eventually ages determined from fossils in the cores) were incorporated into early hydrocarbon investigations spanning the 1920s to 1950s. By then, Jurassic- and Cretaceous-aged outcrops were relatively well known, as most of the State had been mapped for the first time. However, it was not until the 1950s that the presence of Triassic strata was proven in the Perth Basin (based on ammonites in core from the Geraldton Racecourse water bore drilled in 1896–98) and Canning Basin (based on plants, spinicaudatans and lingulids). Earlier fossil finds from beds now considered Triassic at Port Keats and near Derby were not attributed to this period at first, and Early Triassic fossils collected from the Canning Basin by Arthur Wade during his 1934–35 survey for the Freney Kimberley Oil Company initially were regarded as Permian.

Following increased interest in hydrocarbons after World War II, oil was discovered in 1953 at Rough Range 1 within a Cretaceous reservoir. This was the first modern petroleum well drilled within the State, but the oil was not produced until the 1990s. After this early success, exploration soon shifted offshore to the North West Shelf. The first major oil discovery within a Mesozoic reservoir was in 1964 on Barrow Island, initially in the Upper Jurassic, although the main reservoir is within the Lower Cretaceous. Since then, exploration within Mesozoic units has largely been concentrated offshore, with an exponential increase in drilling and seismic reflection surveys (see ***Hunting for hydrocarbons***, p. 48). Many discoveries with substantial production followed over the succeeding decades. Recent discoveries include Dorado in 2018, Phoenix South in 2014 and Roc in 2015 within the Roebuck Basin, and Bratwurst and Orchid (both in 2019) in the western Bonaparte Basin.

Exploration for mineralization in Mesozoic rocks was sporadic until the 1980s except for heavy mineral sands (HMS) investigations, which began in the 1940s and focussed mainly on Cenozoic strandlines along the Swan Coastal Plain. These deposits were mostly reworked from Mesozoic sources, but some include the underlying Cretaceous or lie entirely within the Cretaceous, as in recent discoveries across the Dampier Peninsula, (see ***Heavy mineral sands — ancient shorelines***, p. 46). The search for phosphate also began in the 1940s and accelerated in the 1980s, as did exploration for uranium among other resources; however, subsequent discoveries of both commodities in Cenozoic deposits or the Precambrian have overshadowed those within the Mesozoic. The Donnybrook goldfield — largely mined during 1898–1903 with meagre results — may extend from the Yigarn Craton into Mesozoic strata of the Perth Basin (see **Resources**, p. 43).

Basins, sub-basins and depocentres

Mesozoic sedimentary successions are mostly contained within the major basins flanking the State's Precambrian cratons: the Bight, Perth, Southern Carnarvon, Northern Carnarvon, Roebuck (previously the offshore Canning), Canning, Browse and Bonaparte Basins (from south to northeast). With the exception of the Bight, Perth, Southern Carnarvon and Canning Basins, these collectively have been grouped within the 'Westralian Superbasin' — a term that has not been widely accepted, especially by the exploration industry (see ***North West Shelf vs 'Westralian Superbasin'***, p. 10). The only places where

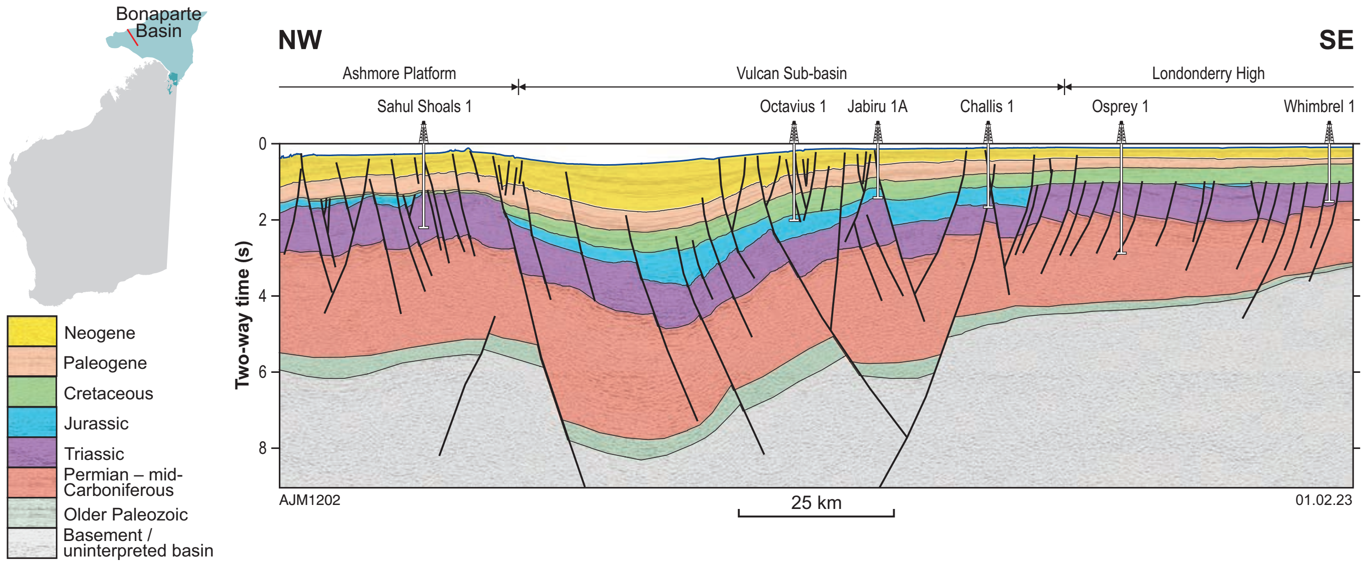


Figure 3. Seismic line n98/r02 across the northwestern Bonaparte Basin. Location shown on frontispiece (reproduced with permission of Geoscience Australia)

the Mesozoic does not fall within areas classified as sedimentary basins are where the Upper Jurassic and younger sediment overlies oceanic crust, and isolated Cretaceous outcrops on the margins of the Pilbara Craton and Capricorn Orogen. Along the southern margin of the continent, the Bight Basin extends eastwards into South Australian waters (see frontispiece) and transitions into a set of coeval basins.

The Mesozoic depocentres along the North West Shelf broadly equate to offshore sub-basins between 'shelves' flanking the present coast and outboard 'platforms' (see frontispiece). However, this was not always the case, particularly during the Middle to Late Triassic, when thick sand facies extended across most of that region and the Perth Basin, or for the latest Cretaceous, when subsidence in the rift centres diminished, thereby allowing carbonate platforms to prograde over the entire system across the North West Shelf throughout most of the Cenozoic.

The Bonaparte Basin encompasses three major depocentres, of which the north-northwesterly trending Petrel Sub-basin extends onshore and is flanked by 'shelves' characterized by onlap of the Phanerozoic onto Precambrian basement. In the Petrel Sub-basin, the Mesozoic thins appreciably to the south across the Paleozoic depocentre, especially over the Londonderry High, a region in which the Paleozoic is relatively shallow (Fig. 3). Farther offshore, the other two major troughs or grabens are Mesozoic depocentres that are almost orthogonal to the Petrel Sub-basin but with slightly different orientations (ENNE for the Vulcan Sub-basin – Nancar Trough in the west and EENE for the Malita Graben in the east). These sub-basins lie inboard of two structural platforms (the Ashmore and Sahul Platforms, respectively) separated by the approximately north-northwesterly oriented Sahul and Flamingo Synclines, and Laminaria and Flamingo Highs. These grabens were active in the Middle to Late Jurassic, whereas only the eastern graben system was significantly structured during the mid-Cretaceous.

The main depocentres of the Browse Basin (Figs 4a,b) are within the southeastern parts of the Barcoo and Caswell Sub-basins, just outboard of the Leveque and Yampi Shelves where the Mesozoic onlaps the Precambrian Kimberley Basin. Magnetic imagery across these shelves reveals the structure of the underlying Precambrian because the Mesozoic is comparatively thin there (see Map 2, First vertical derivative magnetic image, p. 67). The Scott Plateau, to the northwest of the main depocentres, appears to have been a relatively elevated region from at least the Late Jurassic until breakup, after which it gradually subsided to its present depth and was blanketed by post-breakup Cretaceous and younger sediment.

In the Roebuck Basin, truncation of northwesterly thickening Triassic and Lower Jurassic successions next to oceanic crust (Fig. 5a) suggests that equivalents in formerly adjacent terranes, now preserved in Southeast Asia, were also thick. Unlike adjoining basins, an outboard basement high is absent and structuring of the Mesozoic succession is

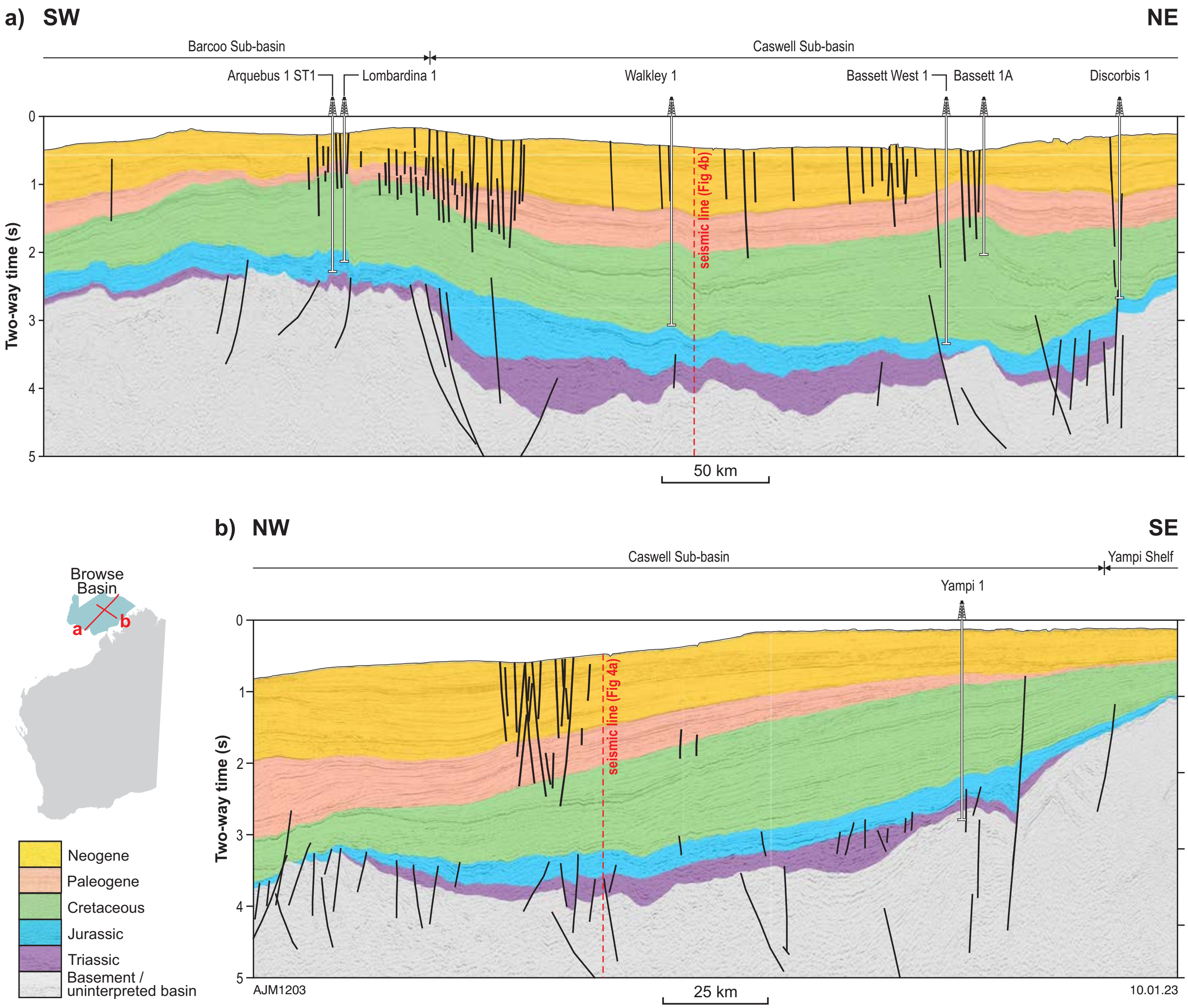


Figure 4. Seismic lines from the Browse Basin: a) BBHR15 and b) BBHR07. Locations shown on frontispiece (reproduced with permission of Geoscience Australia)

relatively simple apart from some complex features within the thick Triassic volcanic succession.

The North Carnarvon Basin contains a thick Triassic deltaic section (Mungaroo Formation), which appears to maintain a relatively uniform thickness across the basin based on regional seismic lines, notwithstanding the numerous faults that sole out in the Lower Triassic Locker Shale, especially across the Exmouth Plateau. The Jurassic and Cretaceous are thickest in the inboard Exmouth Sub-basin (Figs 5b,c), with the adjacent sub-basins to the northeast, which formed failed-rifts, thinning to the northwest. Those sub-basins (especially the adjoining Barrow, Dampier and Beagle Sub-basins) have had a complex history of faulting, starting with synrift faulting with crestal erosion of fault blocks mostly pre-dating the onset of deposition following breakup. In the Southern Carnarvon Basin, the Triassic and Jurassic are largely absent, with the Cretaceous encroaching over older sub-basins.

In the Perth Basin, the major depocentres are the offshore Houtman, Abrolhos and Vlaming Sub-basins and the mostly onshore Dandaragan and Bunbury Troughs, all of which have substantial thicknesses of Mesozoic sedimentary successions, although comparatively less so in the Bunbury Trough. The onshore Dandaragan Trough and its southern extensions (including the Bunbury Trough) thicken eastwards against the Darling–Urella fault system. In contrast, the Mesozoic thickens dramatically offshore westwards from the Beagle Ridge to Gascoyne Platform into the Abrolhos Sub-basin

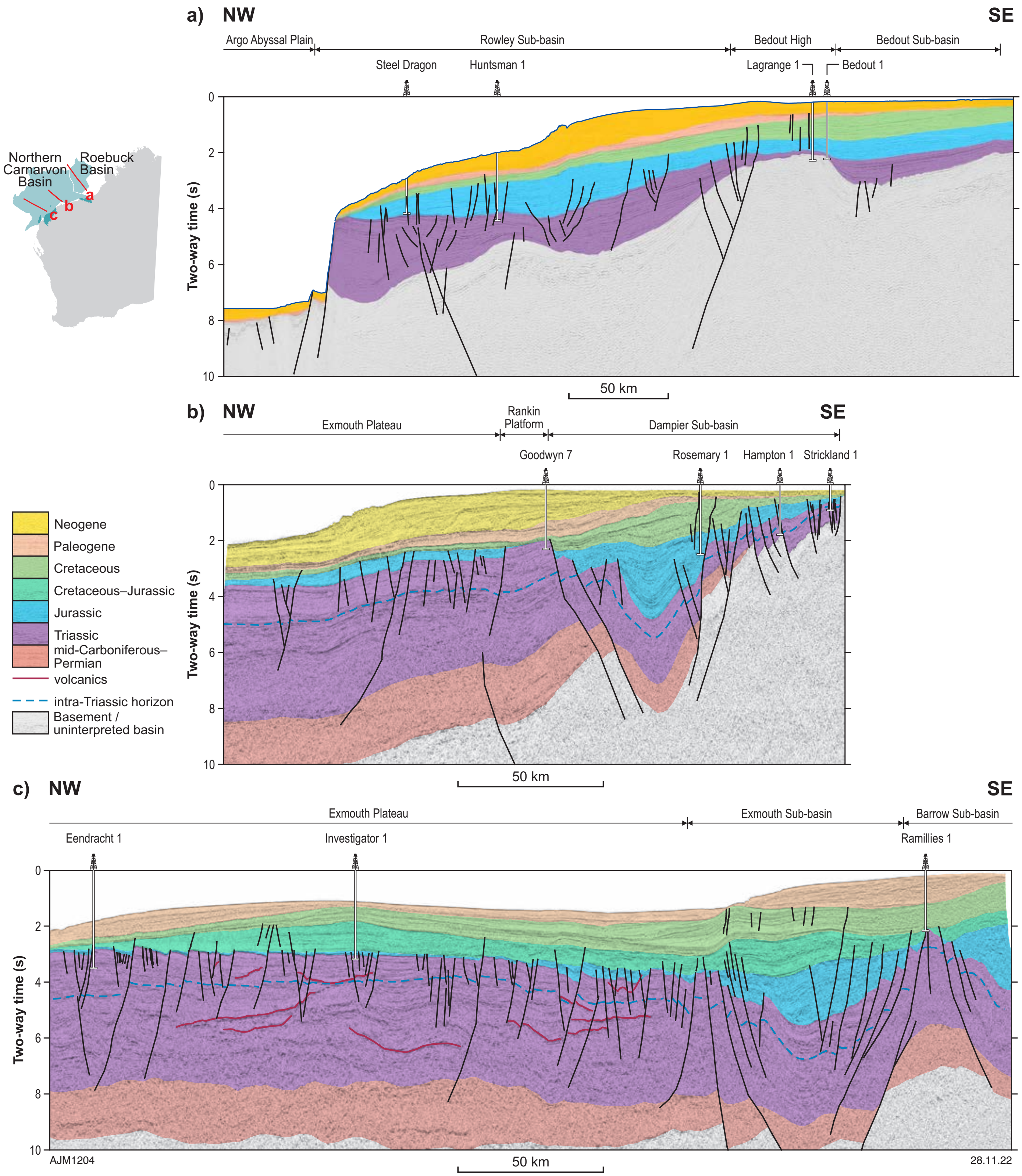


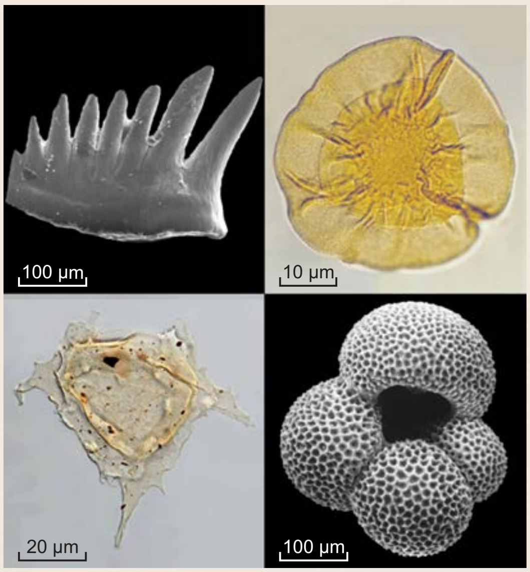
Figure 5. Seismic lines across the Roebuck and Northern Carnarvon Basins: a) s120/01; b) 110/12 and c) 101r/09 (reproduced with permission of Geoscience Australia). Locations shown on frontispiece

and adjoining Houtman Sub-basin to the northwest (Fig. 6a). To the south, the Vlaming Sub-basin contains up to 6 km of Neocomian deltaic facies. This abuts against the Yallingup and Vasse Shelves where basement is shallow (probably an extension of the Proterozoic Pinjarra Orogen from the Leeuwin Inlier) and the Mesozoic thins considerably. Farther southwest, in the Mentelle Basin and Naturaliste Plateau, Upper Jurassic and younger deposits onlap oceanic volcanic rocks in waters 2–5 km deep. Along the Beagle Ridge near the present coast in the northern Perth Basin, shallow basement lies between a half-graben to the east controlled by the Darling–Urella fault system and formations that thicken to the west (Figs 6b,c). Many of the designated onshore ‘sub-basins’ in this region are relatively small, akin to structural trends within the Barrow, Dampier and Beagle Sub-basins in the Northern Carnarvon Basin, or the Vulcan Sub-basin in the Bonaparte Basin.

In the offshore Bight Basin along the State’s southern margin, a Middle Jurassic (Callovian) to Cretaceous succession overlies Precambrian igneous and metamorphic rocks, and is mostly preserved in a series of south-dipping half-grabens. Upper Cretaceous units onlap these grabens and intervening basement, and thicken markedly to the south (Fig. 7).

Dating the Mesozoic

The apparent paucity of Mesozoic volcanic and volcanoclastic rocks means few absolute ages have been determined from formations of this era in the State and adjacent waters. Furthermore, many of these rocks are intrusive, or extensively oxidized, and therefore do not constrain the age of associated stratigraphic or biostratigraphic units. About 5% of zircons dated for provenance studies along the North West Shelf have yielded ages spanning the Triassic – Early Cretaceous (~250–115 Ma; see ***Provenance — where did the sediment come from?*** p. 40) but their origins are uncertain. Of these young zircons, about 85% are Triassic, which is the age of the sampled intervals — presumably, even younger zircons are caved from higher in the sampled wells but they at least indicate the possibility of obtaining radiometric dates from the Jurassic and Cretaceous.



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Representative Mesozoic microfossils (from Mantle et al., 2010, Australian biozonation chart). Clockwise from top left: *Neospathodus* sp. (Early Triassic conodont), *Callialasporites dampieri* (Jurassic–Cretaceous pollen), *Globigerina woodi* (Early Cretaceous foraminifera) and *Phoberocysta neocomica* (Cretaceous dinocyst)

Biostratigraphy, especially palynology, is the dominant method to date and correlate Mesozoic successions in the State, especially in the subsurface. Marine microorganisms (primarily conodonts, foraminifera, calcareous nannofossils and dinoflagellates) currently provide the highest precision biostratigraphic schemes (there have been relatively few studies of ostracods and radiolarians) and are more useful to correlate subsurface sections than marine macrofossils such as ammonoids. However, many of these groups are temporally restricted, thereby limiting their usefulness — e.g. conodonts became extinct at the end of the Triassic and dinoflagellates are relatively rare prior to their diversification in the Pliensbachian (Early Jurassic). In Australia, groups such as nannofossils and foraminifera (both planktonic and benthic) are biostratigraphically most useful for Cretaceous–Cenozoic successions.

Extensive exploration along the North West Shelf has provided tightly constrained and finely divided chronostratigraphic schemes with zones associated with named seismic horizons and regional ‘play’ intervals (see Fig. 9), yet few zones pre-dating the mid-Jurassic can be tied directly to the international chronostratigraphic scheme. Preliminary work by Geoscience Australia linking high-resolution geochronology and Cretaceous dinocyst zones indicates these schemes, typically considered highly robust within Australia, require recalibration using isotopic dating. Of all the biostratigraphic schemes, the reliability of the continental spore-pollen zonation is unclear at some levels due to local environmental and climatic influences (see ***Climate***, p. 17) and the protracted duration of some zones. Nevertheless, it is widely used for correlating the Mesozoic across the State and adjacent waters. At present, the primary regional tie points for microfossil zonations in west Australia come from marine incursions, especially during the Induan to Anisian (Early to early Middle Triassic), early Bajocian (Middle Jurassic) and several levels in the Cretaceous from the Aptian to the Maastrichtian.

The Australia-wide spore-pollen scheme incorporates parallel ‘eastern’ and ‘western’ zones with changes in datums between northern and southern basins in an attempt to manage this regionalism (see ***Flora — greening Western Australia***, p. 16) but issues with local applicability of some zones and correlating parallel zones remain largely unresolved. Another difficulty is that marine facies pre-dating the Cretaceous are relatively rare in the south of Western Australia such that Triassic and Jurassic biostratigraphy typically depends on low-precision spore-pollen zones.

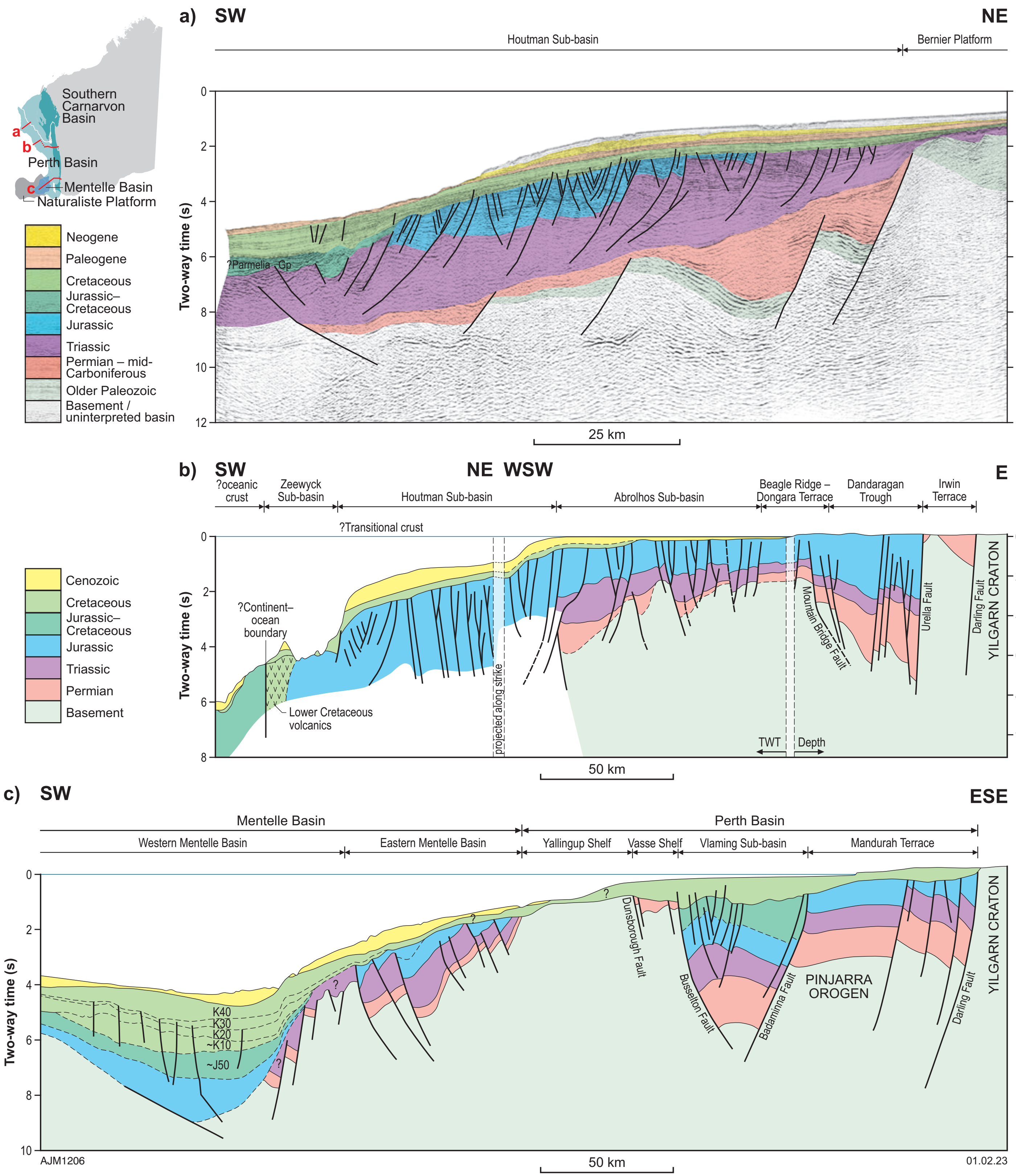


Figure 6. Seismic transects across the Perth and Mentelle Basins: a) GA349/1024 across the Houtman Sub-basin, northern Perth Basin; b) transect after Norvick (2004), northern Perth Basin; and c) GA280/04 over the Mentelle Basin extended across the southern Perth Basin (reproduced with permission of Geoscience Australia). Locations shown on frontispiece

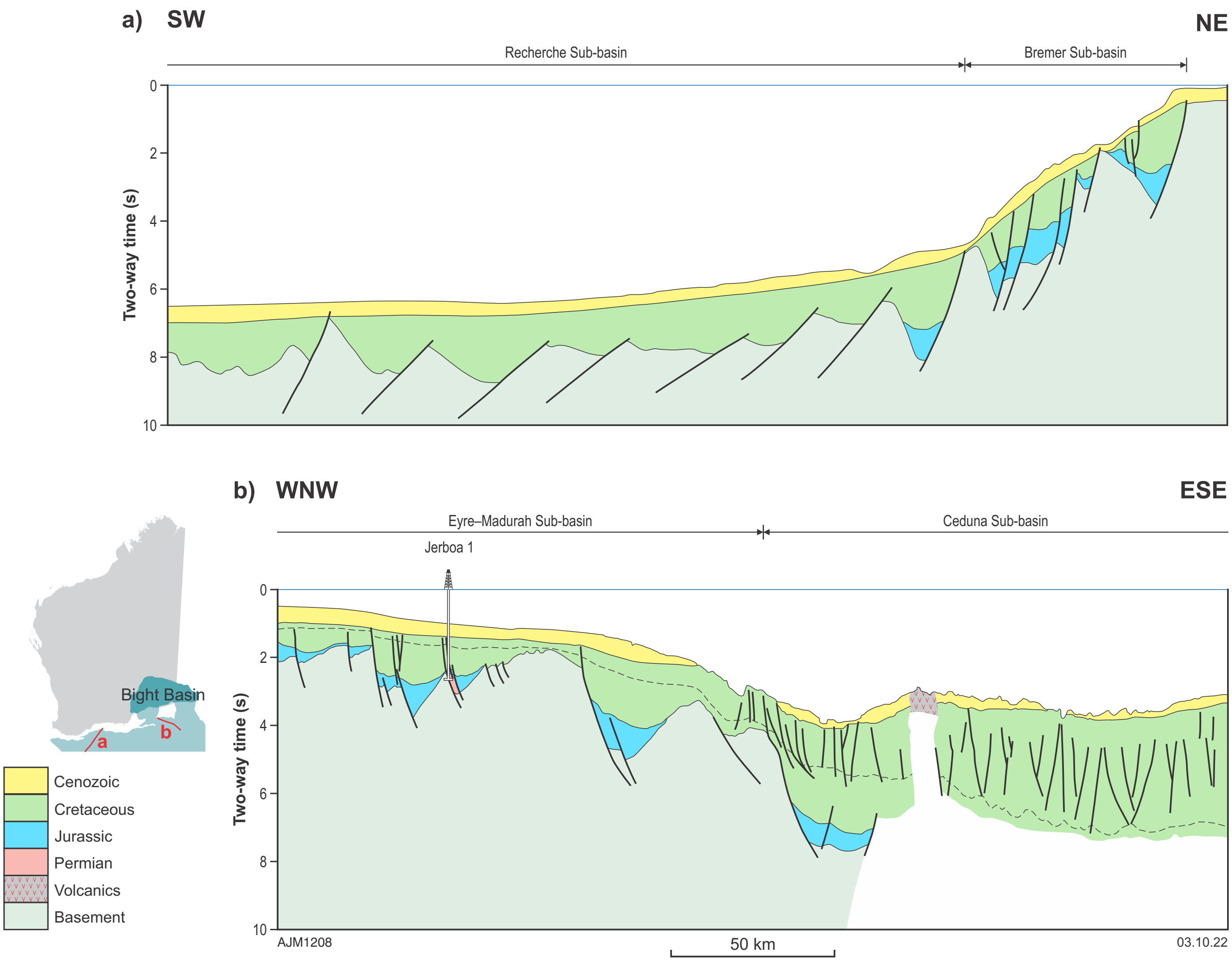


Figure 7. Transects based on seismic sections across a) the Recherche (line 280-18) and b) Eyre–Ceduna (line PP-3545-6) Sub-basins, Bight Basin (reproduced with permission of Geoscience Australia). Locations shown on frontispiece

The four main offshore Mesozoic structural trends presumably reflect at least some degree of homogeneity within underlying Precambrian basement and similarities in their subsequent deformation history:

1) The Bight Basin along the southern margin formed when Middle Jurassic – Cretaceous extension reactivated older easterly trending structural fabrics in the Mesoproterozoic orogens that flanked east Antarctica and the Yilgarn Craton, such as the Albany–Fraser Orogen in Western Australia. Breakup in this region began during the Late Cretaceous, with the basin progressively opening to the east until Australia and Antarctica separated completely in the Eocene.

2) The northern Perth Basin probably inherited structural trends from the underlying Proterozoic Pinjarra Orogen, although, in the northwest, the Wallaby–Zenith Fracture Zone is deflected to the north-northwest — a change that may be associated with the northern extent of Greater India.

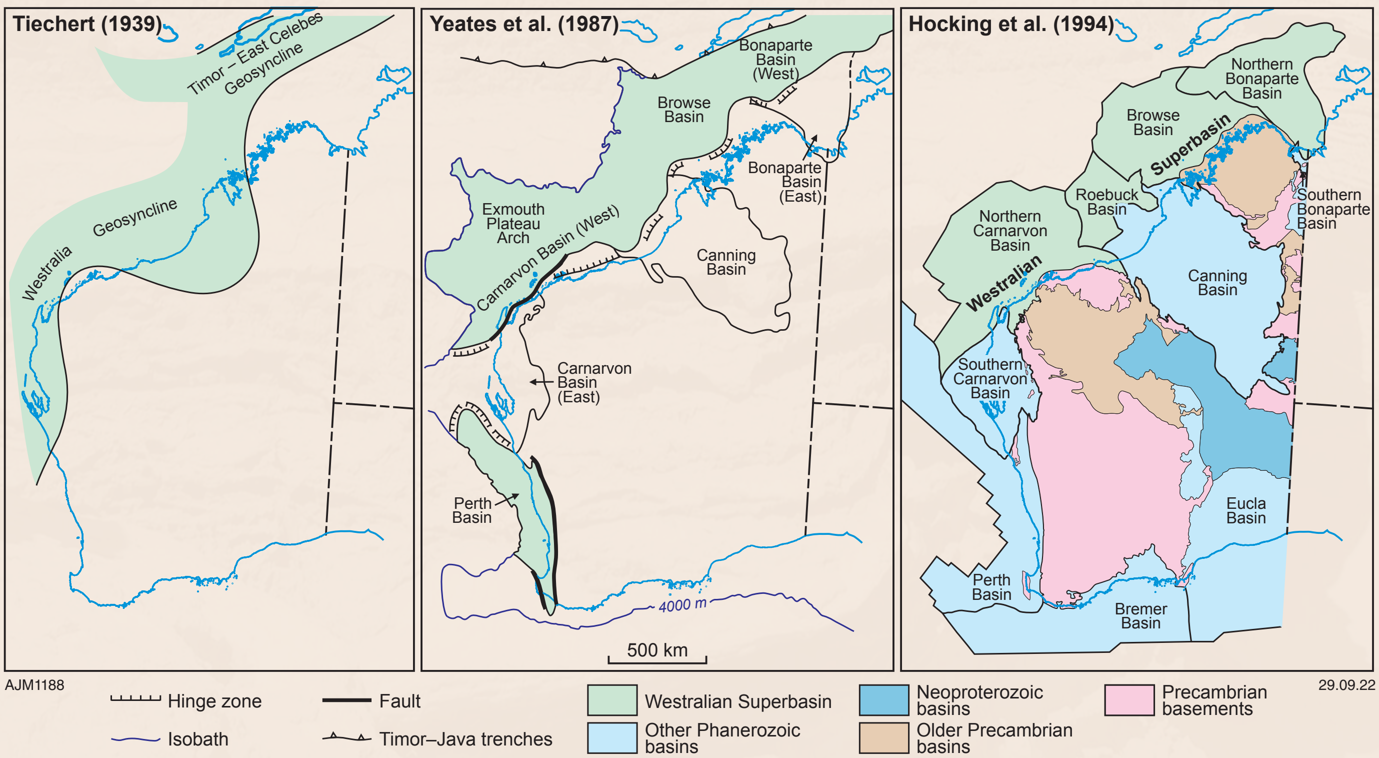
3) A dominantly northeastern trend along the North West Shelf extends from the Exmouth Sub-basin of the Northern Carnarvon Basin to the Vulcan Sub-basin of the western Bonaparte Basin, and includes associated faulted terraces and basement highs farther offshore. The inshore depocentres may have developed over Precambrian mobile zones, whereas outboard highs included relatively homogeneous terranes severed from crustal fragments. These terranes separated from the Australian continent in the Permian and Mesozoic and are now preserved in Southeast Asian mobile belts.

North West Shelf vs 'Westralian Superbasin'

The terms 'North West Shelf' and 'Westralian Superbasin' are commonly considered exchangeable, even though they refer to geographic vs geological entities, respectively

The 'North West Shelf' is an informal physiographic name for Australia's northwestern margin encompassing the continental shelf to water depths of about 4–5 km. The region incorporates chains of atolls, reefs, banks and shoals extending to the shelf break, the continental slope with a marine platform or terrace down to about 600 m, and the deep-water Exmouth and Scott Plateaus. The term follows Otto Krümmel's 1907 use of 'Nordwestaustralschelf', which he listed as one of the 'more important shelves' worldwide, extending approximately 2400 km from North West Cape to Cape Van Diemen on Melville Island in the Northern Territory. Although there have been minor variations in its nomenclature, the term is well-established due to the importance of the 'North West Shelf Project/Venture'.

The term 'Westralian Superbasin' resurrected the outdated 'Westralia Geosyncline' concept, originally coined by Teichert in 1939, in an attempt by Yeates and others in 1987 to place the 'relicts' of 'the Permian to Cretaceous sedimentary fill, generally around 10 km thick, preserved along the western margin of Australia' into a modern geological context. Earlier uses of 'Westralian', such as by Clapp in his negative 1926 assessment of the State's oil prospectivity (see *Hunting for hydrocarbons*, p. 48), appear to have been entirely geographic in context. Implicit in the broad definition of the superbasin is its extension into coeval northern Gondwanan terranes such as the Money Shoals, Arafura and Carpentaria Basins, Timor and farther north, although Yeates and his co-authors excluded Timor. Other users of the superbasin concept restrict it to the Northern Carnarvon to Bonaparte Basins, largely coincident with the North West Shelf and incorporated Cenozoic strata. Initially omitted from the superbasin were the Petrel Sub-basin and more southern parts of the Bonaparte Basin, as well as the Canning Basin, Naturaliste Platform, Mentelle Basin and Wallaby Plateau. This was possibly because Mesozoic successions in the first three of these basins are incomplete and little was known of the latter three regions at the time. Although initially included within the 'Westralian Superbasin', the Perth Basin is now excluded. Use of 'Westralian Superbasin' is not widely supported, presumably because it encompasses such a broad region and has been either poorly defined or applied in an inconsistent manner (e.g. the variable inclusion/exclusion of the Petrel Sub-basin of the Bonaparte Basin). The name is now attached to the Triassic–Cenozoic petroleum supersystem extending from the North West Shelf into the Papuan Basin.



Evolution of the 'Westralian Superbasin' concept

4) In the eastern Bonaparte Basin, the more easterly orientation of the Malita Graben, compared to the Vulcan Sub-basin to the west, may be due to a change in basement rheology and minor rotation across the zone of Precambrian crustal thinning, which underpins the north-northwesterly trending Petrel Sub-basin.

Basin and sub-basin boundaries

Although there has been an exponential increase in subsurface data in the last three decades, few basin or sub-basin boundaries have been revised, possibly because many are gradational, poorly defined or arbitrary. In addition, differentiation of superimposed Phanerozoic sedimentary basins is patchy within the State as opposed to elsewhere in the continent, e.g. the overlapping Cooper–Galilee, Eromanga and Lake Eyre Basins in eastern and central Australia. Although this is partly due to the lateral continuity and relative completeness of offshore sedimentary sequences in a passive-margin setting, at least for the Mesozoic, the wish for clearly defined boundaries in the administration of exploration and resource development by government departments has also inhibited the recognition of ‘stacked’ basins and meaningful geological boundaries. Apart from the Perth Basin, onshore sub-basins are mostly differentiated using Paleozoic structures and are effectively indistinguishable at Mesozoic stratigraphic levels. In the post-breakup successions, the lateral continuity of offshore marine deposit facies is such that most of the Cenozoic, and some of the uppermost Cretaceous, arguably form a ‘circum-Australia’ carbonate shelf rather than a set of basins. Similarly, the majority of onshore Cenozoic units in Western Australia, especially thin, fluvial, eolian, paleovalley and regolith deposits, are inherently difficult to relate to tectonic events and rarely form basins.

Despite the ostensible difference between the geographic ‘North West Shelf’ and tectonic ‘Westralian Superbasin’ (see ***North West Shelf vs ‘Westralian Superbasin’***, p. 10), the former term is widely applied to the geological province. Although some major physiographic sea-floor features and underlying sedimentary depocentres appear related — e.g. the sea-floor ‘Browse and Bonaparte Depressions’ outlined by J. Gentilli and R.W. Fairbridge in the early 1950s and the eponymous sedimentary basins — modern sea-floor bathymetric imaging does not support a direct correlation.

In many respects, inadequacies in some offshore basin (and sub-basin) definitions originated in the early 1970s when knowledge of deep structure was limited, and followed attempts to deduce deep structure by juxtaposing sea-floor features against onshore sedimentary basins. Many of these have not been re-evaluated using modern data. For example, the western edge of the Seringapatam Sub-basin in the Browse Basin, originally drawn from gravity images, is close to the 1000 m bathymetric contour, seemingly based on free-air gravity rather than an isostatic residual. Although this example could be atypical, and the lower reaches of the continental slope may be structurally controlled, essentially all offshore western and northwestern Australian basins are inherently geographic/administrative entities, as they are differentiated using ‘boundaries’ from different structural levels projected to the surface or sea floor. In places, these boundaries are gradational or arbitrary and lie below major depocentres that arguably form younger, overlying basins, especially if unaffected by deeper structure. A different example of an administrative influence on some geological maps is the omission of structural elements beyond Australia’s northern maritime boundary.

Ambiguities can arise from the application of terms such as ‘shelf’, ‘terrace’, ‘plateau’, ‘platform’ and ‘trough’ to both geographic/physiographic features and geological depositional–tectonic entities. Such terms have long been applied in a geological sense in Australia and globally, so there may be some confusion where names apply to both sea-floor and underlying geological features, e.g. the Exmouth, Wombat and Wallaby Plateaus, or by the Naturaliste Plateau being underlain by a ‘platform’ with the same name.

To date, superimposed basins are recognized only in the south and southeast of the State. These include the Cenozoic Eucla Basin and the underlying, mostly offshore, Mesozoic Bight Basin, which encroach over the southernmost end of the Paleozoic Canning Basin, and progressively overlap the Neoproterozoic–Cambrian Officer Basin and several older basins. Stacked basins are not differentiated elsewhere in Western Australia, but could be so along the North West Shelf and the Perth, Mentelle and Naturaliste Basins. Such differentiation is required as, for example, the present boundary between the Southern and Northern Carnarvon Basins, along the northernmost subcrop of the Permian, discounts the Paleozoic extending much farther north in the subsurface. Some authors have restricted sub-basin names temporally to refer to a part of the succession, e.g. 'Southern Carnarvon Platform' has been used for just the Cretaceous succession over this structurally elevated area whereas 'Gascoyne Platform' is applied by GSWA to the entire sedimentary succession in the same area. The former usage is not without merit given the gap spanning about 120 Ma between the Paleozoic and Cretaceous across that region, and the minimal structuring seen in the Cretaceous.

The desire for simplicity in basin definitions has led to some inconsistencies in how basins are differentiated as well as some whimsical boundaries. Onshore basins, where distinguished from their offshore extensions, are commonly discriminated as containing a Paleozoic succession with a relatively thin Mesozoic cover compared to offshore portions with a considerably thicker Mesozoic succession. Rather than superimposed entities being distinguished, basins are typically differentiated using deep structural features, even where younger strata are unaffected by these structures. Moreover, there seems to be little reason to divide areas categorized as shelves — especially where the Mesozoic (mostly the Cretaceous) directly overlies Precambrian basement rocks — or assign portions to different basins. Examples include the Lambert and Peedamullah Shelves adjoining the north-northwestern Pilbara Craton, and the Yampi and Leveque Shelves of the eastern Browse Basin. Until recently, parts of the Lambert Shelf have been variously (seemingly arbitrarily) assigned to the Northern Carnarvon, Roebuck or Canning Basins.

The previous division of the Bonaparte Basin into northern and southern portions is no longer made, as the supposed boundary along a Devonian 'hingeline' between shelfal carbonate and basinal siliciclastic facies ignores the overlying sedimentary successions. The southwestern edge of the basin links the similarly oriented northeastern edge of the Precambrian Kimberley Basin with the southern edge of the Ashmore Platform with little regard for the intervening region. On the eastern side of the

Bonaparte Basin, the Jurassic–Cenozoic onlaps onto Precambrian rocks across the Darwin Shelf and into the adjacent Money Shoals Basin immediately to the east, but there is little to discriminate these regions as the strata are the same age, are generally undeformed and show no obvious depocentres.

The use of a mixture of criteria to distinguish the northwestern limit of the Canning Basin against the Roebuck Basin (previously termed the 'offshore Canning Basin' or 'Western Canning Basin') is such that a re-evaluation is required. Near the southern end of the Canning Basin, Mesozoic marine facies unconformably overlying Permian glacial facies were placed in the 'Gunbarrel Basin' even though they are contiguous with apparently non-marine units of the same age to the north. The definition of that 'basin' has had several iterations, each covering different stratigraphic intervals, but the Permian and Mesozoic are now assigned to the Canning Basin, with the older Phanerozoic and Neoproterozoic sedimentary successions allocated to the Officer Basin.

Notwithstanding the vague manner in which many basins and sub-basins are discriminated, their identification and subdivision according to their present structural configuration is biased towards their post-burial history. Although practical for administrative purposes, this has led to inconsistencies that cannot be easily resolved unless either their equivocal nature is accepted or a detailed understanding of the temporal and spatial distribution of facies is developed. The latter could incorporate likely sources, thickness variations, and how these facies and breaks within the sedimentary successions are related to various tectonic episodes, both within and external to the Australian continent; however, this could be challenging to implement.

Angular unconformity at the base of the Lower Cretaceous Winning Group next to Jubrico Creek 18 km west of Nanutarra Roadhouse, Peedamullah Shelf, Northern Carnarvon Basin

Macrofaunas

In general, macrofossils are mostly recovered from outcrops, whereas samples from drilling, even when core is recovered, are relatively small and more suitable for the extraction of microfossils and palynomorphs (see ***Dating the Mesozoic***, p. 7).

Dinosaurs and other terrestrial vertebrates

Only isolated bones from non-avian dinosaurs and pterosaurs are known from Western Australia. These include:

- a partial theropod tibia and a sauropod caudal vertebra from the Middle Jurassic near Geraldton;
- a theropod toe bone and possible ornithocheiroid (a pterosaur clade) jaw fragments from the Upper Cretaceous near Gingin; and
- incomplete, possible azhdarchid (a family of large pterosaurs) remains from the uppermost Cretaceous in Giralia Range.

In contrast to the meagre body fossil record, there are diverse and abundant dinosaurian ichnofossils from non-marine facies of the Lower Cretaceous Broome Sandstone along the Dampier Peninsula coast. There are at least 21 different types of track attributed to large-bodied theropods, sauropods, ornithopods and thyreophorans (armoured dinosaurs; such tracks provide Australia's only clear evidence for stegosaurians). The tracks indicate these animals were active in coastal plain environments during the Early Cretaceous. Outcrops that are destratified or with chaotic contortions are possibly due to wallowing or similar activity — together with the tracks, these are designated as 'dinoturbaton'. In spite of this trace fossil record, dinosaurian bone material from the peninsula has yet to be confirmed.

Aquatic vertebrates

Mesozoic vertebrates have been identified in Lower Triassic, Middle Jurassic, and mid-Lower and Upper Cretaceous marginal to open-marine facies. The most prolific of these are:

- the Lower Triassic Blina Shale (Canning Basin), known mostly for its temnospondyl amphibians, and Kockatea Shale (Perth Basin), which also contains amphibians;
- the Lower Cretaceous 'Windalia sandstone member' of the Muderong Shale (Southern Carnarvon Basin), which has yielded abundant bones and partial skeletons of ichthyosaurs and plesiosaurs; and
- the mid-Cretaceous Gearle Siltstone (Southern Carnarvon Basin), rich in chondrichthyans (a group of cartilaginous fishes including sharks) and coprolites most likely originating from marine aquatic vertebrates (see ***Silver and sulphides***, p. 60).

Dinosaur footprints from Broome

The remains of three pliosaurs (*Leptocleidus clemai*) in the Lower Cretaceous 'Windalia sandstone member' near Kalbarri include both femora, parts of a tibia and right humerus, pelvis, ulnae and radius, and 45 vertebrae. These small (less than 4 m long) pliosauroids seemingly preferred shallow inshore waters, perhaps due to competition from larger genera. Mid- to outer-neritic facies of the uppermost Gearle Siltstone, and the part of the overlying Haycock Marl straddling the Cenomanian–Turonian boundary, also bear rich elasmobranch (cartilaginous fish) faunas, numerous bony fish, rare ichthyosaur, plesiosaur and turtle remains, and possible bird material. Fragmentary mosasaur and pliosaur bones are also present in the Molecap Greensand near Dandaragan (see ***Greensands — fertilizer and fossils***, p. 52).

Triassic invertebrates

Early Triassic marine to marginal-marine invertebrates from the Kockatea and Blina Shales (onshore Perth and Canning Basins, respectively) are well known. Coeval formations extend along almost the entire North West Shelf but are rarely cored, hindering recovery and recognition of fossils apart from microfossils. In the Perth Basin, mixed marine taxa are dominant and include representatives of agglutinated foraminifera, lingulids (brachiopds), bivalves, gastropods, ammonoids, ostracods and conodonts. These are associated with fresh/brackish-water and terrestrial organisms such as spinicaudatans, insects and austriocaridid crustaceans, as well as vertebrate and plant remains. By comparison, assemblages from the Canning Basin contain fewer groups, perhaps reflecting the interior setting of the facies in these outcrops. Non-marine components either flourished during periods of greater freshwater influx or were transported from adjacent biotopes. Overall, the faunas indicate a coastal zone within the interior of eastern Gondwana.

Jurassic invertebrates

In the Middle Jurassic, the southernmost extent of a regional marine highstand into the northern Perth Basin deposited thin beds of fossiliferous sandy limestone. This marine interval provides a link between biostratigraphic schemes in Western Australia and those established in the northern hemisphere. Near Geraldton, the abundantly fossiliferous Newmarracarra Limestone contains a fauna dominated by bivalves and ammonites,

AJM1226 22.08.22

Current-aligned belemnites, in exterior cladding at Elizabeth Quay, from the Jurassic Melligo Sandstone, Canning Basin, Dampier Peninsula

AJM1213 23.06.22

Slab of Bajocian (Middle Jurassic) Newmarracarra Limestone containing the trigoniid mollusc *Coxitrigonia moorei* from east of Geraldton, northern Perth Basin, on display in the Edward de Courcy Clarke Earth Science Museum, The University of Western Australia

AJM1211 23.06.22

Bajocian (Middle Jurassic) ammonite *Newmarracarroceras clarkei* from the Newmarracarra Limestone, northern Perth Basin east of Geraldton (image taken by Kris Brimmell, WA Museum)

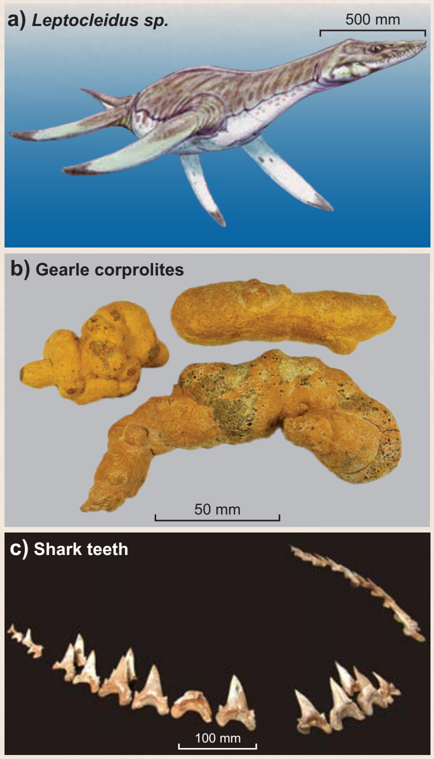
with less-common gastropods, brachiopods, belemnites and echinoid spines. Some of these fossils were mentioned in 1861 by the explorer Francis Thomas Gregory, with descriptions provided by Charles Moore in 1870 — the first formally described fossils from the State — including *Coxitrigonia moorei* named by John Lycett to honour his friend. The marine interval with these fossils extends south to the Hill River area, east of Jurien, but macrofossil diversity and abundance in that region is considerably lower. Also present are insect remains in Lower Jurassic fluviodeltaic facies near Jurien (Cattamarra Coal Measures), in which the most common groups are beetles (Coleoptera) and 'roachoids' — the latter are ancestors to modern cockroaches (Blattodea), mantids (Mantodea) and termites (Isoptera).

Cretaceous invertebrates

Apart from the Birdrong Sandstone, the post-breakup succession is especially fossiliferous, with the greatest diversity in upper Cretaceous chalk deposits in which coccoliths (the calcareous internal plates of eukaryotic phytoplankton) and microplankton are especially abundant. Invertebrate macrofossils are mostly known from outcrops, but in the subsurface are difficult to identify in the absence of core. In the northern Perth Basin, the Gingin Chalk lies between two greensands with relatively little macrofauna and is exposed between Gingin and Badgingarra where it also contains annelids, brachiopods, corals, crinoids, crustaceans (ostracods and barnacles), echinoids, foraminifera, molluscs (ammonites, belemnites, bivalves and gastropods) and sponges (as well as shark teeth). In the Southern Carnarvon Basin, outcrop of the partially equivalent Toolonga Calcilutite extends from Kalbarri to Exmouth Gulf and contains a similar fauna but is enclosed by fossiliferous units. Onshore, both units are typically no more than 20 m thick but equivalent offshore intervals reach up to 300 m. Farther north in the Canning Basin, upper Cretaceous strata are unknown, and the Lower Cretaceous above the Broome Sandstone contains mostly molluscan invertebrates.

AJM1212 23.06.22

Pecten in Lower Cretaceous Windalia Radiolarite, northern Kennedy Range, Merlinleigh Sub-basin of Southern Carnarvon Basin



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Aquatic vertebrates: a) the small plesiosaur *Leptocleidus clemai* (reconstruction by Dmitry Bogdanov); b) coprolites from aquatic marine vertebrates, Gearle Siltstone, Southern Carnarvon Basin, Hill Springs Station; and c) lower jaw teeth of the lamniform shark *Cardabiobon ricki* arranged as in its jaw (provided by Mikael Siversson, WA Museum)

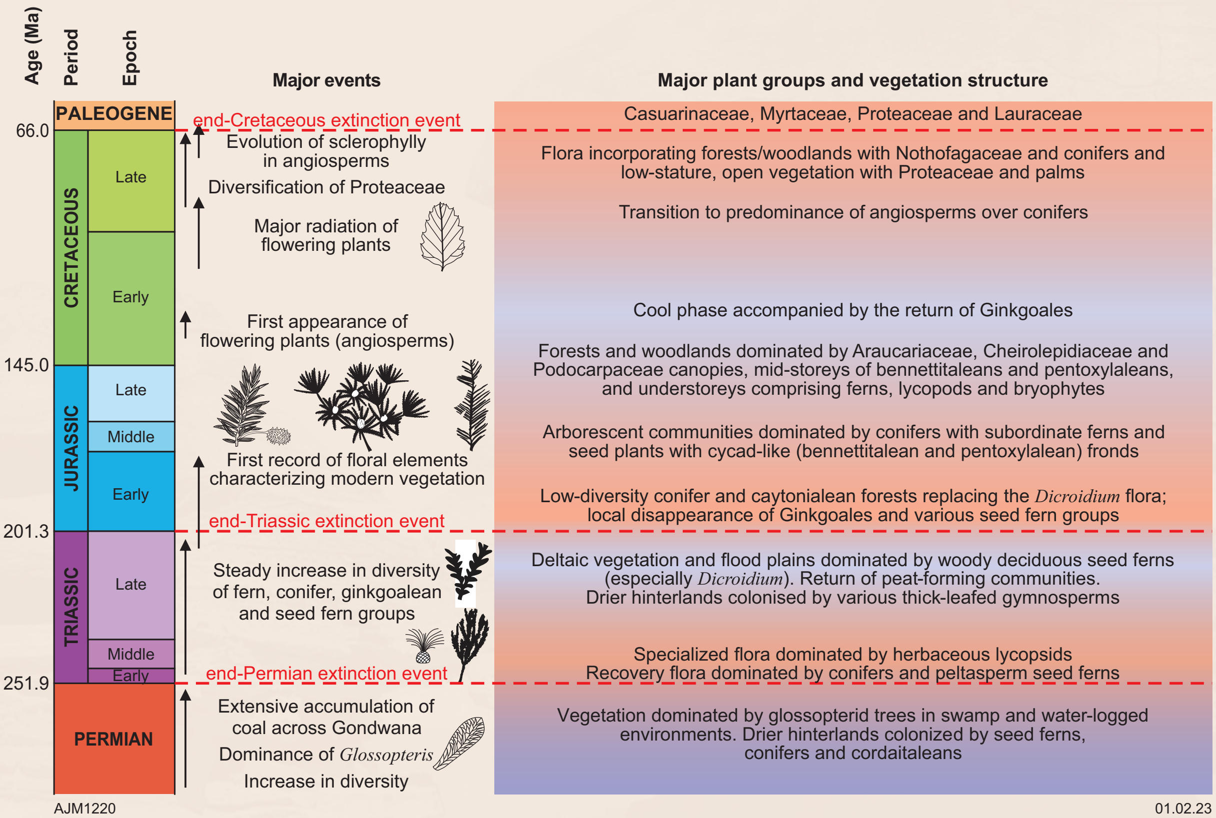
Flora — greening Western Australia

Floral evolution in the Mesozoic largely involved the gradual appearance of now-widespread modern groups such as conifers, ginkgoales, cycadophytes and angiosperms. A prominent floral turnover in the Early–Middle Triassic saw the introduction of small, near-cosmopolitan, coastal lycopsids and the *Dicroidium* group of 'seed ferns', all of which became widespread across Gondwana, including Australia. The spore-pollen fossil record of this distinctly Triassic *Dicroidium* flora, named after the iconic 'seed fern' foliage of this period, contains dominantly bisaccate pollen with a distinctive distal germinal aperture (e.g. *Falcisporites*). In palynofloral assemblages from the Northern Carnarvon and Bonaparte Basins, diverse monolete spores are attributed to *Aratrisporites*, also of probable lycopsid affinity. Across Gondwana, palynofloras of this era are broadly divided into northern 'Onslow-type' and southern 'Ipswich-type' assemblages, denoting a degree of regionalism. The transition from 'seed fern' to pteridosperm–conifer floras at the start of the Jurassic has been attributed to a drying climate; however, low-diversity and long-ranging components in late Triassic to mid-Jurassic palynological assemblages point to a relatively stable climate (see ***Climate***, p. 17). Jurassic macrofloras are common in the State, and include extinct conifer families and species typical of younger Southern Hemisphere mesic and subtropical forests. This pattern is also shown in palynofloral assemblages, which include common to dominant pollen attributed to extinct (e.g. Cheirolepidiaceae) and extant (e.g. Podocarpaceae and Araucariaceae) conifers. In the mid-Early Cretaceous, the start of the 'Cretaceous terrestrial revolution' saw flowering plants (Class Angiospermae) established in eastern Australia at the expense of groups such as the bennetitaleans and pentoxylaleans; however, angiosperm macrofossils are scarce in the Western Australian Mesozoic. Jurassic and Cretaceous palynofloral (and macrofloral) assemblages include a diverse assortment of spore-producers attributed to fern families such as the Gleicheniaceae and Schizaeaceae, which were the dominant herbaceous vegetation. Typical modern Australian flowering plants such as the Proteaceae and Nothofagaceae first appeared in the Late Cretaceous.

Paleolatitudinal changes and increasing isolation from other parts of Gondwana in the Mesozoic drove the the development of distinctly Australian floras with modern vegetation first appearing in the Jurassic – Early Cretaceous

The fern *Dicroidium zuberi* from the Blina Shale near Culvida Soak, eastern Canning Basin (specimen GSWA F9152)

The fern *Microphyllopteris gleichenoides* from the Winning Group near Kalbarri, Southern Carnarvon Basin (photo by Ken McNamara)



Major plant evolutionary events and vegetation changes in Western Australia. The blue and red backgrounds depict cooler and warmer episodes, respectively (from Peyrot et al., 2019, fig. 9)

Climate

For almost all of the Mesozoic, Australia lay between about 30° S and 75° S (Fig. 8), and the climate alternated between warm and cool periods. Such fluctuations may have been sufficient to allow the development of polar ice, but there is little evidence of extensive ice in Australia or other locations during this era.

At the end of the Permian, the climate changed from a cool temperate greenhouse, with widespread gymnosperm forests, to hot and dry in the Early Triassic when much of the land surface was deforested with a complete loss of persistent peats (the global 'coal gap'). During the Triassic, most of Australia lay at high latitudes, with eastern Australia the closest part of the continent to the South Pole. Atmospheric carbon dioxide was about three times greater than today, and the climate was generally hotter and drier, with a large part of the continent subjected to a polar monsoonal regime. Coal swamps virtually disappeared at the start of the Triassic and did not reappear until the Late Triassic in eastern Australia. The appearance of the distinct 'Onslow-type' palynofloras in northern Australia (see ***Flora — greening Western Australia***, p. 16) has been ascribed to a mild maritime influence of the Tethyan Ocean to the north of the continent.

At the beginning of the Jurassic, Australia became wetter, allowing plant life and a diverse fauna to flourish and a floral transition from peltasperm- (seed ferns) to conifer-dominated. Early to mid-Jurassic palynological assemblages were relatively static with little diversification, implying moderately stable climatic conditions. The lack of polar ice increased humidity and weakened differentiation of climatic belts. Coal swamps were common across the continent during the later Early and Middle Jurassic when CO_2 levels peaked at about seven times greater than today. Distinct microflora changes throughout in the later part of this period point to a progressive decrease in temperature.

In the Early Cretaceous, Australia was again at high latitudes, with the southeastern part of the continent within the Antarctic Circle, and experienced seasonal photoperiod variability (polar nights). Despite this, the climate was cool and wet overall, with rapid changes in floral communities indicating marked climatic fluctuations. Glendonites in South Australia and cryoturbation (frost churning in soil) structures in Victoria point to cold conditions in the Aptian and earliest Albian; however, the shallow inland Eromanga Sea that spread across nearly one-third of the continent in the mid-Cretaceous probably ameliorated further cooling. Temperatures increased from the late Albian onwards as Australia moved progressively north. This and the extensive interior Eromanga Sea possibly assisted the early formation of duricrust–laterite across the continent (see ***Duricrusts***, p. 33).

Mesozoic evolution of Western Australia

During the Mesozoic, Australia lay between approximately 30° S and 75° S and rotated anticlockwise by roughly 30° (Fig. 8). An interior rift initially formed within Gondwana along the continent's western and northern margins (Fig. 2) prior to breakup, after which it became a passive margin with several terranes detaching to end up in present-day Southeast Asia. It was not until the Eocene that the continent began to move rapidly northwards following final separation from Antarctica. The four overall extensional tectonic phases evident in the continent's western Mesozoic basins are:

1. continued intracratonic rifting from the Permian into the Late Triassic
2. Early–Middle Jurassic rifting
3. Late Jurassic – Early Cretaceous breakup and separation, and
4. mid- to Late Cretaceous trailing-edge rifting and marginal sag.

Robust biostratigraphic studies combined with mapping of seismic horizons across the North West Shelf have allowed the recognition of regional sequence stratigraphy units, generally referred to as 'play intervals', as well as much finer subdivisions of the Mesozoic than shown in Figure 9. Unfortunately, differentiating even the broad 'play intervals' can be difficult in southern, central and eastern parts of the State due to poorer seismic quality and sparse or imprecise biostratigraphic information, especially where non-marine facies are prevalent (see ***Dating the Mesozoic***, p. 7). Thus, only broad correlations (Fig. 9) are possible across the entire State, and the time represented by each of the paired paleogeographic and isopach images in the following sections is correspondingly inexact. Furthermore, the age of some reputedly Mesozoic units is difficult to verify, particularly for isolated outcrops lacking fossils such as near Donnybrook, and in the south and northeast of the Canning Basin; these units may be confused with, or perhaps incorporate, Permian or Cenozoic sedimentary deposits.

Late Paleozoic – Triassic intracratonic rifting

Late Paleozoic rifting during the early stages of the fragmentation of Gondwana created the set of elongate north-to-northeasterly trending basins along the west of the Australian continent. The northwestern margin of these basins probably extended into the Tethyan Ocean, which first developed outboard of Cimmeria (paleo-Tethys), whereas marine connections to the south were sporadic and did not extend into the southernmost Perth Basin until well after oceanic crust was emplaced inboard of Cimmeria[1] (meso-Tethys). The rifting appears to have begun in the late Carboniferous, with northwesterly extension normal to the present coast. Cimmeria (including the Sibumasu[2] and Qiangtang[3] continental terranes, which originally lay outboard from the Roebuck and Northern Carnarvon Basins) appears to have detached in the late Cisuralian (early Permian). Although now preserved within structurally separate terranes in Southeast Asia, Sibumasu has shared Gondwanan features, notably *Glossopteris* floras and Permian glaciomarine diamictites. In the earliest Permian, the Lhasa (now part of the Himalayas) and West Burma terranes probably bordered Qiangtang and Sibumasu on the northern edge of Greater India. Lhasa may have separated from Gondwana in the middle Permian; however, the timing of this event is unclear and instead it could have been during later Mesozoic rifting that formed younger oceanic crust (ceno-Tethys). A series of uppermost Permian volcanic intrusions, including lamproite dykes in Edel 1 within the northern Perth Basin and mostly doleritic intrusions in the northwestern Canning Basin, are inexactly dated by K–Ar so their relationship to external tectonic events is poorly understood.

1 The string of Gondwanan microcontinents now accreted to Eurasia, named after an early Indo-European tribe.

2 The name reflects its present distribution in Sino (China), Siam (Thailand), Burma (Myanmar), Peninsular Malaysia and Sumatra.

3 A major part of the Tibetan Plateau containing Carboniferous–Permian metasedimentary and Triassic high-pressure metamorphic rocks.

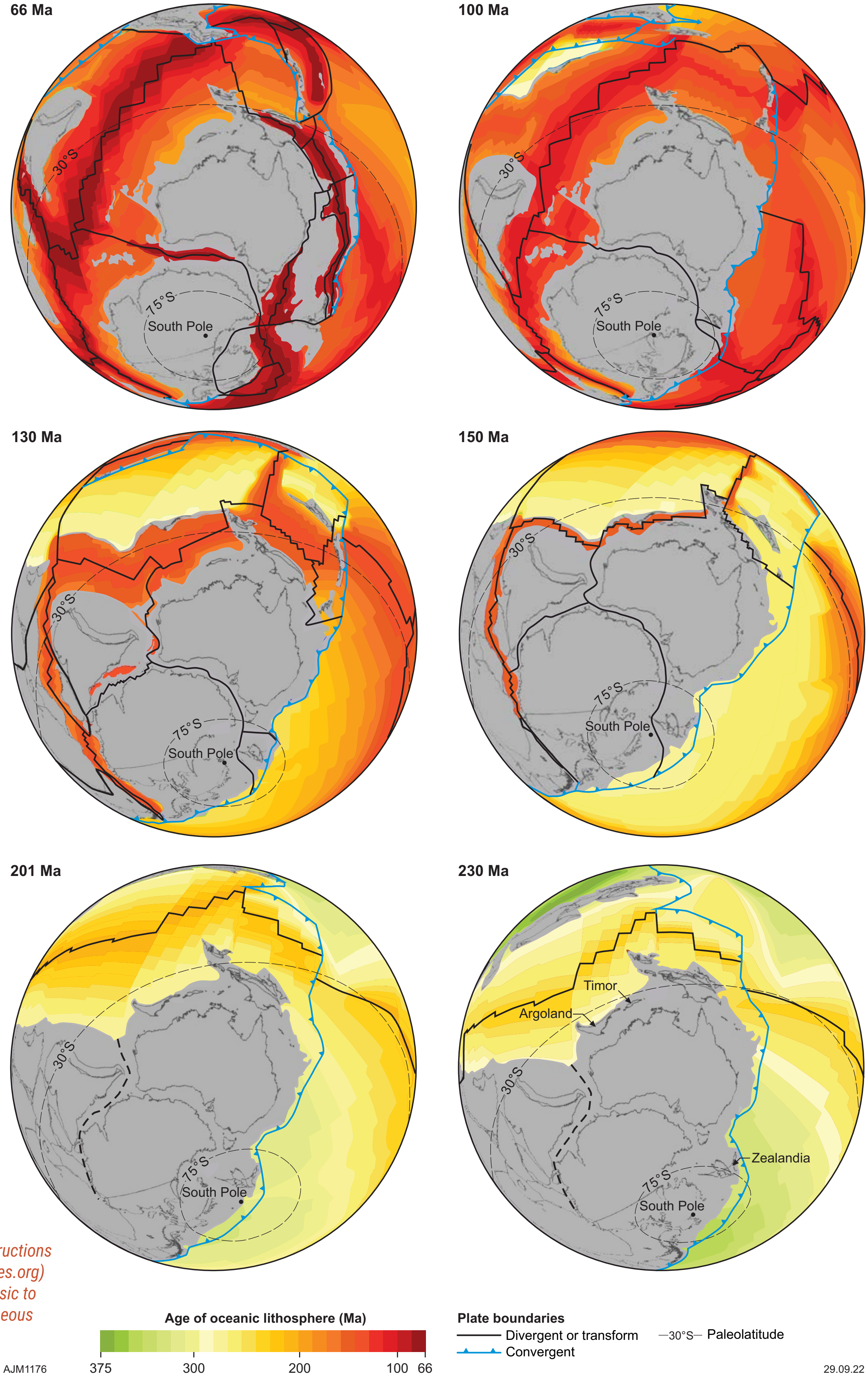


Figure 8.
Tectonic reconstructions (from www.gplates.org) for the Late Triassic to end of the Cretaceous

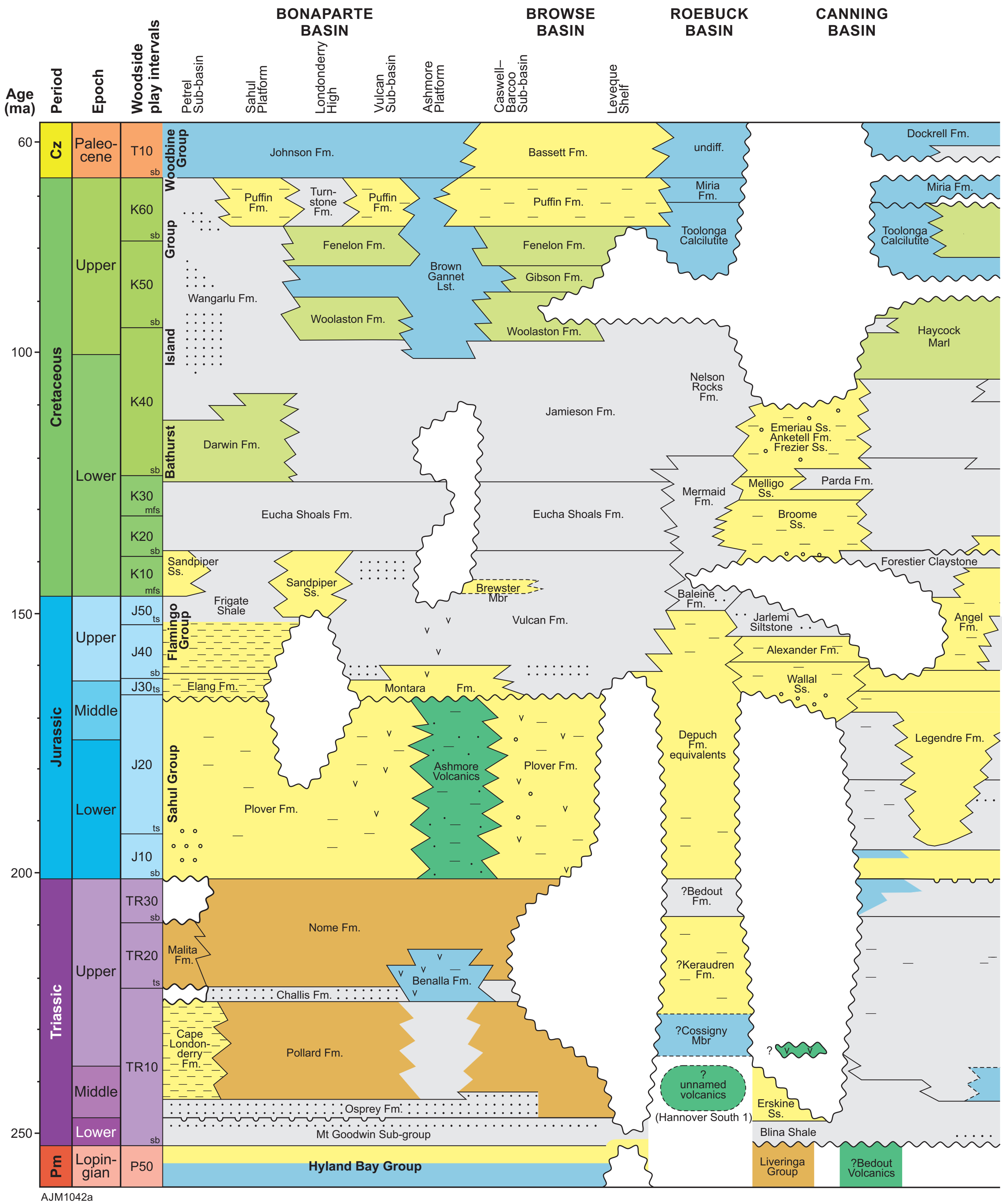
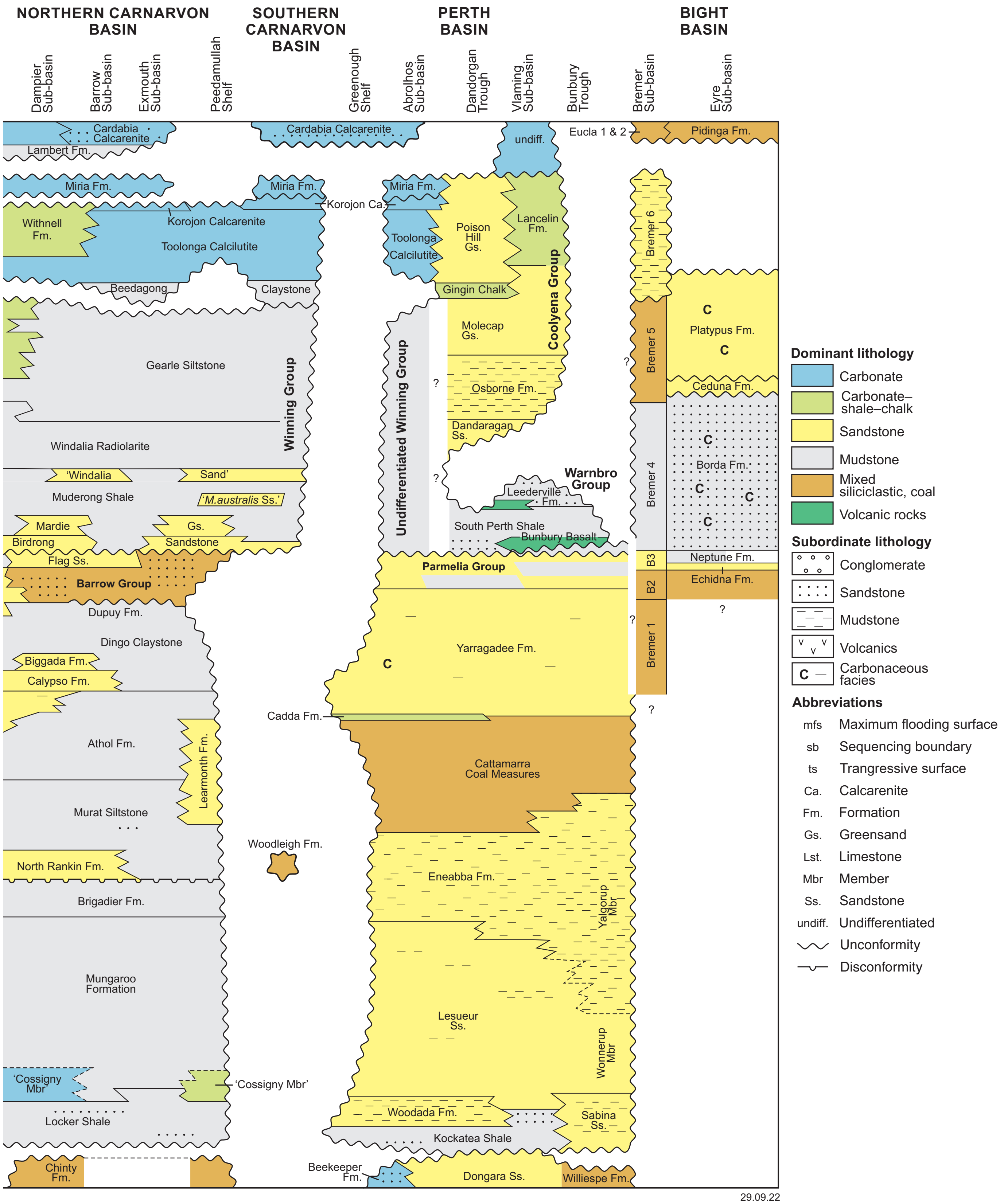


Figure 9. Time–rock correlation of the main formations within Western Australian Mesozoic basins, based on Geoscience Australia's biozonation and stratigraphy charts


NORTHERN CARNARVON BASIN
SOUTHERN CARNARVON BASIN
PERTH BASIN
BIGHT BASIN
Dampier Sub-basin
Barrow Sub-basin
Exmouth Sub-basin
Peedamullah Shelf
Greenough Shelf
Abrolhos Sub-basin
Dandorgan Trough
Vlaming Sub-basin
Bunbury Trough
Bremer Sub-basin
Eyre Sub-basin
Cardabia Calcarenite
Lambert Fm.
Cardabia Calcarenite
undiff.
Eucla 1 & 2
Pidinga Fm.
Miria Fm.
Miria Fm.
Miria Fm.
Korojon Ca.
Withnell Fm.
Korojon Calcarenite
Toolonga Calcilutite
Toolonga Calcilutite
Poison Hill Gs.
Lancelin Fm.
Bremer 6
Beedagong
Claystone
Gingin Chalk
Coolyena Group
Molecap Gs.
C
Platypus Fm.
C
Gearle Siltstone
Winning Group
Undifferentiated Winning Group
Bremer 5
Osborne Fm.
Ceduna Fm.
Windalia Radiolarite
Dandaragan Ss.
C
Borda Fm.
C
C
C
'Windalia
Sand'
Muderong Shale
'M.australis Ss.'
Warnbro Group
Leederville Fm.
Bremer 4
Mardie
Gs.
Birdrong
Sandstone
South Perth Shale
Bunbury Basalt
Flag Ss.
Parmelia Group
B3
Neptune Fm.
Barrow Group
B2
Echidna Fm.
Dupuy Fm.
Dingo Claystone
Yarragadee Fm.
C
Bremer 1
Biggada Fm.
Calypso Fm.
Cadda Fm.
Athol Fm.
Learmonth Fm.
Cattamarra Coal Measures
Murat Siltstone
Woodleigh Fm.
North Rankin Fm.
Eneabba Fm.
Yalgorup Mbr
Brigadier Fm.
Mungaroo Formation
Lesueur Ss.
Wonnerup Mbr
'Cossigny Mbr'
'Cossigny Mbr'
Woodada Fm.
Sabina Ss.
Locker Shale
Kockatea Shale
Chinty Fm.
Beekeeper Fm.
Dongara Ss.
Williespe Fm.
29.09.22
Dominant lithology
Carbonate
Carbonate–shale–chalk
Sandstone
Mudstone
Mixed siliciclastic, coal
Volcanic rocks
Subordinate lithology
Conglomerate
Sandstone
Mudstone
Volcanics
Carbonaceous facies
Abbreviations
mfs Maximum flooding surface
sb Sequencing boundary
ts Trangressive surface
Ca. Calcarenite
Fm. Formation
Gs. Greensand
Lst. Limestone
Mbr Member
Ss. Sandstone
undiff. Undifferentiated
Unconformity
Disconformity

Northwestern margin structure

The dominant northeast trend along the North West Shelf follows deep structural fabrics reactivated several times throughout the Phanerozoic, especially during rifting events. The underlying structural fabric probably controlled not only the direction of extension during the Mesozoic but also the intensity of deformation. Extension during late Carboniferous – Permian rifting created prominent rotated fault blocks in older strata. Offshore, early rifts are mostly too deep or poorly imaged to distinguish their internal stratigraphy or detailed original structural trends clearly. Early Carboniferous to Permian rift extension associated with igneous intrusions in the Canning and Northern Carnarvon Basins led to extreme thinning of the crust, especially across the Exmouth Plateau. Some authors consider large-scale volcanism emplaced Permian oceanic crust, which now underlies the Exmouth Plateau, but most suggest the old rifted margin lies outboard of that region with continental crust beneath the Permo-Carboniferous rift sequences. In the Southern Carnarvon and northern Perth Basins, these early rifts include the north-northwest to north trending Coolcalalaya and Merlinleigh Sub-basins. By comparison, reactivation of northwesterly structural trends, prevalent in the Canning Basin and Petrel Sub-basin of the southern Bonaparte Basin, was minor during the Mesozoic, seemingly because their main structural orientations are nearly perpendicular to that of the North West Shelf and did not favour significant reactivation.

Basins beneath the North West Shelf transitioned from extension to a post-rift phase of thermal subsidence in the late Permian, when widespread unconformities (similar to the Valanginian breakup unconformity) developed. Separation of Sibumasu and opening of the Tethyan Ocean led to marine flooding in the latest Permian to Early Triassic along the North West Shelf and West Burma, the last Southeast Asian terrane to separate from the Australian continent (in the Middle to Late Jurassic). This flooding also coincided with the major extinction event at the end of the Paleozoic (see ***Extinction events***, p. 25). Thick shallow-marine to deep-water facies indicate regional flooding across the Northern Carnarvon and Roebuck (Locker Shale), Canning (Blina Shale), Browse and Bonaparte (Mount Goodwin Subgroup) Basins (Figs 9, 10a). This sequence contains proven hydrocarbon source-rock intervals in the northern Perth Basin, where the facies are principally marginal marine (Kockatea Shale, especially the Hovea Member), and in the Roebuck Basin (Locker Shale and Keraudren Formation). Structurally, these units also enclose major detachment surfaces, thereby controlling the geometry of many later Mesozoic faults.

Large-scale prograding geometries evident in some seismic sections within the middle to western parts of the Barcoo and Caswell Sub-basins of the outer Browse Basin and in the Roebuck Basin are interpreted as a Triassic lava delta complex up to 10 km thick. The thickest volcanic section drilled to date is in the northeastern part of the Rowley Sub-basin (in Hanover South 1). Although the basalts are too oxidized for radiometric dating, they are interbedded with shale yielding Middle to early Late Triassic palynomorphs. Possible onshore manifestations of the volcanic system include Permian–Triassic dolerite intrusions in the Fitzroy Trough, although the available feldspar K–Ar dates seem unreliable, and basalt sills in the southwestern Canning Basin from which $^{40}Ar/^{39}Ar$ dating has yielded Carnian–Norian ages. The latter intrusions within the Samphire Graben are associated with basalt flows apparently favouring paleovalleys on the unconformity surface associated with the Fitzroy Transpression (Fig. 11). Onshore, deformation of strata overlying this Middle Triassic to Middle Jurassic break, which extends across most of the Canning Basin, consists of wrench features along the Fitzroy Trough and points to a significant reduction in tectonism. Offshore, this event coincides with a major early Norian (Late Triassic) sequence boundary (TR20), even though the break in deposition there was relatively minor. Nevertheless, this break coincides with the end of Triassic tectonism, with significant earlier unconformities in the Anisian and Ladinian, especially in the Roebuck Basin. A possible carbonate margin near the southern edge of the Roebuck Basin flanks the western Beagle Sub-basin and extends westwards into the northern Exmouth Plateau. Rhaetian (Late Triassic) carbonate facies developed when a regional transgression encroached over the base TR30 sequence boundary and the underlying volcanic complex in the Roebuck Basin.

Post-rift thermal subsidence throughout the Triassic allowed the accumulation of thick (up to 6 km across parts of the Exmouth Plateau), largely non-marine to deltaic facies (Mungaroo Formation and its equivalents; Figs 9, 10b). Although the Lower Triassic thins markedly across this region, it is uncertain if this outboard high supplied sediment

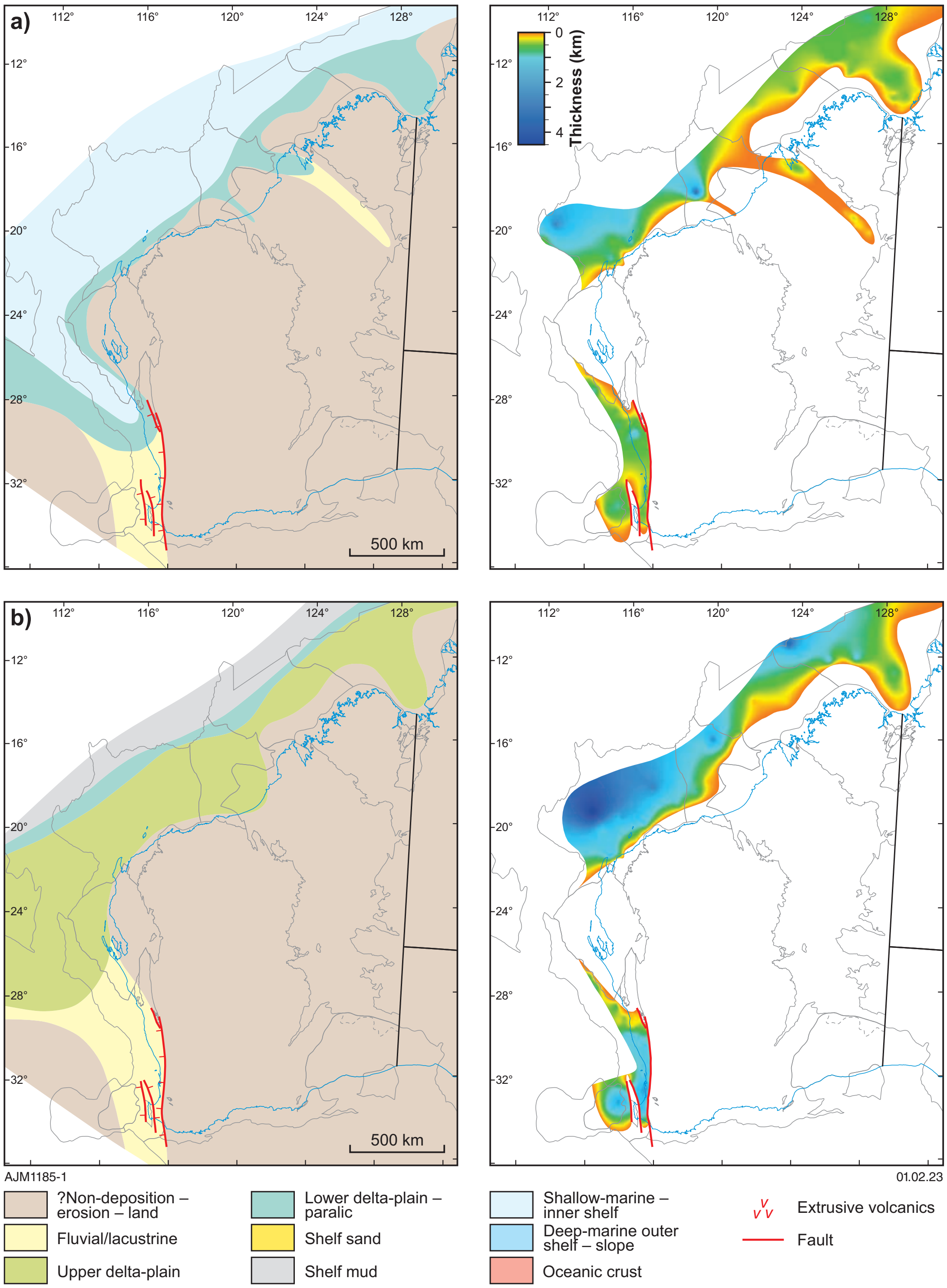


Figure 10. Triassic paleogeography and isopach images for Western Australia: a) ~Induan–Anisian and b) ~Ladinian–Rhaetian. Note that all palaeogeographic images are simplified after those in Longley et al. (2002), whereas the isopach images are derived mostly from wells shown in Map 6

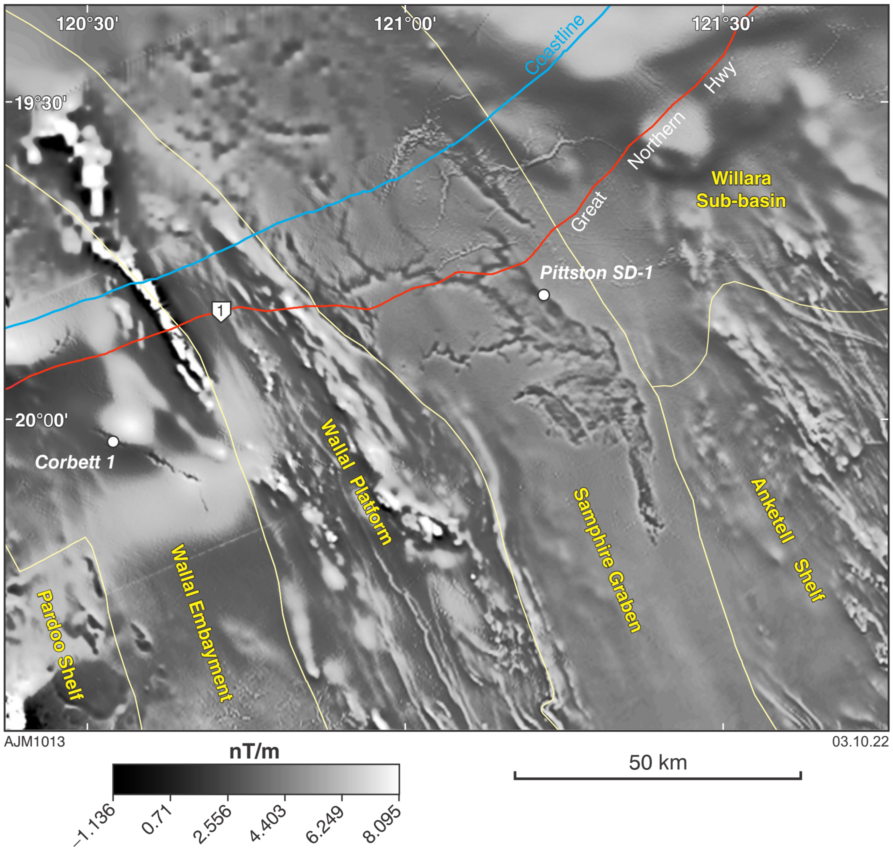


Figure 11. Aeromagnetic first vertical derivative image across the Samphire Graben showing Middle Triassic basalt flows breaking out from sills emplaced along faults on the eastern side of the graben

into the Late Triassic Mungaroo delta system. This sand-dominated system hosts the main reservoirs in the large gas and condensate fields along the North West Shelf. In some areas, erosion of the Upper Triassic, especially around the basin margins and onto the Triassic shelf–slope facies, created widespread Norian and Rhaetian unconformities, some of which are associated with basal boundaries of the TR20, TR30 and J10 sequences (Fig. 9). Faulting in these formations was mostly planar normal, although growth between fault blocks was common.

The end of the Triassic marks a transition to dominantly siliciclastic deposition. Thermal uplift and erosion accompanied rift onset, and local unconformities developed across many sub-basins. Once stretching associated with rifting began, flexural uplift on the fault blocks allowed substantial erosion of the Upper Triassic, especially on the rift flanks. These unconformities are commonly found over the crest of collapse folds or anticlinal trends above basement highs where erosion has removed up to 1–2 km of the section, or on the downthrown side of major faults. The eroded areas indicate inversion and compression across several areas along the North West Shelf, such as along the northeastern edge of the Dampier Sub-basin, and anticlinal trends in the Browse Basin at Scott Reef 1 and Brecknock 1, as well as uplift and erosion on the margins of the Bonaparte Basin and farther south in the Perth Basin.

In the Canning Basin, the Fitzroy Transpression produced right-lateral oblique inversion along graben-bounding faults, wrench folding and north-trending shear zones in the Fitzroy Trough and Gregory Sub-basin. Although small-scale compressional Late Triassic features are also present in other intracratonic basins across central and eastern Australia, they and larger scale, offshore features are not necessarily directly associated with the Fitzroy Transpression. Nevertheless, there may be temporal relationships, such as that evoked for a fault gouge in the Mesoproterozoic Edmund Basin (part of the Capricorn Orogen between the Yilgarn and Pilbara Cratons), which has yielded a Late Triassic age. As with the steeply dipping Permian outcrop along the Iragana Fault on the Ryan Shelf, eastern Canning Basin, the remoteness of such deformation from the mild tilting caused by the Fitzroy Transpression or breakup in the northwestern part of the basin excludes a direct association with those events. In the Canning and Bonaparte Basins, diapiric salt movements may have been associated with the Fitzroy Transpression, although the last remobilizations were mostly during the Cenozoic (see ***Salt structures — Mesozoic mobilization***, p. 57).

Recent high-quality 3D seismic data and research using 3D restoration techniques indicate many Triassic structures formed by extensional and subsidence tectonics over basement features along the North West Shelf. These are evident from thick packages of parallel strata in the Northern Carnarvon Basin, whereas folds associated with faults or large synclinal structures, which can develop in both compressional and extensional settings, are present along the central depocentres of the Roebuck and Browse Basins. Tectonism in the Triassic appears to have ceased at the end of the Norian (TR20/30) along the entire western margin of the continent but it is uncertain whether these events were associated with the Fitzroy Transpression in the Canning Basin.

Western margin structure

The Perth and Southern Carnarvon Basins on Australia's western margin contain a series of mainly north- to north-northwesterly striking structural trends in contrast to the dominant northeasterly trends within basins of the North West Shelf and northwest-directed structural trends in the Canning and Bonaparte Basins. These trends are disrupted around the Neoproterozoic Northampton and Neoarchean–Paleoproterozoic Carrandibby Inliers, both of which have a northeasterly structural fabric. Both basins formed along reactivated older structures, especially the Wandagee – Kennedy Range and Darling fault systems that lie along the eastern margin of the Gascoyne Platform and the craton to the east, respectively. These faults appear related, with their major movement during Jurassic and Early Cretaceous rifting and breakup masking earlier displacements, with the intermediate area around the Carrandibby Inlier possibly forming a relay ramp. However, it is not clear why the Perth Basin has a relatively complete Triassic–Jurassic succession, whereas this interval is almost entirely

Extinction events

The Mesozoic lies between major global faunal and floral extinctions at the start of the Triassic and end of the Cretaceous, and includes a lesser extinction at the end of the Triassic. Only the end-Ordovician and mid-Late Devonian (at the Frasnian–Famennian boundary) events are more significant than the Mesozoic-bounding extinctions.

The Permian–Triassic boundary

This boundary coincides with one of the largest Phanerozoic events when approximately 70% of land vertebrate families and 90% of marine species died out. The extinction, attributed to a rapid deterioration in the Earth's atmosphere and associated toxicity and anoxia in many shallow seas, may have been a direct consequence of the volume of carbon released by the Siberian Traps, a giant igneous province. In contrast to most extinctions, which last no more than about 1 Ma, the biotic crisis following the Permian continued for about 10 Ma, with conditions improving in several steps during the Early–Middle Triassic (see ***Climate***, p. 17), and this possibly explains the global 'coal gap'. The Permian–Triassic boundary, as located within core from Hovea 3 (Fig. 12) and Redback 2 in the northern Perth Basin, coincides with a change from inertinitic to sapropelic facies, with the uppermost ~4.5 m of the former facies designated as the mass-extinction interval.

The Triassic–Jurassic boundary

This event encompasses a series of smaller extinctions towards the end of the Triassic when about half of known marine genera perished, although fewer terrestrial taxa were affected. The extinctions are attributed to changes in sea level, a marked increase in ocean acidification, euxinia and the discharge of large volumes of gases (especially CO_2, SO_2 and halogens) from the Central Atlantic Magmatic Province during the initial breakup of Pangea. Identification of this boundary across much of Western Australia is imprecise due to the predominance of non-marine facies and floral provinciality, although it is associated with a major floral turnover between the *Falcisporites* and succeeding *Callialasporites dampieri* spore-pollen Superzones. The age of the Woodleigh impact structure (see ***Impact structures***, p. 58) is close to this boundary but its effect on climate, even locally, is unclear.

The Cretaceous–Paleogene boundary

At the end of the Mesozoic, the impact event causing the 150 km-diameter Chicxulub crater in the Gulf of Mexico, the release of gases by the Deccan Traps in India and sea-level changes drastically disrupted the Earth's climate. These events eradicated about 80% of plant and animal species, most notably the non-avian dinosaurs, ammonites, calcareous plankton, plesiosaurs, mosasaurs and rudist bivalves. Iridium — one of the rarest elements in the Earth's crust — and other platinum-group elements are associated with the Cretaceous–Paleogene boundary where its abundance is about 20–100 times greater than is typical; however, this does not definitely mean an extraterrestrial source for these elements. Ejecta from Chicxulub have a wide global distribution, but that horizon has yet to be identified in or near Australia even though the Cretaceous–Paleogene boundary has been pinpointed in many places along the North West Shelf.

absent from the Southern Carnarvon Basin. Both basins appear to overlie Precambrian terranes with similar rheologies, primarily the Proterozoic Pinjarra Orogen, whereas the Capricorn Orogen is inferred to have been restricted to east of the Gascoyne Platform. The lack of a Triassic–Jurassic succession in that region is possibly due to adjoining tectonic units, perhaps including the Wallaby Plateau, exerting manifestly different structural influences during the Mesozoic.

Depositional history

The late Carboniferous was a period of widespread glaciation, with a regional break in sedimentation possibly caused by an extensive ice sheet inhibiting sediment transport. The succeeding latest Carboniferous – early Permian deglacial facies are the earliest deposits to transcend individual basins. Permian subsidence gradually opened up shallow seaways from the north, which allowed deposition of marine facies grading upwards into deltaic–marine sediment at the end of the Permian. The Early Triassic saw a marine transgression flooding all the western and northern basins with deposition changing to mostly fine-grained marine clastic facies with minor carbonate. The resulting succession is up to several kilometres thick and spans about 5 Ma (Figs 9, 10a). This section is over 3 km thick near the Dorado field in the Roebuck Basin, pointing to local tectonic control and possibly explaining nearby Triassic incised canyons. The two narrow belts of fluvial facies in the Canning Basin that extend to the southwest (Fig. 10a) were likely deposited at the far end of a long transport pathway, as there is little other evidence that nearby hinterlands directly supplied sediment to the northwest (see ***Provenance — where did the sediment come from?***, p. 40).

The Early Triassic marine transgression is a useful datum for regional correlations (***Dating the Mesozoic***, p. 7). Marine facies of this age have distinctive biostratigraphic assemblages, organic compositions and log signatures, and a homogeneous seismic character. The Lower Triassic contains excellent hydrocarbon source-rock facies towards the base (particularly the Kockatea Shale and Mount Goodwin Subgroup), though few wells have penetrated the basal parts of the Locker Shale. These transgressive sequences pass upwards into more shallow and marginal-marine sequences as sediment supply caught up with a slowing in the rate of subsidence.

Due to the great thickness of the offshore Mesozoic succession, exploration wells rarely reach the Permian–Triassic (P–T) boundary. Deeper wells in the onshore Perth and southern Bonaparte Basins show a basal Triassic mudstone overlying coarse-grained Permian shoreface and intertidal siliciclastic facies; however, in the northern Perth Basin, core from Hovea 3 places the P–T boundary at a sharp contact between relatively oxygenated and anoxic marine facies (Fig. 12). Conodonts and macrofossils (brachiopods and bivalves) indicate the P–T boundary coincides with this contact, but calibration of spore-pollen zones to the international time scale by dating zircon from tuffs in eastern Australia at this level is inexact. The underlying fossiliferous, shallow-marine black mudstone, sandy siltstone and shelly storm beds are variably bioturbated and host a diverse benthic community with inertinitic coaly detritus and spinose acritarchs. Overlying sapropelic beds consist of alternating dark brownish-grey, finely laminated, organically rich, pyritic, calcareous mudstone and thin limestone

Figure 12. Permian–Triassic boundary at 1980.95 m (arrowed), Hovea 3, northern Perth Basin. The thin-shelled bivalves in the upper part of the image are Claraia *sp.*

with algal mats and small stromatolites. These beds contain a sparse biota — including fish fossils — able to flourish in low-oxygen conditions, such as the thin-shelled bivalve *Claraia* spp. Although attributed to the Permian–Triassic boundary extinction, this abrupt change in fauna may represent a local change in environment (see ***The Permian–Triassic boundary*** in ***Extinction events***, p. 25).

Triassic hydrocarbon source rocks

Globally, Triassic global anoxic events tend to be associated with prolific petroleum source rocks. The Permian–Triassic extinction event (see ***Extinction events***, p. 25) and following transgression allowed the deposition of several key source-rock units across most west Australian basins.

The Early Triassic marine transgression reached into the northern Perth Basin, where the Kockatea Shale was deposited primarily under shallow, restricted-marine conditions. Where buried deeply, this formation provides a locally significant source rock, which can charge adjacent Permian or basal Triassic reservoir rocks. Organically rich facies deposited in marine embayments (basal Hovea Member) generated light, waxy oil. Some organically rich (exinite–alginite) lacustrine shale facies are also present in the Woodada Formation in the Abrolhos Sub-basin.

In the Northern Carnarvon and Roebuck Basins, the Locker Shale, a regional equivalent of the Kockatea Shale, contains shallow-marine facies, although organically rich beds are not widely distributed. Light oil/condensate discoveries at Phoenix 1 and Roc 1 in the Roebuck Basin indicate a Triassic hydrocarbon source probably from marine shale facies of the lower Keraudren Formation. In the Bonaparte Basin, the same Triassic marine transgression deposited similar mud facies; however, Triassic oil- or gas-prone source rocks from the Mount Goodwin Subgroup have not been linked to any accumulations. Fields in the Bonaparte Basin were charged mainly from prolific Jurassic facies and older Permian, or possibly Devonian, source rocks.

The extensive Triassic delta systems along the northern margins include mixed terrestrial source intervals containing mostly vitrinite, exinite and inertinite (mainly derived from woody material and spores) but also including freshwater alginate. These source rocks lie within deltaic and lacustrine mud, interdistributary coal and associated back-barrier lacustrine facies, whereas detrital inertinite is prevalent in prodeltaic mud facies. Hydrocarbons in the majority of the large gas and condensate fields were sourced primarily from deltaic–lacustrine facies, which lie either directly below the reservoir sections in the big fault blocks or deep in adjacent synclines. This juxtaposition has affected the maturation rank and, in turn, the wet:dry gas ratio, in addition to the relative proportions of different types of organic matter.

Mungaroo deltas

The climate became warm to temperate, humid and possibly monsoonal during a prolonged period of thermal subsidence in the Anisian that extended into the latest Norian (Middle to Late Triassic) — see ***Climate,*** p. 17. Broad uplift across much of Gondwana yielded little or minor deposition in most basins by the Norian, with delta systems fed from a transcontinental drainage system. These regressive systems deposited extensive fluvial and deltaic facies across most of the Perth Basin (Lesueur Sandstone) and mostly deltaic facies in the Northern Carnarvon and Roebuck Basins (Mungaroo Formation and equivalents; Fig. 10b), with sediment supplied from distant sources to the east and south (see ***Provenance — where did the sediment come from?***, p. 40). In the eastern Northern Carnarvon Basin, this succession is over 4000 m thick and onlaps, or abuts against, older rocks. Although truncated by Upper Jurassic unconformities, seismic reflection data from deeper parts of the basin indicate the deltaic succession exceeds 6000 m in thickness. Initially, carbonate reef complexes could have developed along an emerging shelf break in distal parts of the Northern Carnarvon and Roebuck Basins; if so, such carbonate build-ups are unlikely to have survived inundation by clastic sediment in the Middle to Late Triassic, although they are present within Rhaetian successions.

Similar fluviodeltaic deposits extended across the Browse and Bonaparte Basins, but fluvial sand facies were minor (Pollard and Nome Formations) and the Norian is present only locally. Marginal-marine conditions gradually transgressed back over the non-marine sections in the Late Triassic, with marine-shelf facies seaward of prodeltaic and deltaic facies (e.g. Eneabba and Brigadier Formations of the Perth and Northern Carnarvon Basins, respectively). Amalgamated channel sandstone facies in these fluviodeltaic sequences form high-quality reservoirs in many of the commercial gas and condensate fields within the Northern Carnarvon Basin. Late

Triassic erosion of large fault blocks containing such reservoirs generated effective traps where directly overlain by thick, sealing marine facies. This exploration play has not been as successful in the Perth and Bonaparte Basins where sandy Triassic successions overlain by sandy Jurassic facies lack sealing lithologies. The thick deltaic facies also include organically rich shale and coal, which are interpreted as source rocks for the large gas and condensate fields along the North West Shelf in areas where they are buried deep enough.

Early–Middle Jurassic rifting

This rifting phase probably began in the Rhaetian. There are isolated examples of extensional faulting, mainly in the south of the North West Shelf, that signify the onset of a long period of extension. This process intensified along the entire margin of the continent, possibly resulting in separation of the Argoland continental terrane around this time. Remnants of Argoland now lie in West Burma and possibly parts of Indonesia — the northern parts of that terrane now appear to lie beneath Southeast Asia.

This phase of rifting appears to have inverted older rifts, with thick Permian–Triassic sections in outboard areas forming structural highs such as the Exmouth Plateau and the Scott, Ashmore and Sahul Platforms. The inboard areas became the focus of extension, with the thickest Jurassic sediment accumulation in deep, narrow, presumably tectonically controlled, contiguous, inboard depocentre trends (Exmouth–Barrow–Dampier–Beagle and Rowley–Barcoo–Caswell Sub-basins, Vulcan Graben – Nancar Trough, and Malita–Calder Grabens). Deltaic facies (within the Yarragadee, Legendre and Plover Formations) fed by fluvial feeder systems built out in all basins, with the deep Dampier, Barrow and Exmouth Sub-basins being underfilled allowing marine facies to accumulate to the west. Some authors correlate this depositional phase with the separation of Lhasa from the southern part of Argoland.

North-northeast-striking extensional faults across the Exmouth Plateau and Roebuck Basin imply east-northeast extension and are associated with the separation of Greater India from the Australian continent. The extension phase along the similar fault trends at the edge of the Peedamullah Shelf and to the north controlled the location and orientation of the Barrow Sub-basin. However, the Dampier and Exmouth Sub-basins follow the trend of underlying northeast-striking Permian faults, producing oblique extension on en-echelon faults within the Rankin Platform and at the western margin of the Exmouth Sub-basin. Extensional faults in the Browse Basin and western Bonaparte Basin uniformly strike northeast, implying extension to the northwest consistent with the orientation of magnetic anomalies across the Argo Abyssal Plain and the northwesterly migration of Argoland.

Callovian regional uplift, erosion and volcanic activity associated with the Argo breakup unconformity was widespread across the outer sub-basins (Exmouth Plateau, Rowley and Scott Sub-basins) of the North West Shelf, at a time when extensional faulting was more restricted in this region. The magnetic anomalies across the Argo and Gascoyne Abyssal Plains point to approximately late Oxfordian formation of oceanic crust in isolated compartments (Fig. 13a). This event corresponds to the cessation of extension and development of Oxfordian unconformities. The following widespread marine flooding extended at least as far as Irian Jaya and deposited dominantly muddy sediment to form a regional seal for hydrocarbon accumulations.

In the Southern Carnarvon Basin, the only record of Early Jurassic deposition is within the 50-km-diameter Woodleigh impact structure. In spite of its size and age close to the Triassic–Jurassic boundary (see ***Impact structures***, p. 58), the effect on the region beyond its extremities is unknown and its economic potential is uncertain.

Depositional history

At the onset of the Jurassic, Australia's climate became more temperate and wetter than during the Triassic (see ***Climate,*** p. 17). This allowed the growth of tropical rainforests dominated by conifers, cycads and ferns (see ***Flora — greening Western Australia***, p. 16) and the localized development of swamps (see ***Coal — buried ancient swamps***, p. 50). Large deltas and fluvial floodplain channel belts continued to develop (Fig. 13a), although they were not as extensive as in the Triassic. Subsidence increasingly controlled rapid deposition in fault-bounded grabens. In the southern Perth Basin, the Late Triassic sandy fluvial system transitioned into redbeds with pedogenic facies transgressing northwards across the Triassic–Jurassic boundary. Jurassic fluvial-dominated systems extended over most of the basin, with the greatest deltaic influence during the mid-Early Jurassic (Cattamarra Coal Measures) in the northern part of the basin.

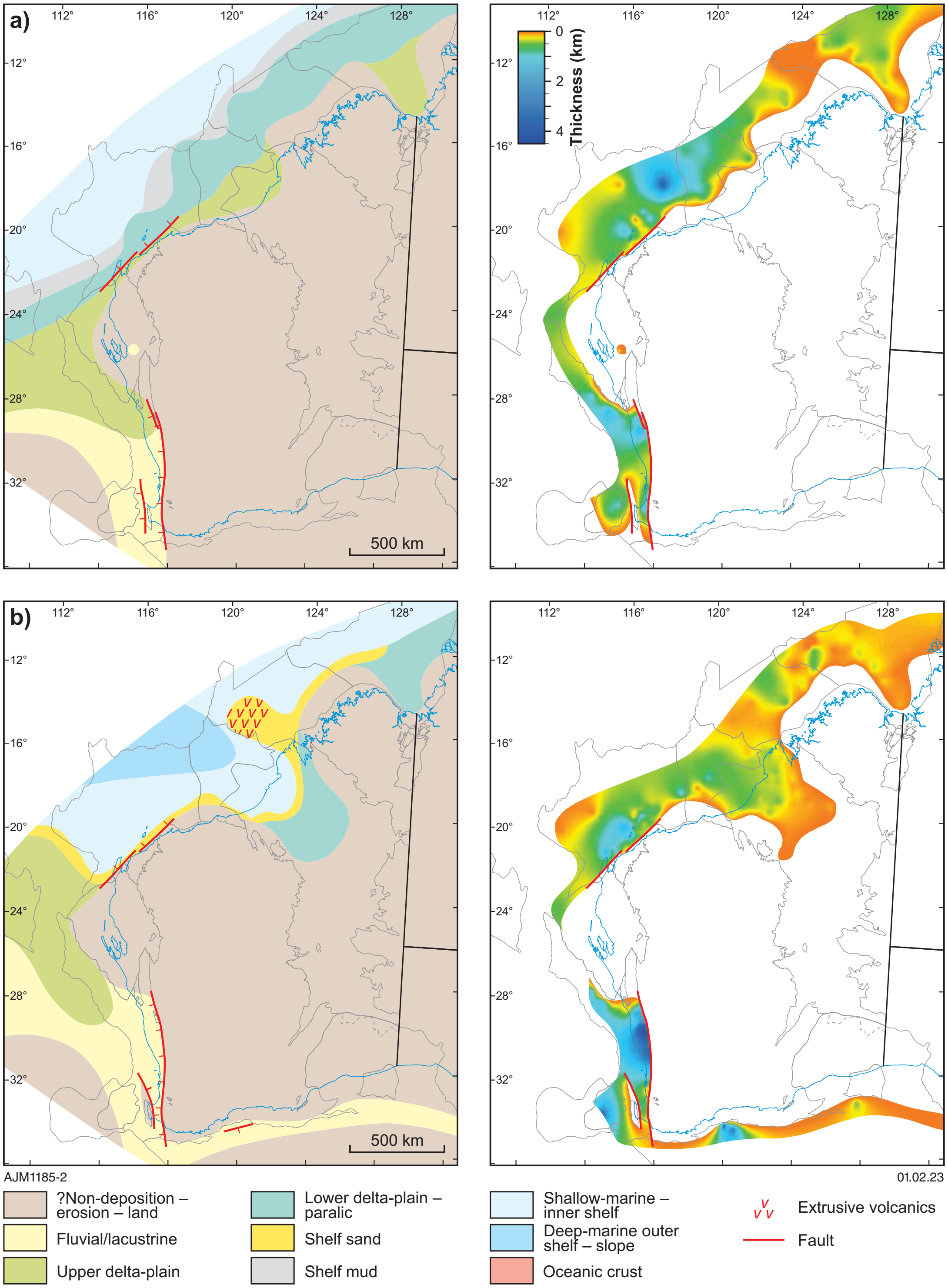


Figure 13. Jurassic paleogeography and isopach images for Western Australia: a) ~Hettangian–Bajocian and b) ~Bathonian–Kimmeridgian

Early Jurassic sedimentation in the Northern Carnarvon Basin was mainly under muddy shallow- to marginal-marine conditions (Murat and Athol Formations). Middle Jurassic deltaic sands (Legendre Formation) extended across the Beagle and Dampier Sub-basins. These facies form reservoirs in some fields, including the giant Perseus gasfield in the offshore Dampier Sub-basin.

Large, sandy deltaic and fluvial systems extended into the Roebuck Basin (Depuch Formation) and into the Browse and Bonaparte Basins (Plover Formation). At the end of the Callovian, nearly all of these deltas retreated to locally confined areas (e.g. Elang, Laminaria, Montara and Calypso Formations), and were followed by marine flooding during the Oxfordian at breakup. The largest fluviodeltaic systems formed in the Middle to Late Jurassic within the Dampier Sub-basin of the Northern Carnarvon Basin (Legendre to Angel Formations) and Perth Basin (Yarragadee Formation). The thickness of the Yarragadee Formation points to substantial renewed movement along the Darling Fault during an extensional tectonic phase, i.e. synrift.

Jurassic hydrocarbon source rocks

In the Early Jurassic, an upwards transgressive cycle in the Perth Basin developed from a lowstand fluvial succession (Eneabba Formation) into a marginal-marine and deltaic system (Cattamarra Coal Measures), followed by a widespread marine transgression in the Bajocian (Middle Jurassic Cadda Formation). Source-rock intervals in the upper part (Cattamarra Coal Measures and the Cadda Formation) are principally gas-prone. The following regression deposited fluviodeltaic sediment (Yarragadee Formation) and extended into the earliest Cretaceous (Parmelia Group). Although the Upper Jurassic is locally organically rich — total organic carbon (TOC) is up to 11% — and potentially capable of generating both oil and gas, no hydrocarbon accumulations have been identified as sourced from this level.

Thick Lower to Middle Jurassic mudstone intervals within the Dampier Sub-basin contain gas-prone facies from the prograding Legendre Formation deltas that charged the Rankin Platform gasfields (including North Rankin, Goodwyn, Angel and Perseus). The post-rift thermal sag succession of the Northern Carnarvon Basin incorporates Oxfordian flooding (*Wanaea spectabalis* Zone), starting with restricted-marine conditions in the incipient rifts. This deposited the marine facies of the Dingo Claystone, one of the most prolific oil-prone source intervals of the North West Shelf, which charged many economic accumulations in the Barrow, Dampier and Exmouth Sub-basins. These include the productive oilfields hosted by deep-water fan systems of the Angel Formation (Wanaea, Cossack and Lambert–Hermes) and the Barrow Group deltas (Griffin, South Pepper, Harriet, Barrow Island, Pyrenees, Vincent, Enfield). Notably oil-prone are Oxfordian mud facies within the *W. spectabilis* Zone, sourced largely from marine exinite (alginite) mixed with exinitic land-plant organic material.

In the adjacent Roebuck Basin, potential source intervals are chiefly within the Jurassic coaly and algal-rich mudstone and prodeltaic marine shale. The middle to upper Depuch Formation incorporates potentially gas-prone and oil-prone source intervals, respectively, but are typically immature.

Within the thick Jurassic to lowermost Cretaceous synrift succession in the Browse and Bonaparte Basins, Oxfordian to Kimmeridgian restricted-marine mudstone facies (Vulcan Formation and Frigate Shale of the Flamingo Group) contain the best oil-prone sources. Deltaic facies within the Lower to Middle Jurassic Plover Formation also generated large volumes of gas and condensate in the Browse and Bonaparte Basins (e.g. the Calliance, Brecknock, Torosa, Ichthys, Prelude, Bayu–Undan, Sunrise, Barossa, Caldita and Echuca Shoals fields). In the Vulcan Sub-basin, similar facies delivered a wet-gas-prone system in the Browse Basin (e.g. in the Brewster Member of the Swan Group) and waxy oil in the Maret and Montara fields. Mature source rocks in the Vulcan Sub-basin are also present within the underlying Montara Formation. Units of this age have provided major source kitchens for the Vulcan and Flamingo Sub-basins, Ashmore Platform and Londonderry High. These source rocks generated a variety of liquid hydrocarbons as well as gas, charging a large variety of reservoirs in structurally complex settings and via multiple migration pathways. Examples include fields with light oil and condensate such as Jabiru, Challis, Laminaria, Corallina and Elang.

Late Jurassic – Early Cretaceous breakup and separation

During the Middle Jurassic to Early Cretaceous, seafloor spreading moved progressively southwards in broad phases separated by unconformities mapped as regional seismic surfaces by exploration companies. The most important horizons are JC dated at ~165 Ma (Callovian), which originated in the north of the Bonaparte Basin; JT at ~150 Ma (late Kimmeridgian), eminating from near the Argo and Gascoyne Abyssal Plains; KV at ~136 Ma (Valanginian), adjacent to the Perth Abyssal Plain; and KA at ~120 Ma (Barremian – early Aptian). The first phase coincides with rifting and separation of the West Burma terranes, and was followed by rifting and separation from Greater India. In the Bonaparte Basin deposition across active faults continued until the Callovian (Fig. 13) in contrast to areas close to the Indo-Australian rift, such as the Exmouth Plateau and the Barrow, Exmouth and Dampier Sub-basins that show minor extension related to Greater India during the Oxfordian–Valanginian. Uplift and erosion of the southern basins in the Berriasian–Valanginian was associated with rift onset between Greater India and Australia. The Valanginian breakup unconformity, which extends across all North West Shelf basins, forms a distinct stratigraphic marker easily recognized in seismic reflection data (Figs 4, 5).

The western margin of the continent formed one of the arms associated with a triple junction between Australia, Greater India and Antarctica. Rifting continued to the early Valanginian and culminated in extensive volcanism, which included both subaerial and submarine flows across the Wallaby Plateau. Over time, the locus of oceanic crust generation propagated north to the Wallaby–Zenith Fracture Zone and farther south on the Greater India – Antarctica margin (Fig. 13b). The period of thermal subsidence saw reduced faulting in the Perth Basin and virtually none in the interior of the State.

The most pronounced volcanism associated with breakup was in the Perth and Northern Carnarvon Basins (Fig. 14), with numerous intrusions and at least two phases of extrusion in the southern Perth Basin (Fig. 15). Basalt flows in the onshore Bunbury Trough have yielded Valanginian to Hauterivian dates (136.96 ± 0.43 Ma, 132.71 ± 0.43 Ma and 130.45 ± 0.82 Ma) from $^{40}Ar/^{39}Ar$ analysis of plagioclase grains. Although aeromagnetic images reveal flows with two different polarities along paleovalleys (Fig. 15), only the western (negative polarity) flow has been dated. An estimated 90 km^3 of basalt was extruded, possibly from vents along the Darling Fault (Fig. 15; see ***South West gold — abandoned mines***, p. 57) and faults in the Bunbury Trough, and is now quarried for road aggregate (see ***Construction materials — society's building blocks***, p. 54). The basalt appears related to the

Figure 14. Outcrop of Bunbury Basalt 2 km northwest of Black Head, southern Perth Basin (photo by Peter Haines)

Greater Kerguelen large igneous province that developed at breakup. The effects of this event seemingly extended at least 130 km east of the southern Perth Basin, where a northeast-striking basaltic dyke in Proterozoic coastal exposures has been consigned a breakup age, albeit by invoking Pb loss to explain the mildly discordant zircon dates of ~250 Ma.

Early Cretaceous flooding that deposited thick, mud-rich facies (Muderong Shale, Windalia Radiolarite and Gearle Siltstone of the Winning Group; Figs 9, 16) created a regional seal across many hydrocarbon reservoirs, especially in the Exmouth Sub-basin. The succeeding series of shelf–platform carbonates with minor marine sandy facies built out over older sedimentary deposits. Thermal subsidence was punctuated by several inversion events starting in the mid-Cretaceous that have continued to the present due to the collision of Australia's northwestern continental margin with the Indonesian Plate to the north. These compressional strains became prominent at ~25 Ma, when the first continental crust of the Australian Plate made contact with Southeast Asia and a strike-slip boundary developed in northern New Guinea.

Evidence of Mesozoic tectonism across the State's Precambrian terranes, probably during breakup, is limited to a few examples. The possibility of earlier Mesozoic deformation across those terranes cannot be discounted entirely, even though the effects of breakup are dominant in most of the Phanerozoic basins. The obvious example is the Collie Sub-basin overlying the Yilgarn Craton, in which the Permian displays broad folds and faults, and dips up to 75° along its southwestern faulted margin. It follows that many of the west-southwest-striking faults in the southwestern Yilgarn Craton were also active during the Mesozoic, although none obviously displace the Darling Fault. Other examples include faulted outcrops near Ockerburry Hill, 40 km east of Leinster where the lower Permian dips at up to 25°, and over the Paleoproterozoic Earaheedy Basin 40 km south of the eponymous homestead where dips reach up to 8°. Other support for Mesozoic reactivation in Precambrian terranes includes an Early Cretaceous Sm–Nd date (122 ± 24 Ma) from fluorite within the Yungul (Speewah) carbonatite in the east Kimberley, which shows at least fluid movement along faults in the Halls Creek Orogen during breakup. In the Pilbara, Late Jurassic – Early Cretaceous Th–Pb ages (152 ± 6, 132 ± 4 and 119 ± 4 Ma) from rhabdophane in Archean shales reveal similar reactivations.

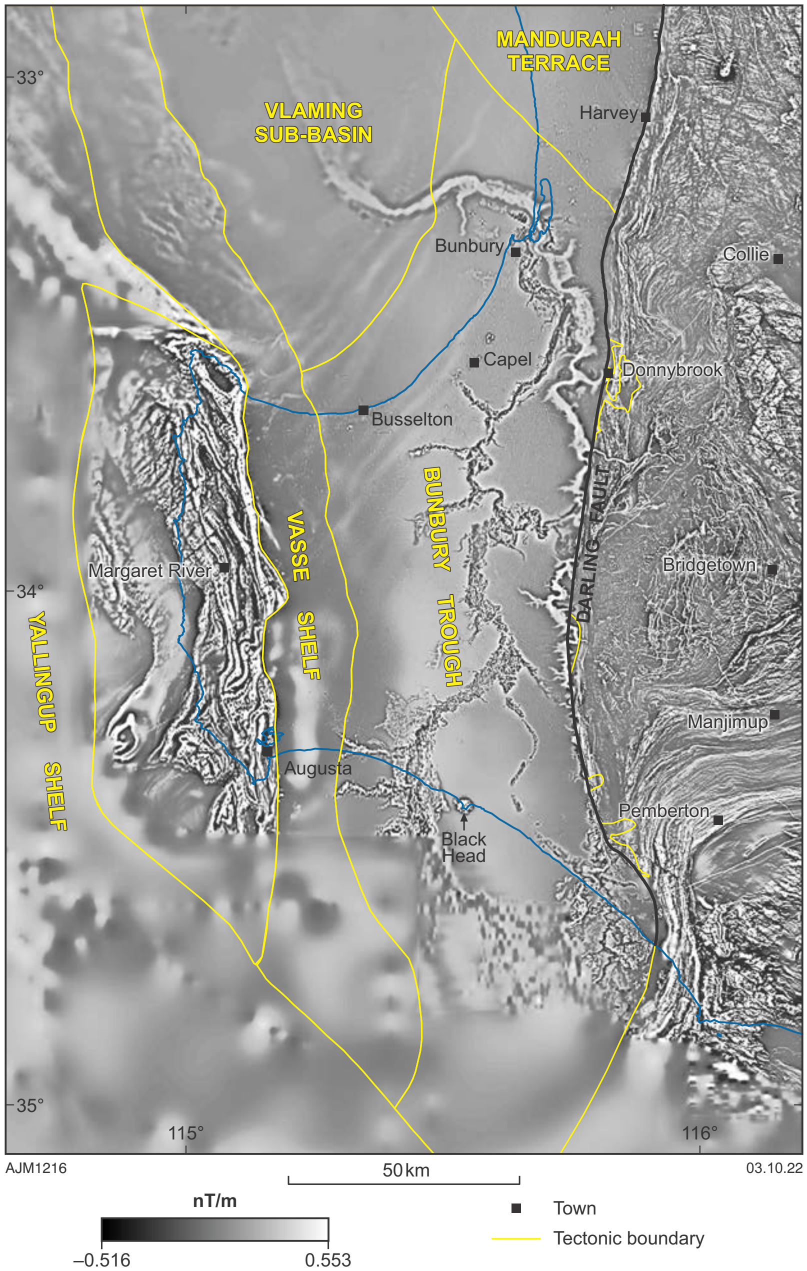


Figure 15. Aeromagnetic first vertical derivative image, southern Perth Basin, showing two Lower Cretaceous flows within the Bunbury Basalt recognisable from their different polarities

Southern continental margin

The Mesozoic successions along Western Australia's southern margin are assigned to the Bight Basin where Bathonian – early Callovian (Middle Jurassic) rifting between Antarctica and Australia produced a series of northeast-southwest-trending, south-dipping, en-echelon half-grabens controlled by oblique extension and basement fabric. The Denmark, Bremer, Eyre, Ceduna and Duntroon Sub-basins within this basin are partly coeval with the Otway, Sorrell, Bass and Gippsland Basins along Australia's southern margin.

Extension restarted during the mid-Valanginian to late Aptian. Existing faults were reactivated in the western and eastern parts of the Bight Basin, allowing large roll-over and flat-ramp anticlines to develop. Extension reduced by the late Aptian and, in the west, the Bremer Sub-basin entered a period of subsidence with reduced tectonic activity lasting until the Turonian (Fig. 16). This subsidence spans up to 0.8 sec TWT in seismic reflection data but is considerably less in adjacent areas. This suggests faster subsidence rates within the central part of the Bremer Sub-basin relative to the eastern and western flanks. Initiation of sea-floor spreading in the Bight Basin was at ~83 Ma (latest Santonian or early Campanian) in the Denmark Sub-basin, and it progressively extended eastwards. Spreading rates were initially slow at 1.5 – 10 mm/yr, and abruptly increased to 20 mm/yr in the Middle Eocene.

Depositional history

The separation of Australia and Greater India, which ceased in the Valanginian, created a series of rift basins allowing deposition of deep-marine sediment, especially in the north. Subsequent deposition was mainly within prograding, passive-margin shelf settings. In the centre of the Dampier Peninsula, the Broome Sandstone contains heavy mineral sands, typically considered to be nearshore deposits (see ***Heavy mineral sands — ancient shorelines***, p. 46), whereas along the present coast near Broome the formation contains coastal to delta-plain facies with abundant dinosaur trackways (see ***Macrofaunas***, p. 14). This signals that Early Cretaceous deposition, at least in this region, progressively back-stepped to the east across a low-relief coastal plain. Presumably, various paleodrainage systems were re-established across the hinterland at this time (see ***Provenance — where did the sediment come from?***, p. 40), to supply siliciclastic sediment into the surrounding basins.

Barrow delta

The Barrow delta is a Tithonian–Valanginian (J50–K10) fluviodeltaic to shallow-marine system that prograded into the Exmouth and Barrow Sub-basins from the south during the final phase of rifting, to deposit a sedimentary section over 2500 m thick (Figs 16a, 17). Domal uplift in the southern portion of the Exmouth Plateau,

Duricrusts

Duricrusts include hardened regolith deposits enriched in silica (silcrete), aluminium sesquioxides (bauxite) and iron sesquioxides (ferricrete). Such deposits form in high-rainfall areas with good, but not rapid, drainage, thereby allowing alteration of primary clay minerals and dissolution of minerals containing Si, Ca, Na and K, during long-term deep chemical weathering. Duricrust development takes place between the biomantle and the mottled zone close to the water table — together these intervals make up the pedolith above the pallid zone, which is composed of saprolite and saprock, above bedrock. These deposits typically develop where erosion is minimal and little, if any, sediment can build up, notably below long-lived paleo-land surfaces (see ***Mesozoic erosion of the hinterland*** in ***Provenance — where did the sediment come from?*** p. 40). Duricrusts also may be enriched in manganese, gold, nickel or cobalt — about 10% of the State's gold output appears related to regolith processes including laterites.

Although some paleomagnetic studies of weathered saprolite suggest duricrusts over the Yilgarn Craton near Leinster and Kalgoorlie are of Mesozoic age, this method is imprecise. Because duricrusts form by long-lived processes, their chemistry may be progressively overwritten, which parsimoniously explains the lack of Mesozoic ages from other methods. Similarly, near-surface supergene enrichment of iron ore deposits in the Archean–Paleoproterozoic Hamersley Basin and Yilgarn Craton is commonly attributed to Cenozoic processes, but the development of some bedded martinite–goethite deposits and massive goethite bodies possibly began late in the Mesozoic — similar to duricrusts, their dating is problematic or ambiguous.

On regional climatic grounds, ages from Late Cretaceous to Late Neogene are possible for the extensive bauxite deposits across the Mitchell Plateau (see ***Climate***, p. 17), although the limited (U–Th)/He isotopic dating indicates a Miocene–Pleistocene age. In the Northern Territory, lateritic deposits next to the Gulf of Carpentaria lie within, or directly overlie, marine facies of Cenomanian (Late Cretaceous) age — at Groote Eylandt, large manganese resources are present within the Cretaceous, whereas at Gove the bauxite lies directly above. By comparison, such deposits in the southwest of the Yilgarn Craton overlie fossiliferous Eocene and Oligocene fluvial sediment. The bauxite deposits on the Mitchell Plateau are excluded from mining as they now lie within a national park, whereas those along the Darling Range near Perth are actively mined despite their grades being amongst the lowest in the world that are considered economic.

Many of the extensive lateritic profiles across much of the central and eastern Yilgarn Craton are regarded as having formed in the late Cretaceous – mid-Cenozoic but these ages are poorly constrained. Isotopic geochronology on manganese oxides and goethite from plateau-weathering profiles in other Australian states include latest Cretaceous dates, but these have yet to be obtained from Western Australian samples. If duricusts did form in the Cretaceous, the lack of evidence for clasts from this stratigraphic level may be a function of limited outcrops and core availability.

Undulating surface capped by partly eroded ferruginous duricrust overlying Archean–Proterozoic banded iron and chert in the Hamersley Ranges (photo by Dave Martin)

possibly linked to mantle plume activity, may have influenced this rifting phase. At the same time, a large fluvial-dominated system (Parmelia Formation) transported sediment northwards within the Perth Basin. It is possible these systems were linked for part of their history; if so, any evidence has been removed during separation and uplift during the formation of the Cuvier Abyssal Plain in the Valanginian.

The basal section of the Barrow Group consists of deep-water, sandy gravity-flow deposits (Macedon Member), mud facies (Murion Member) and a local upwards-coarsening, progradational facies (Pyrenees Member) on the fringes of the 'Macedon high' in the Exmouth Sub-basin. The overlying main part of the Barrow Group consists of a large, northwards-prograding shelf edge with associated deep-water muds and turbidite sand facies — with a massive, wave-influenced braid delta to feed this system as it moved across the Exmouth Plateau — and the Barrow and Dampier Sub-basins. The Valanginian post-rift saw the system begin to drown and shut down such that it became restricted to the Barrow Sub-Basin in the east, where deltaic sandstone reservoirs host hydrocarbons in deep-water facies within the Flag Sandstone, delta-plain facies in the Zeepaard Formation and shoreface facies in the Birdrong Formation.

Shelf canyons and slides — Tithonian submarine fans

Callovian rifting and Oxfordian post-rift sag established deep-water conditions along the North West Shelf. The delta fronts shifted towards the hinterland, thereby creating shallow shelf slopes in many sub-basins along the North West Shelf. Canyon systems beyond the deltas cut into these slopes, down which density currents episodically deposited large clastic submarine fans in newly formed deep-marine depocentres. The best examples are Tithonian fan facies of the Angel Formation, which flowed towards the centre of the Dampier Sub-basin from the north and east with minor slumping from the western margin into this deep-water depocentre. Little of the deltas supplying these fans is preserved, as they were subsequently eroded, reworked and redeposited. Deep-water deposits of the same age also fed into the nearby Barrow and Exmouth Sub-basins, and the Bonaparte Basin to the north, indicating a regional control on tectonics and sedimentation at this time. With all these, fan facies initially prograded towards depocentres before retreating at the end of the Tithonian. Clean, coarse-grained sand facies formed thick, stacked beds in the axial heads of the fans, in contrast to fine grained and thinly bedded facies in their distal terminations. In the case of the Angel Formation, interbedded marine siltstone beds host trace fossils and bioturbation, indicating deposition in moderate water depths via a combination of hemipelagic sedimentation and settling of the fine-grained turbidity current plumes.

Generation of hydrocarbons from deeply buried source rocks in the Dingo Claystone in synclines — and their migration into adjacent 'Angel fan' reservoirs of the large Wanaea, Cossack, Lambert and Hermes oilfields, and other smaller accumulations — did not take place until the early Cenozoic. The proximal fan reservoir for the Angel gasfield was charged mainly from deeper Lower to Middle Jurassic source rocks. The field is now approaching depletion, leading to speculation that it is suitable for future CO_2 or H_2 storage.

Southern margin deltas

Fluviolacustrine sedimentation in the Middle–Late Jurassic associated with rifting was followed by largely non-marine Early Cretaceous deposition (Fig. 16b) during slow thermal subsidence. The first marine influence was during the Aptian–Albian, followed by a period of accelerated subsidence and the first major marine flooding of the basin during the mid-Albian to early Cenomanian (Fig. 18a). Progradation of deltaic sediment into this seaway began in the Cenomanian, following uplift and erosion along the eastern margin of the continent. This fed sandy fluvial sediment from much of the centre and east of the continent that then flowed south.

Lower Cretaceous hydrocarbon source rocks

Lower Cretaceous marine shale, especially where associated with the main flooding event (*Muderongia australis* Zone; ~K30), may have good source potential but in most areas is not buried deeply enough to generate an economic volume of hydrocarbons. The Lower Cretaceous Echuca Shoals Formation, in some

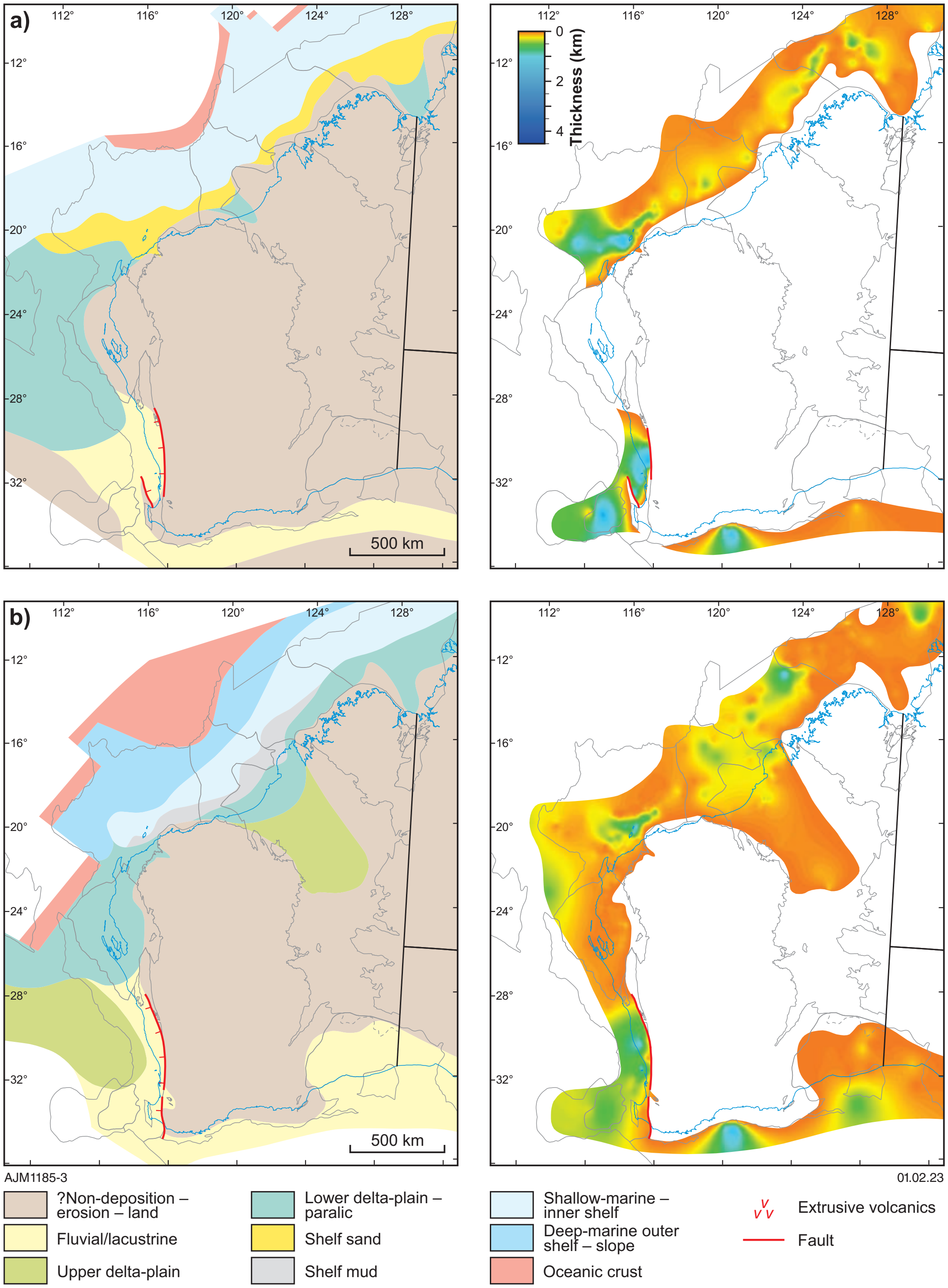
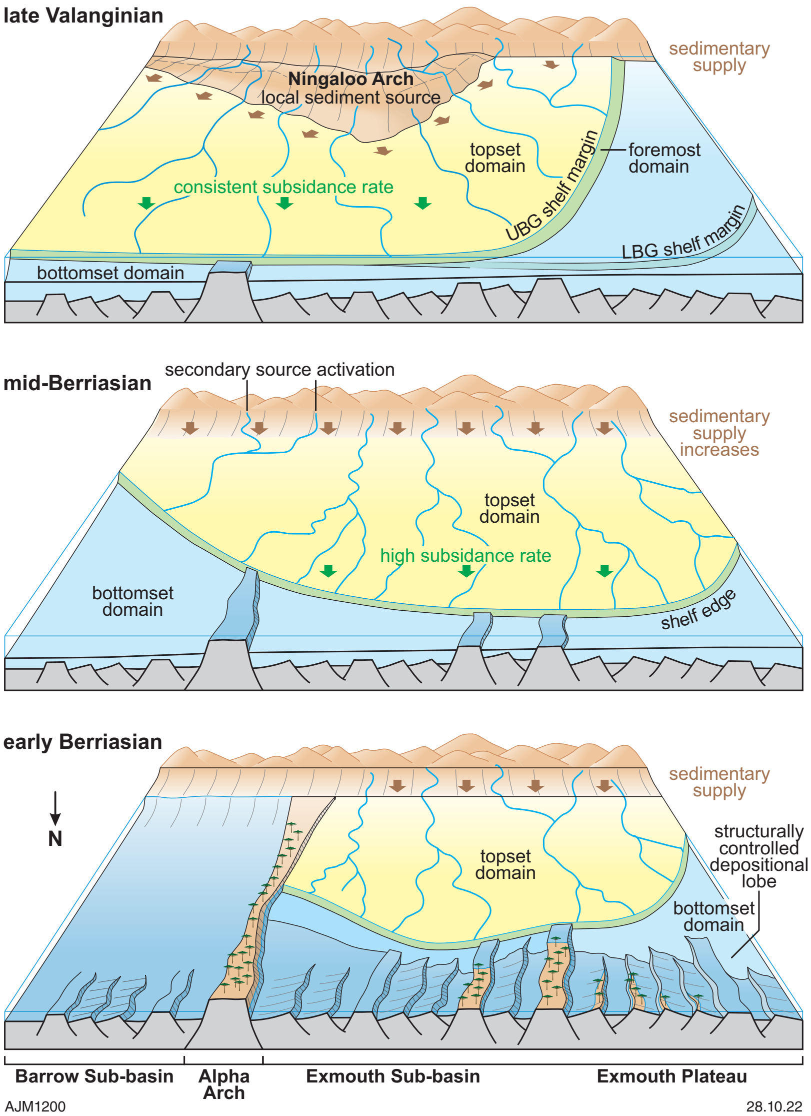
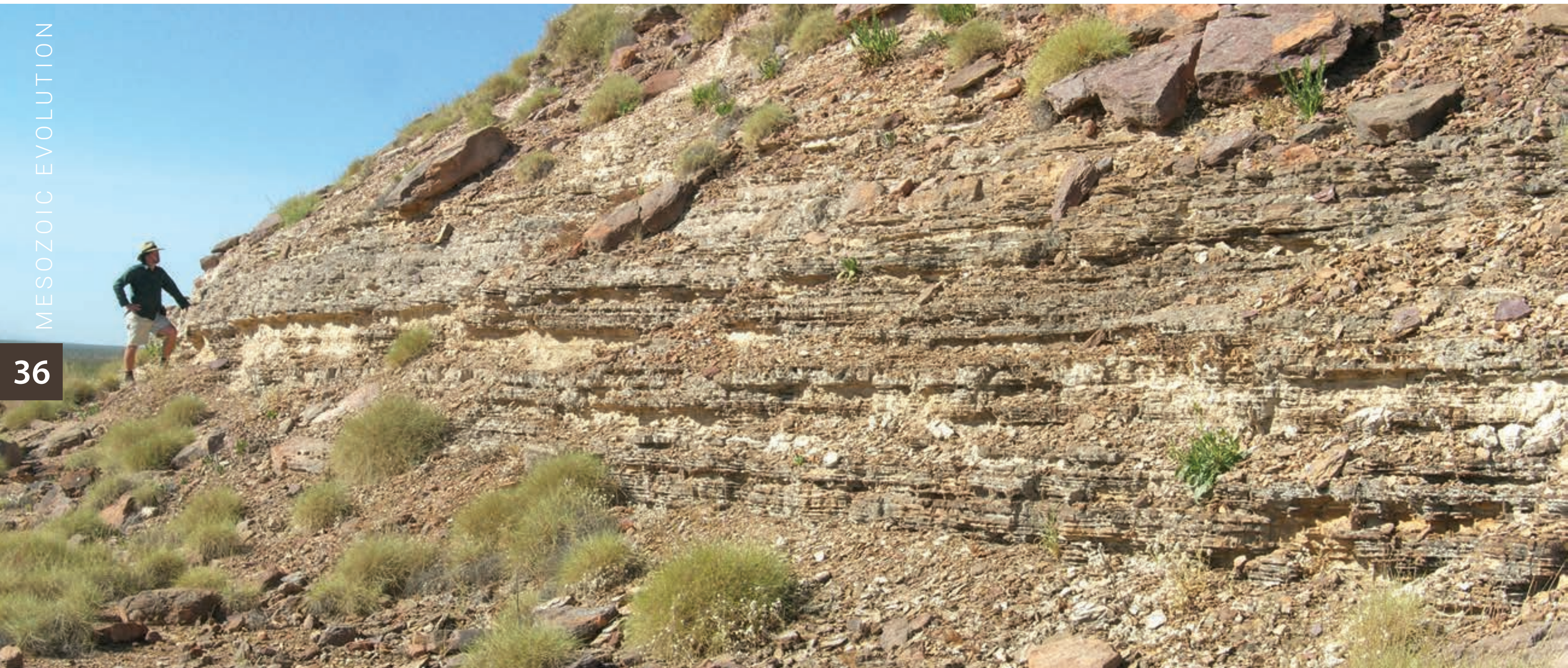


Figure 16. Latest Jurassic – earliest Cretaceous paleogeography and isopach images for Western Australia: a) ~Tithonian–Berriasian and b) ~Valanginian–Hauterivian

Figure 17. Reconstruction of Barrow Group delta based on seismic time slices. Abbreviations: UBG, upper Barrow Group; LBG, lower Barrow Group. (From Paumard et al., 2018, fig. 17)



Minor erosion surface (at level of person's knee) in thinly bedded and burrowed siltstone and fine sandstone facies, Lower Triassic Blina Shale, Erskine Point, 98 km southeast of Derby, Fitzroy Trough, Canning Basin



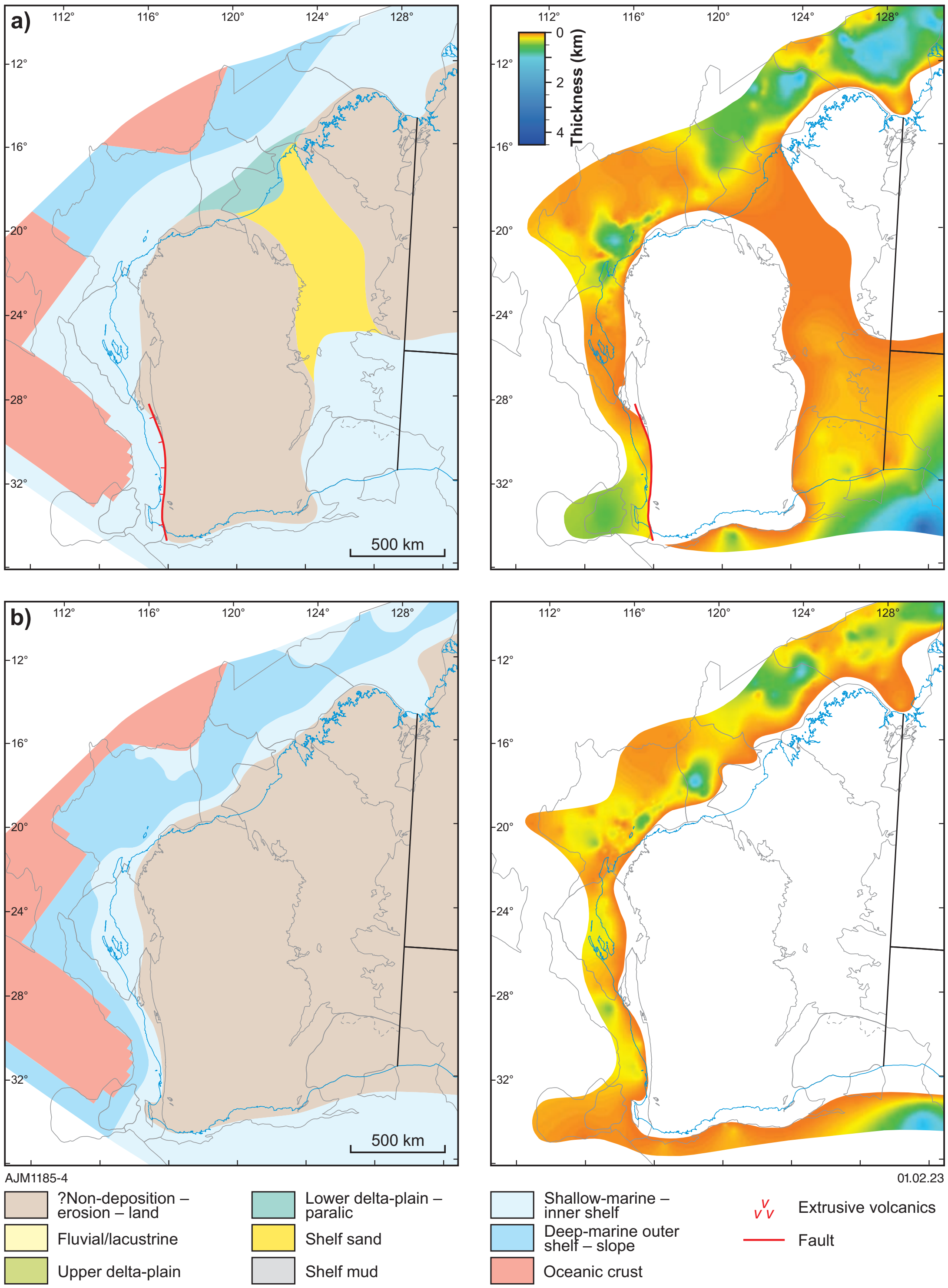


Figure 18. Mid- to Late Cretaceous paleogeography and isopach images for Western Australia: a) ~Barremian–Santonian and b) Campanian–Maastrichtian

of the deeper depocentres or grabens of the Browse and Bonaparte Basins, has been linked geochemically to the Caswell and Elang West oil accumulations. Equivalent sequences in the Roebuck Basin are potential source rocks with fluid-inclusion studies pointing to widespread oil migration within the Mesozoic, with the main limitation being viable traps.

In the Northern Carnarvon Basin, a widespread flooding event (Figs 9, 16b) is deduced from units such as the Muderong Shale and Windalia Radiolarite, both of which have good potential source rock facies. However, in the majority of areas drilled, burial was insufficient to generate hydrocarbons, even though many shaly sections are overpressured. Similarly, the laterally equivalent South Perth Shale in the Perth Basin is too shallow to generate substantial hydrocarbons from the areas drilled to date.

Mid- to Late Cretaceous trailing-edge rifting and marginal sag

This phase followed the separation of Greater India from Gondwana. Rifting between Antarctica and southern Australia became pronounced in the Cenomanian with the progradation of deltaic facies across the Bight Basin, which continued until about the Campanian when a significant reduction in sediment supply allowed carbonate facies to develop (Fig. 18b). These carbonate facies became widespread around the continent in the Cenozoic (Fig. 9), even in cool waters along the southern margin. Lateritic processes that formed widespread duricrusts were also active across the hinterland (see ***Duricrusts***, p. 33). The present low-relief surface of the Yilgarn Craton has evolved through alternating phases of planation, shallow reburial and deep weathering encompassing many periods of duricrust–saprolite formation. Apart from the likelihood of a complex origin incorporating alternating deposition and pediplanation, possibly commencing following Mesozoic breakup, a detailed understanding of the evolution of the craton prior

Flat-lying Lower Cretaceous Nanutarra Formation capped by thin Cenozoic channel iron deposits, 86 km east of Onslow, northern Peedamullah Shelf, Carnarvon Basin

to the Cenozoic is not possible at present due to the lack of datable events or Mesozoic strata.

Along the southern coast, wet and cold conditions prevailed in the late Cretaceous, with evidence of sea ice in South Australia. Seasonal variations in rainfall hindered the proliferation of conifer and cycad forests, which may have aided the emergence of flowering plants (angiosperms). In the mid-Aptian (~117 Ma; Fig. 18a), a marine transgression, probably driven by a combination of greenhouse conditions and subsidence, flooded much of central Australia across connected inland lake systems to form the inland Eromanga Sea. Flooding extended across the Canning Basin to the southeast, and from the north via the Gulf of Carpentaria into the Eromanga and Surat Basins in southern Queensland and adjoining regions. The eastern and western seaways connected via the southern Canning Basin by the mid- to late Aptian, essentially subdividing Australia into three landmasses covering the Kimberly, the West Australian Craton and eastern Australia. Marine deposition inundated much of the western margin of Western Australia and the developing southern rifts, spreading eastwards into the Bight Basin, and reaching the Bremer Sub-basin in the Aptian and at least as far east as the Eyre Sub-Basin by the end of the Albian. At this time, Australia's inland sea split the region into two distinct climatic zones (see ***Climate,*** p. 17). The southern shore of the Eromanga Sea possibly looked similar to southeastern Australia's present coast. The extensive Albian shallow seas were home to a pelagic fauna including ammonites, belemnites and armoured fish, as well as large predators such as ichthyosaurus, pliosaurs and long-necked plesiosaurus (see ***Macrofaunas,*** p. 14).

Along the northern shores of the Eromanga Sea, conditions were predominantly warm and dry, allowing the proliferation of cycads, palm-like plants, ferns and conifers. Forests dominated by araucariacean pines with inter-grown ancient gingko trees and cycads were able to grow to the water's edge, with an undergrowth of mostly royal ferns, relatives of the modern king ferns, which still flourish along the eastern coast of Australia (see ***Flora — greening Western Australia***, p. 16). In the Perth Basin, mixed siliciclastic and glauconitic sediment accumulated across a low-gradient, locally undulating, broad continental shelf, with a water depth of approximately 100 m in the Late Cretaceous.

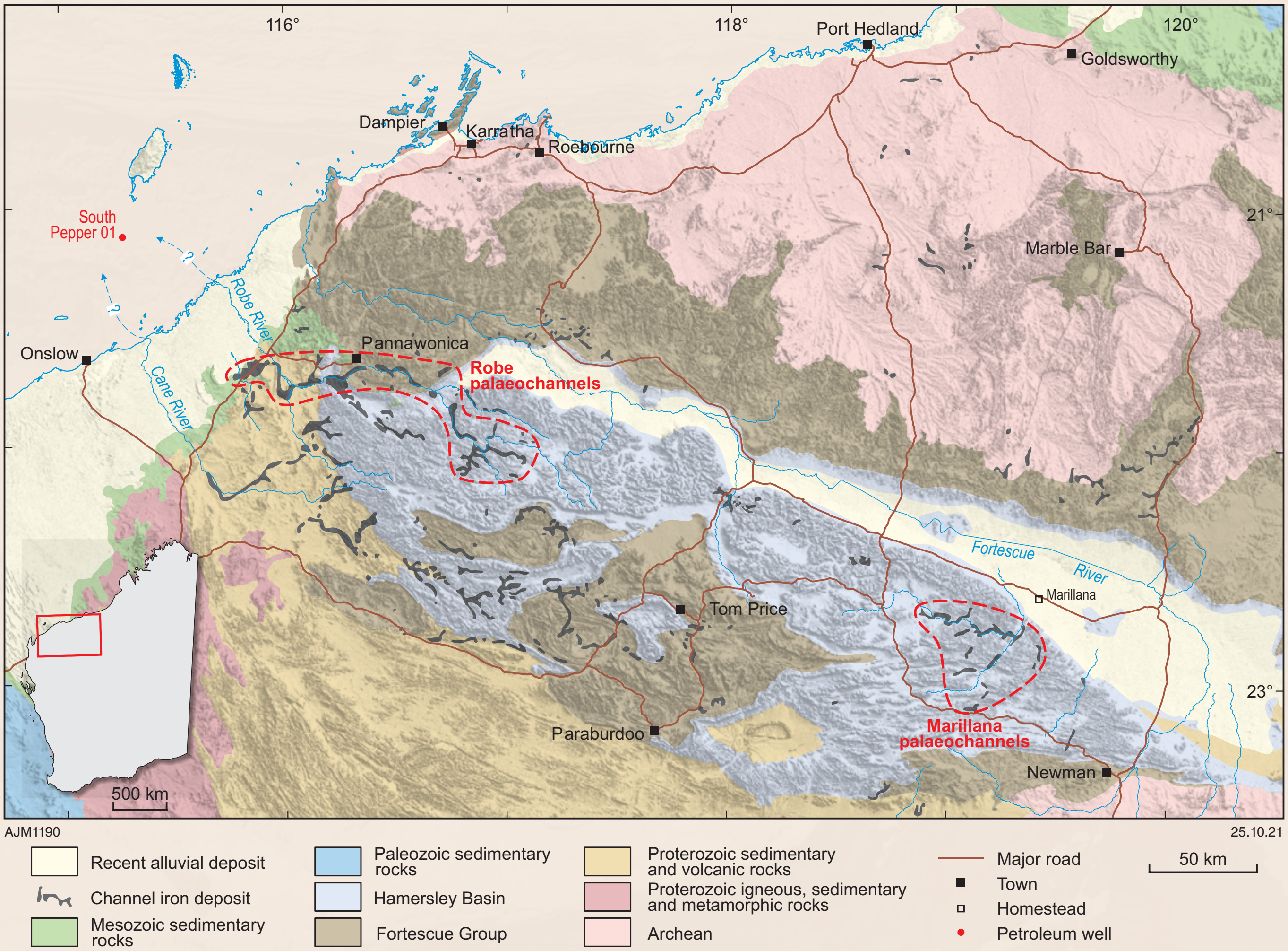
Provenance — where did the sediment come from?

Zircon provenance studies, especially of the Middle to Upper Triassic Mungaroo and Lesueur Formations (Northern Carnarvon and Perth Basins, respectively), indicate paleodrainage systems traversed the State carrying sediment from distant sources. The U–Pb age distribution of detrital zircons from pre-breakup strata reveals a relatively minor input from the adjacent Yilgarn or Pilbara Cratons in comparison to sources from Antarctica, the Pinjarra and Albany–Fraser Orogens in southern Western Australia, and central Australia. However, some Triassic zircons with volcanic characteristics point to a local source near the Exmouth Plateau — this aspect requires further work as these deductions are based on cuttings samples. Seemingly, it was not until breakup that closer regions supplied substantial volumes of sediment into the Mesozoic basins.

It is unlikely that sediment from distant terranes was supplied directly to the main Mesozoic depocentres — instead it probably moved progressively northwards across the continent during successive episodic phases of transportation. The lack of a record for such temporary events across the State is presumably due to the lack of accommodation, apart from in the Perth Basin. Pre-breakup strata along the North West Shelf yield few zircons originating from this craton, suggesting it was largely a passive area of low relief that did not contribute significant volumes of sediment, and possibly that it lay away from major transportation routes during at least the Triassic–Jurassic. A major change in provenance followed uplift of Precambrian terranes associated with Greater India's breaking away from the Australian continent in the latest Jurassic – Early Cretaceous, thereby introducing sediment from the West Australian Craton into peripheral basins.

Mesozoic erosion of the hinterland

Laterite-capped mesas across some Precambrian terranes and adjacent basins overlie land surfaces that possibly pre-date breakup (see ***Duricrusts***, p. 33). Dissection of these surfaces, associated with Cenozoic uplift, weathering and erosion across the West Australian Craton, began in the Eocene or earlier, as shown by valley fill and channel deposits of this age such as those targeted for uranium or groundwater that are mostly directed to the southeast (e.g. Cowan, Raeside and Lefroy paleovalleys north of Esperance). Although weathered regolith profiles near Kalgoorlie and Leinster have yielded Mesozoic paleomagnetic ages and commensurate $\delta^{18}O$ values (not necessarily from the same localities), these are not precise and await confirmation by other techniques. Consequently, determining the age of Mesozoic erosion surfaces depends largely on regional stratigraphic and geomorphological relationships.



Distribution of channel iron deposits, including the Robe and Marillana paleochannels, across the Hamersley Province (after Ramanadou and Morris, 2010)

However, their ages seem tenuous given the rarity of Paleozoic and Mesozoic strata to constrain events across the Yilgarn Craton. For example, the Jurassic age inferred for the inception of paleodrainage across the southeast of the craton from the oldest strata in the Bight Basin is uncertain, but could be tested by a provenance study of that succession.

Significant cooling, and hence erosion, of the Yilgarn and Pilbara Cratons, claimed to post-date the Early Permian based on apatite fission-track analyses, could equally well pre-date the Permian given the presence of clasts from these terranes in lower Permian glacial deposits in adjacent sedimentary basins. By comparison, the Triassic–Jurassic break across the Canning Basin (the Fitzroy Transpression) possibly involved up to 1200 m of exhumation across the Kidson Sub-basin but, given how incomplete the Mesozoic succession is in this region, this estimate may incorporate erosion during breakup. Whereas onlap of the Lower Cretaceous across onshore Paleozoic terranes, including the Permian, in the Southern Carnarvon Basin points to at least some erosion preceding, or associated with, breakup, thermal maturities in the older units are low. This suggests that any Triassic to Jurassic section had been relatively thin and this basin did not significantly supply sediment into the thick depocentres along the North West Shelf, at least prior to the Callovian.

Reworked pebbles in Birdrong Sandstone: 2372 m, South Pepper 1, Barrow Sub-basin, Northern Carnarvon Basin

Erosional surfaces and drainage systems

Because of the discontinuous preservation of erosion surfaces, the pattern of Mesozoic drainage across the State's Precambrian hinterland is uncertain, even though there are possible remnants such as conglomerate deposits across the southwestern Yilgarn Craton, likely post-dating Early Cretaceous breakup. The disconformable relationship between the Cretaceous and Paleozoic across the southern Canning Basin implies pre-breakup weathering across much of the West Australian Craton, whereas provenance studies of samples from the North West Shelf point to broadly north-northwesterly directed drainage traversing the continent. In addition, basalt flows in the southwestern Canning Basin and southern Perth Basin appear to have filled Triassic or Jurassic, and Early Cretaceous, drainages, respectively (see *Late Paleozoic to Triassic intracratonic rifting*, p. 18, and *Late Jurassic – Early Cretaceous breakup and separation*, p. 31). In the former example, the drainage is mostly confined to the Samphire Graben, and presumably headed north-northwest from the Pilbara, whereas in the latter area basalt infilled northwards-trending valleys along the hanging wall of the Darling Fault shortly after breakup.

In the Pilbara, locally undulating, elevated areas overlain by ferruginous hardcap preserve remnants of the Hamersley Surface, which probably originated in the Mesozoic, although clearly modified by Cenozoic events. Flat-lying Lower Cretaceous strata, which onlap onto the Pilbara Craton, extend across the Peedamullah and Lambert Shelves, and for about 140 km along the southwestern margin of the Canning Basin between the Ord Ranges and Callowa station. The unconformity points to erosion during the Mesozoic and is possibly associated with the Hamersley Surface. East of the Peedamullah Shelf, the Lower Cretaceous extends eastwards over Precambrian rocks for at least 40 km to near Pannawonica, with an isolated remnant preserved 30 km southeast of the town.

Channel iron deposits, apparently derived from Paleoproterozoic banded iron formations across the Pilbara, generally overlie Oligocene sediment within, or just downstream from, depressions in the Hamersley Surface. The drainage systems hosting the channel iron deposits, some of which are up to 100 m deep, probably originated in the Mesozoic, most likely following breakup. Although scarce, palynological evidence indicates broad Cretaceous ages. Of the drainage systems, the Robe River paleochannel, near the course of the modern river, is the longest, with iron deposits extending, albeit now discontinuously, 150 km east of the Peedamullah Shelf. Chert and a pebble with komatiite-like texture from the Berriasian–Tithonian Barrow Group in the South Pepper gasfield, 44 km west-northwest of the Robe River mouth, seemingly were transported via such a paleodrainage from the Precambrian, including Archean volcanic outcrops. This drainage system probably included a precursor of the Fortescue River initiated by uplift associated with the breakup of Gondwana. Zircon dating and apatite fission-track analysis of Pilbara Craton samples (mostly granitic), by comparison, suggest major Devonian–Carboniferous erosion. Similarly, paleovalleys filled with Cenozoic sediment across the southeastern Yilgarn Craton may have had Mesozoic or older antecedents that fed sediment into the Bight Basin. By comparison, north-flowing paleovalleys (e.g. the Avon and Cowan systems) now cut off near the southern end of the Yilgarn Craton possibly had headwaters in Antarctica pre-dating Jurassic rifting — the regolith incised by such paleovalleys could be at least that old.

Across the onshore portion of the Bight Basin, the Lower Cretaceous on the Madura Shelf onlaps various Proterozoic basement rocks thereby preserving an undulating erosion surface that gradually deepens southwards. Onshore drilling shows crystalline basement descends from about 75 m AHD at the northern end of the shelf to 500 m below AHD near the coast, approximately 25 km west of Eyre 1 where a southerly directed broad valley appears to incise basement below the Cretaceous.

North of the Bight Basin, thin Cretaceous directly overlies the Permian sedimentary succession of the Canning Basin. Scarce thermal maturity data from the Permian indicate little erosion at this break, at least south of the Kidson Sub-basin, seemingly at odds with major sediment transportation from Antarctica to the North West Shelf via this route prior to breakup. Nevertheless, the base of the Cretaceous undulates between 350 and 450 m AHD across the Sherriff Shelf, and points to broad valleys traversing this region before breakup. However, there is no clear evidence of sediment being transported along paleochannels during the Mesozoic prior to their being filled with Cenozoic sediment, especially across the Eastern Goldfields.

Provenance — where did the sediment come from? continued

Other erosional remnants

Widely distributed inselbergs (isolated hills, ridges or small mountains) and bornhardts (domed hills or mountains) across the southern West Australian Craton are mostly granitic but also include deformed siliciclastic rocks. Various authors have postulated that these features are remnants of widespread Mesozoic weathering and erosion, perhaps interspersed between episodic periods of relatively shallow burial by transient sedimentary deposits, but with little direct evidence. Examples include the Barrens Range (~170 m above the surrounding area), Hyden Rock (~15 m), Mount Augustus (~700 m) and the Stirling Ranges (~850 m). Some show a stepped surface indicating successive phases of erosion, probably during the Cenozoic; the best such example is Mount Ragged, 150 km east-northeast of Esperance near the southwestern end of the Eucla Basin, with its peak over 400 m above the surrounding plain.

Reworked palynomorphs

Reworked palynomorphs can provide another measure of erosion. These are especially abundant in the Tithonian–Berriasian Barrow and Parmelia Groups of the Northern Carnarvon and Perth Basins, respectively, dominantly from the Permian (possibly derived from the Southern Carnarvon Basin for the former region) and Lower Triassic (from the Beagle Ridge). In the Browse Basin, the Jurassic – Lower Cretaceous notably contains the robust Carboniferous spore ***Spelaeotriletes ybertii***, probably derived from the basin margin or an adjoining basin. In general, palynomorphs are durable, so reworked material can be difficult to interpret unambiguously, especially if that material shows little sign of prior deep burial as is typical of sedimentary units on the margins of most basins in the State.

Bluff Knoll, Stirling Ranges, an inselberg formed by Paleoproterozoic metasedimentary rocks rising up to 850 m above the surrounding plain north of Albany (photo by Simon Johnston)

Resources

The Mesozoic history of Western Australia was relatively short compared to three billion years of pre-Gondwanan sedimentation, orogenesis, metamorphism and magmatism, and spanned 186 Ma along an interior rift and subsequent passive margin with minor igneous activity and relatively little deformation mostly by extensional events. Such a setting was not conducive to the generation of mineral deposits, in contrast to the diverse styles developed in strongly tectonized older terranes such as the State's Precambrian or much of the Phanerozoic in eastern Australia. Consequently, exploitation of Mesozoic sedimentary rocks in Western Australia is likely to continue to concentrate on the large offshore petroleum systems along the North West Shelf, especially within deltaic and fluvial-dominated floodplain facies. Onshore, the most significant resources in, or uses of, Mesozoic formations are stratabound HMS deposits (see ***Heavy mineral sands — ancient shorelines***, p. 46), groundwater (see ***Aquifers, p. 49***), geothermal energy (see ***Geothermal potential — deep heat***, p. 55) and greenhouse gas storage (see ***CO_2 geosequestration***, p. 45). Under the right conditions, depleted reservoirs may be suitable to store CO_2 or H_2, but it is also possible to sequester the former compound without a trap, such as within saline aquifers at depths exceeding 800 m.

Minerals

Sediment-hosted mineral deposits and occurrences — such as HMS (p. 46), coal (p. 50), uranium (p. 51), glauconite (greensands; p. 52), gemstones (p. 53), silver and sulphides (p. 60) — require specific depositional and basin settings to form; however, apart from HMS, most of these resources are either relatively minor or have yet to be exploited. By comparison, regolith processes, mostly during the Cenozoic, have concentrated or reworked underlying minerals or metals from Precambrian bedrock, especially across the West Australian Craton. Such processes possibly began in the Mesozoic, although there is little direct evidence that this was the case.

Hydrocarbons

After more than 100 years of exploration — albeit sporadic in the early years (see ***Hunting for hydrocarbons***, p. 48) — at least 350 significant accumulations have been discovered, mostly in Mesozoic reservoirs along the North West Shelf. The past decade has seen significant investments in field development and processing facilities for liquefied natural gas (LNG), with production (and recycling of CO_2 into the subsurface) likely to continue until at least 2050. Western Australia now has six LNG plants in operation or near completion, which, in conjunction with the LNG plants in eastern Australia, will make Australia the world's largest LNG producer. In 2021, exports totalled 80.9 million tonnes (~112 × 10^9 m^3). Offshore, the gas in Western Australian fields is contained within Mesozoic reservoirs, with available large reserves (Fig. 19) including the following.

North West Shelf Venture: Woodside's facilities in Karratha are supplied from 16 fields, including Goodwyn, Perseus and North Rankin (gas) and several small oilfields in the Dampier Sub-basin. The project, which commenced production in 1989, includes tie-ins to floating production storage and offloading (FPSO) facilities and now incorporates five LNG trains with an export capacity of 16.9 million tonnes per annum (MTPA). Gas discoveries farther north in the Browse Basin, at Brecknock, Calliance and Torosa, have the potential to extend the venture for at least another 40 years.

Gorgon: Chevron's facility on Barrow Island has three trains with a capacity of 15.6 MTPA for gas. Production is mostly from Triassic reservoirs in the Exmouth Plateau, Barrow Sub-basin and Rankin Platform (within the Dampier Sub-basin), with reserves estimated at over a trillion cubic metres. The project, which began shipping LNG in March 2016, has a predicted lifespan of over 40 years and encompasses the world's largest CO_2 injection project on Barrow Island (see ***CO_2 geosequestration***, p. 45).

Wheatstone: Chevron's project near the town of Onslow has two trains capable of processing 8.9 MTPA from Upper Triassic reservoirs in the giant Wheatstone and Iago fields on the Rankin Platform. It has been in production since October 2017.

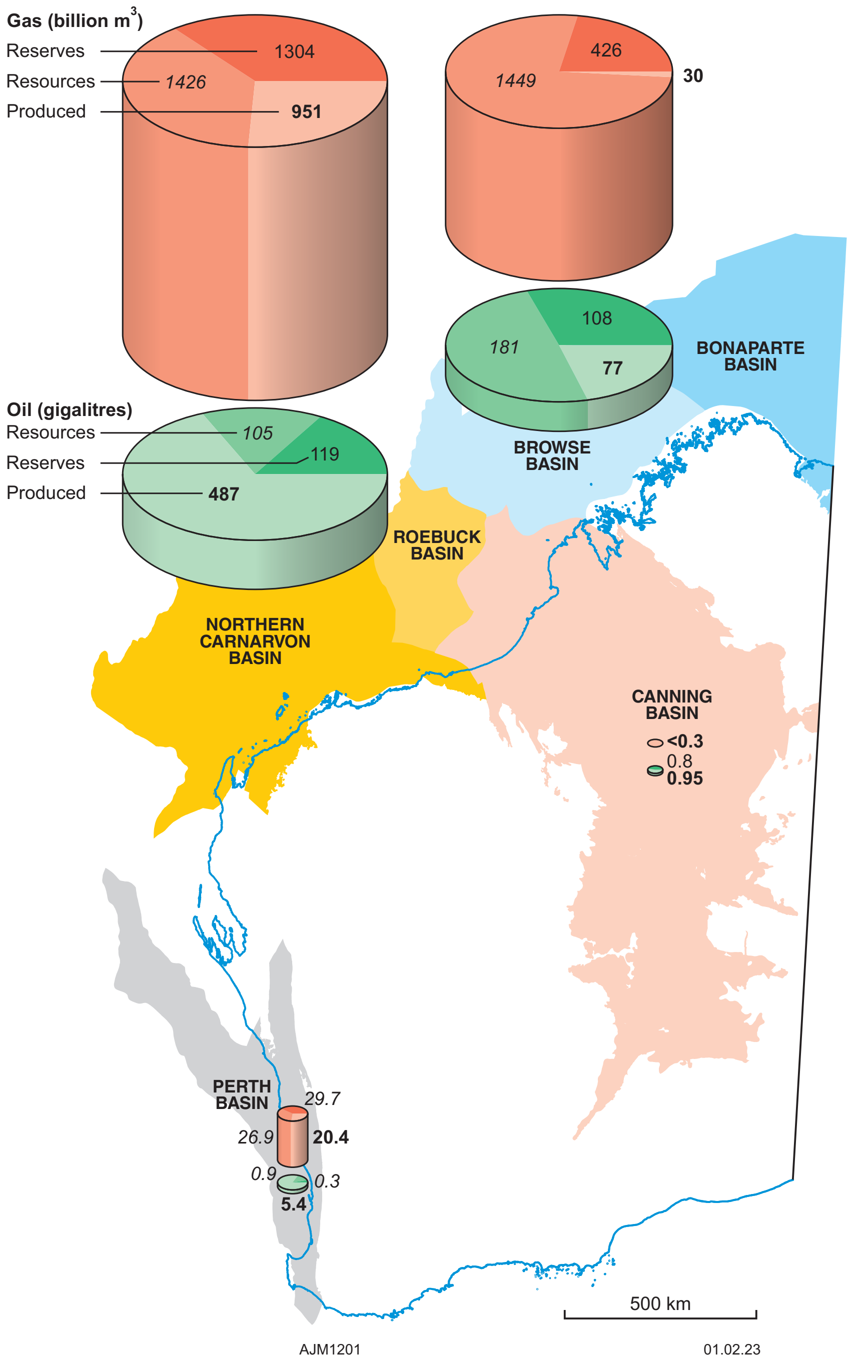


Figure 19. Distribution of hydrocarbons already produced with estimated P2 reserves by basin in Western Australia in 2019 (from Geoscience Australia and the Bureau of Resources and Energy Economics). Not included are preliminary reserves estimates from recent discoveries in the Roebuck Basin in the order of 40 GL and 50 Bm³

Ichthys: Inpex's Browse Basin project connects Jurassic and Lower Cretaceous reservoirs to an onshore processing facility near Darwin via an 890-km pipeline. The plant has a nominal capacity of 8.9 MTPA and is also expected to produce up to 16 000 kL/day of condensate for shipping from the FPSO moored near the gasfield. The first LNG cargo was dispatched in October 2018.

Prelude: Shell's floating liquefied natural gas (FLNG) vessel, 475 km north-northeast of Broome in the southwestern Browse Basin, has a capacity to produce 3.6 MTPA from Jurassic reservoirs within the Ichthys/Prelude gasfields. The first shipments of condensate and LNG were in June 2019.

Low-energy rift fill — organically rich hydrocarbon source rocks

The interplay between synrift and post-rift tectonics, depositional environment and paleoclimate controlled the timing and distribution of the marine, deltaic and lacustrine organically rich facies, which contain a suite of prolific source rocks along Australia's western and northwestern margins. The highest quality oil-prone facies were deposited during major marine transgressions into restricted parts of the basins. Although deltaic facies, especially in the Triassic (Mungaroo Formation) and Jurassic (Plover and Cattamarra formations), formed during regressive phases and generated prolific gas and condensate reserves from terrestrial source rocks in distributary and associated back-barrier lacustrine facies, the three main marine incursions that deposited good-quality source rocks were:

CO_2 geosequestration

Worldwide trends focused on reducing global-warming gas emissions have increased commercial and government interest in their capture and storage but, whereas other gases can contribute to global warming, typically only CO_2 is the focus of such projects. Previously, CO_2 from petroleum wells was reinjected to aid the recovery of combustible gas or was vented into the atmosphere. Two programs within Western Australia aim to reduce both primary and by-product commercial CO_2 emissions by storing this gas in saline Mesozoic reservoirs. The Gorgon project captures CO_2 from the Chevron-led gas project of the same name in the Northern Carnarvon Basin and injects it into the uppermost Jurassic below Barrow Island, whereas the South West Hub research project south of Perth has investigated potential storage of CO_2 within the Upper Triassic. In addition, depleted offshore gasfields can be attractive storage sites because their reservoir characteristics are well known. There may be competing plans to store hydrogen in such fields, although a robust top seal would be needed for this light molecule. Fields already in use to store combustible gas include Dongara (northern Perth Basin) and Tubridgi (Northern Carnarvon Basin). Various assessments of offshore CO_2 storage in the Bonaparte, Browse and Perth Basins indicate saline Jurassic and Cretaceous formations also may be suitable for this purpose.

Gorgon CO_2 injection project

Because gas in the Gorgon field averages 14% CO_2, it is injected after being liquefied via one of three wells drilled to over 2 km beneath Barrow Island into the Tithonian Dupuy Formation. Overall, the project will employ nine directional wells into the Dupuy Formation and six pressure-management wells. The latter comprise four water-extraction wells to reduce the pressure required for CO_2 injection and two to dispose of that water into a shallower formation. The project became operational in August 2019 with about 7 Mt of CO_2 injected by November 2022. Sequestration of about 120 Mt of carbon dioxide equivalent is planned over the estimated 40-year life of the project. Modelling suggests that the plume of greenhouse gas (chiefly CO_2) could migrate laterally by several kilometres from the injection sites during the injection phase but eventually will react with formation waters to form a carbonate cement, thereby inhibiting further migration. Monitoring and management will continue for 15 years after injection ceases, after which responsibility for the site and the captured CO_2 will pass to the Australian Government.

South West Hub

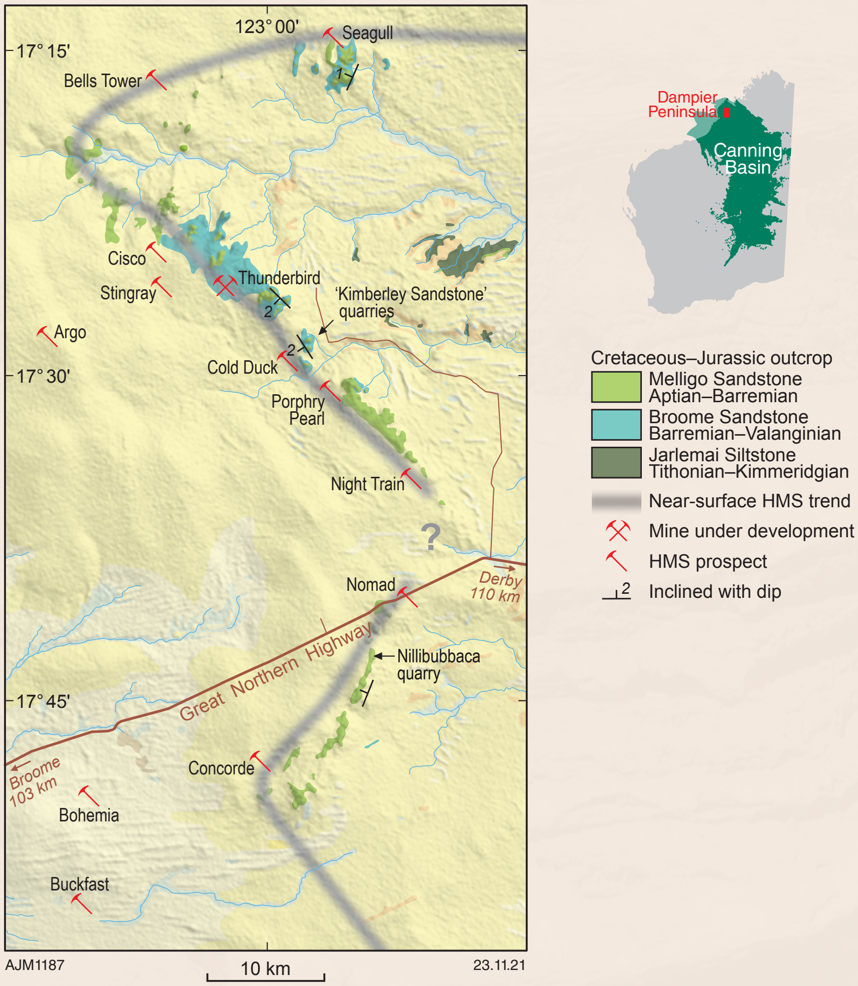
The South West Hub was a government-funded research project during 2011–18 investigating the storage potential of Triassic sandstone (Wonnerup Member of the Lesueur Sandstone) over the 'Harvey Ridge' in the shires of Harvey and Waroona, approximately 150 km south of Perth. Starting with a 2D seismic survey in 2011, a 3D survey and four wells followed, with reservoir characterisation and modelling of the Triassic succession completed in 2018. Storage combining underground injection into Triassic sandstone and chemical processes has yet to be tested with trial injections of CO_2, although modelling based on core and log analysis indicates the 1500 m-thick, brine-saturated sandstone could accommodate at least 800 000 tonnes of CO_2 per annum over 30 years without a structural trap and seal. About 45% of the injected CO_2 is envisaged to be immobilized by capillary forces (residual trapping) and 55% contained due to dissolution in formation water (solubility trapping). Even though government funding has ended, there is growing industry interest in this project.

Heavy mineral sands — ancient shorelines

The majority of heavy mineral sand (HMS) deposits in the State are in Cenozoic strandlines overlying the Perth Basin, but there are also economic Lower Cretaceous deposits within the southern Perth Basin and northern Canning Basin. The main Cretaceous deposits are Beenup, 12 km northeast of Augusta, and Sheffield Resources' Dampier project midway between Broome and Derby. HMS minerals are used in the manufacture of diverse products including paint pigment, paper, plastics, electronics, cosmetics, ceramics, alloys and pharmaceuticals.

Dampier

This project encompasses the Lower Cretaceous Broome Sandstone in the centre of the Dampier Peninsula and contains two major deposits: the larger Thunderbird (discovered in 2005) and smaller Night Train 20 km to the south. Drilling across the Thunderbird mineralized zone, which is 12–48 m thick, indicates a resource of about 3230 Mt, of which 6.9% is HMS (calculated using a 3% HM cut-off), including 18.5 Mt zircon, 5.9 Mt high-titanium leucoxene, 6.5 Mt leucoxene and 61.7 Mt ilmenite. The high-grade zones (calculated using a 7.5% HM cut-off) contain 1050 Mt with 12.2% HM, including 9.65 Mt zircon, 2.9 Mt high-titanium leucoxene, 2.7 Mt leucoxene and 34.3 Mt ilmenite. The deposit has a high proportion of zircon compared to many other deposits worldwide, thereby enhancing its value. Trial mining began in late 2020, with full-scale extraction planned in 2024. Additional prospects to the north and south extend at least 75 km along a sinuous Lower Cretaceous strandline affected by broad folds post-dating deposition. The source of the heavy minerals is uncertain, although the underlying Jurassic was probably part of the transportation pathway.



Distribution of Lower Cretaceous HMS deposits on the Dampier Peninsula, Canning Basin

Beenup

This deposit spans the Lower Cretaceous Leederville Formation (Warnbro Group) and Cenozoic sediments. Mining was limited to 1997–99 because a high percentage of clay and abrasive sand, along with greater consolidation compared to typical Cenozoic deposits, compromised maintenance of the plant. During 1997–2001, 418 620 t of ilmenite concentrate (containing 233 870 t ilmenite) and 3452 t of zircon concentrate (containing 2240 t zircon) was exported via Bunbury port. Also within the deposit are garnet, rutile, leucoxene, staurolite, monazite, xenotime and pyrite.

Other deposits

A series of HMS prospects along the eastern edge of the Proterozoic Leeuwin Complex, near the southern end of the Perth Basin, extend nearly 30 km north from Beenup to about 10 km southeast of Margaret River town. These prospects within the Lower Cretaceous Leederville Formation contain ilmenite, garnet, leucoxene, zircon, rutile and xenotime, but have low prospectivity because they typically are more lithified than Cenozoic deposits. Accumulations along Cenozoic paleo-shorelines traverse the Scott Coastal Plain and mostly directly overlie the Warnbro Group, suggesting the HMS content has been concentrated from these (and older) deposits. In the central part of the Scott Coastal Plain, the Governor Broome deposit contains a resource of 200 Mt at 4.2% heavy minerals (i.e. 8.4 Mt of contained HM), including ilmenite, leucoxene, rutile, zircon and garnet distributed almost evenly between the Warnbro Group and Cenozoic strandlines. Heavy minerals in the Pleistocene Jangardup South deposit, 27 km to the east, may have been further concentrated from the underlying Upper Jurassic Yarragadee Formation, which locally contains up to 2% HM.

Elsewhere, the economic potential for Mesozoic HMS deposits is uncertain. In the Coburn deposit south of Hamelin Pool, Shark Bay, deeper drillholes into the Cretaceous yielded >1% HM and rarely >4% HM. Concentrate production from this deposit began in late 2022. In the northern Perth Basin, heavy minerals in the Cooljarloo and Cataby deposits were transported to the foot of the Gingin Scarp via creeks draining Jurassic outcrops, before being further concentrated by Cenozoic nearshore processes. Possibly some of deposits with ilmenite, zircon, rutile and monazite near Eneabba and to the north are reworked from the lowermost Cretaceous Parmelia Group to the east, which contains ilmenite, zircon, rutile and leucoxene. Other deposits east of the Gingin Scarp, such as McCalls, appear derived from the underlying Cretaceous via nearshore processes.

- Early Triassic (post-rift Kockatea, Locker and Blina Shales, and Mount Goodwin Subgroup);
- Oxfordian (Late Jurassic) synrift, which includes the lower Flamingo, Frigate, Vulcan and Dingo Formations, Otorowiri Member and Sea Lion – Minke sequences;
- Early Cretaceous (post-rift Echuca Shoals and Forestier Formations, Muderong Shale and perhaps the Carnac Formation to South Perth Shale). The associated overlying deeper marine maximum-flood units, such as the Aptian–Albian Windalia Radiolarite and Jamieson Formation, are mostly not buried deeply enough to generate hydrocarbons.

The development of shale oil/gas in Western Australia is uncertain and there are no dedicated projects currently in production. A 2013 study by the US Energy Information Administration estimated that the Triassic Kockatea Shale in the Perth Basin holds almost 200×10^9 m^3 of recoverable shale gas and 80 GL of recoverable oil/condensate, although greatly exceeded by that for the Ordovician in the Canning Basin (over 6.65×10^{12} m^3 and 1.56 TL). Production from shale — typically brittle and buried deeply enough to generate, but not expel, hydrocarbons — requires hydraulic fracturing. Shale gas/oil mostly comes from 2000–4000 m, depths that are generally shallower than for tight sandstone reservoirs. Coal-bed methane (CBM) can be from depths of 300–1000 m or much deeper at 2000–4000 m and normally is only feasibly extracted onshore. In eastern Australia, CBM accounted for 40% of gas production by 2015 but in Western Australia the possibility of such developments from the Mesozoic is limited, apart from in the onshore northern Perth Basin. Elsewhere onshore, Mesozoic shale and coal seams are too shallow or thin to be prospective; similarly, such ventures offshore are typically not viable due to low yields and higher costs.

The resource future

Growing global environmental concerns calling for lower, or net-zero, carbon emissions will seemingly curb the demand for hydrocarbons and coal, and thereby eventually impact production from the North West Shelf. Although long-term CO_2 storage can mitigate such emissions (see ***CO_2 geosequestration***, p. 45), there is increasing pressure to reduce the world's dependency on fossil fuels, such as coal, oil and gas, through greater use of uranium and renewable forms of energy conceivably incorporating hydrogen. However, the worldwide disparity between energy produced from these sources and fossil fuels may prove awkward to bridge quickly. Factors that could inhibit a comprehensive shift to 'green' energy include population growth, emerging economies, the time required and necessity to build new infrastructure, concerns over the safety and cost of using uranium, conflicts between nations, and the inertia inherent in existing large projects given the significant investments they entail. Meeting the challenges of the first four of these factors will require a substantial increase in mining for battery metals (e.g. lithium, nickel, copper and cobalt), rare earth elements and construction materials, with commensurate environmental implications.

Although gas has been cited as facilitating the transition to a low-carbon future because its carbon emissions are lower than coal, at least during combustion, life-of-project estimates incorporating fugitive emissions are unclear how much, or even if, gas is better than coal. Nevertheless, the North West Shelf and some onshore projects, possibly including shale gas, are likely to continue supplying gas, LNG and condensate for many decades, although some practices, such as flaring, are likely to be subjected to greater scrutiny. In the long term, demand for hydrocarbons will continue — albeit reduced compared to present levels given increasing pressure to optimize energy consumption, waste management, land use and recycling — until viable alternative feedstocks are found, especially for the pharmaceutical, petrochemical and aviation industries.

Depleted gasfields, especially onshore (e.g. Tubridgi), may be suitable for temporary storage of hydrogen or gas from other fields. Whereas there is greater emphasis on exploiting low-CO_2 gasfields such as Scarborough in the Northern Carnarvon Basin, in which CO_2 constitutes ~0.1% of the gas, some Browse Basin fields will require long-term storage of their CO_2 content, which can be near 20% of the contained gas (e.g. the Barossa gasfield). There are already plans to utilize large offshore gasfields for such storage, once they are depleted, particularly Bayu–Undan in the northern Bonaparte Basin, which is projected to cease production in 2023.

Early history

The search for petroleum in Western Australia began at the start of the 20th century when oil and gas shows were reported in the south of the State near the Warren River and following dredging in Albany Harbour. News of these shows generated significant interest, but all wells drilled in the next two decades were either dry or with questionable shows. By the late 1920s, the outlook for oil exploration seemed so bleak that Frederick Clapp, an American consulting geologist, remarked: 'Seldom in my experience, has any more discouraging set of conditions been found. Expenditure in drilling for oil is useless and should be discouraged'. Widespread acceptance of his view effectively inhibited exploration until the 1940s when a minor revival led to several geological investigations across the State but no further drilling.

Rough Range — birth of an industry

Systematic onshore exploration programs initiated during the early 1950s focussed on mapping surface structures in the Mesozoic around Cape Range by AMPOL. The first well, Rough Range 1, drilled on the north-northeast-trending Rough Range anticline at the southern end of Exmouth Gulf by WAPET (West Australian Petroleum Pty Ltd) in 1953, encountered an 8.6 m gross oil column within the Lower Cretaceous Birdrong Sandstone. However, of the following 12 appraisal wells, only Rough Range 1A and 1B found oil. Although small and not commercially viable until the 1990s, the discovery renewed interest in exploration over the North West.

Modern exploration

Modern exploration commenced following the Rough Range discovery and included WAPET's mapping the northwards-plunging anticline on Barrow Island from 1954 to 1956, and its island drilling program, which continued into the 1960s. The first commercial oilfield in Western Australia was discovered in 1963 within Lower Cretaceous sandstone reservoirs on Barrow Island — production has declined since 1970 and the field is scheduled to be shut-in in 2025. Coincidentally, the discovery was in the same year that Woodside's application for leases farther offshore than WAPET's was approved. In 1968, the original North West Shelf Venture by Burmah Oil, Shell Development and Woodside made a small oil discovery in Legendre 1, which ensured continued exploration along the North West Shelf. Woodside made two major finds in 1971: Scott Reef 1 in the outer Browse Basin and North Rankin 1 in the Dampier Sub-basin. Subsequent discoveries in the latter sub-basin included dry gas in Angel 1 and the giant Goodwyn gas–condensate field in 1972. Production from the North Rankin gas and condensate field began in 1984, but the Scott Reef discovery remains undeveloped. Oil and gas exploration of a variety of plays within the Mesozoic of the North West Shelf has so far located over 350 economic or potentially economic accumulations, including giant gasfields and large oilfields already under production.

WAPET's Tortoise Island 1, Northern Carnarvon Basin, late 1966 (image 227395PD from the collections of the State Library of Western Australia, reproduced with the permission of Chevron Australia)

Although gasfields discovered along the North West Shelf in the late 1960s to early 1970s were substantial (Fig. 19), low gas prices and political pressure impeded their development until global oil prices rose rapidly during the late 1970s. Delays in the development of the giant Sunrise (found by Woodside in 1974 on the Sahul Platform) and Scarborough (found by Esso in 1979 on the Exmouth Plateau) gasfields have largely been due to water depth and distance from the coast. The former is now under Timor Leste's jurisdiction and Woodside has advanced plans to develop the latter. By comparison, the high CO_2 content of the giant Gorgon gasfield (1981) delayed its development until 2014 (see *CO_2 geosequestration*, p. 45). Other small oil discoveries in the uppermost Jurassic – lowermost Cretaceous (the Barrow delta) during the 1980s include Harriet, South Pepper and Chervil.

Geologist Don Stanley sampling oil from WAPET's Rough Range 1, Southern Carnarvon Basin, in November 1953 (Image BA2889 State Library of Western Australia, reproduced with the permission of the Library Board of Western Australia)

A window for development, using floating production storage and offloading facilities (FPSO), opened with the discovery in the 1980s of larger oilfields in Jurassic and Triassic sandstones at Jabiru and Challis by BHP in the Vulcan Sub-basin. In 1989, BHP found the major Griffin oilfield in the Cretaceous Barrow Group in the Dampier Sub-basin within 'inshore' or State waters, and the North West Shelf Venture discovered oil at Wanaea followed by Cossack, Hermes and Lambert, all in Jurassic high-permeability, deep-marine fan facies. Their proximity allowed connection of the latter four to the Cossack Pioneer FPSO.

Farther south in the Exmouth Sub-basin, BHP discovered a large gasfield (Macedon) and associated heavy oil (Pyrenees field) in the early 1990s. Economic oilfields at the northern end of the North West Shelf include those found by ventures led by Woodside at Laminaria (1994) and Corallina (1995), by Phillips at Bayu and by BHP at Undan (both 1995). Each of the Woodside fields originally contained approximately 16 GL of oil (100 MMB) and they were developed using the Northern Endeavour, a purpose-built FPSO. During the 2000s, more heavy oil was encountered in the Exmouth Sub-basin at Vincent, Enfield and Laverda, which were developed using geo-steering and production via multilateral wells feeding back to large FPSOs. Since then, some of the most significant oil discoveries have been in the Roebuck Basin, especially the Dorado field (2018). To date, over 3000 wells have been drilled into the Mesozoic in west Australia and adjacent waters, and over 350 significant hydrocarbon accumulations have been discovered. By the end of 2019, the North West Shelf had produced 987 Bm^3 of gas and 564 GL of liquids — remaining reserves (P2) total 1730 Bm^3 and 228 GL, respectively (Fig. 19).

Okes-Durrack 1 drilled in 1921–24 on a surface anticline in the Ord Basin, East Kimberley (File 639277 Mitchell Library, State Library of New South Wales)

Aquifers

Mesozoic siliciclastic units include groundwater aquifers within the Perth, Southern Carnarvon and Canning Basins, but the water they contain typically is considerably younger. The greatest use of groundwater is within the Perth Metropolitan area where estimates of renewable supplies of low-salinity water from the Perth Basin are the largest in the State. Although extraction of drinking and irrigation water from groundwater is increasing, desalination plants supply about 45% of Perth's water because decreasing annual rainfall has reduced recharge into aquifers as well as flow into dams in the South West, and per-capita water use in Perth is high compared to other Australian capital cities. Underground aquifers are finite resources and, with decreasing recharge and increasing demand, groundwater levels are falling across most of the South West. This has prompted the State to introduce a range of measures including, since 2017, recharging aquifers with treated wastewater.

Several sedimentary formations within the Perth Basin contain substantial groundwater resources at drillable depths, of which the most utilized are the Leederville and Yarragadee aquifers. The former, which equates to the Lower Cretaceous Leederville Formation, reaches a maximum thickness of 600 m within the Yanchep Syncline north of Perth and contains an estimated 120 GL of groundwater. By comparison, the underlying Yarragadee aquifer (composed of the Jurassic Yarragadee Formation and the Jurassic–Cretaceous Parmelia Group), which extends along virtually the entire length of the Perth Basin south of Dongara, has an average thickness of 2000 m and holds >450 GL of groundwater.

The Lower Cretaceous Birdrong Sandstone in the Southern Carnarvon Basin is an extensive artesian aquifer near the coast — mostly providing stock water — and is in hydrodynamic connection with several underlying lower Paleozoic sandstone aquifers. Because of concerns over the sustainability of these aquifers, a State-funded programme in the 1990s refurbished many of the artesian bores, some of which date back to the 1900s, to stem uncontrolled flow. In the Canning Basin, the principal Mesozoic aquifers are also near the coast and include the Lower Cretaceous Broome Sandstone and Jurassic Wallal Sandstone, exploited mainly for stock, agriculture, mining and the Broome water supply. Extensions of the East Pilbara Water Supply Scheme to local towns and industries, as well as planned Cu-Au-Ag mines in the Proterozoic below the Anketell Shelf, could be from the Wallal aquifer.

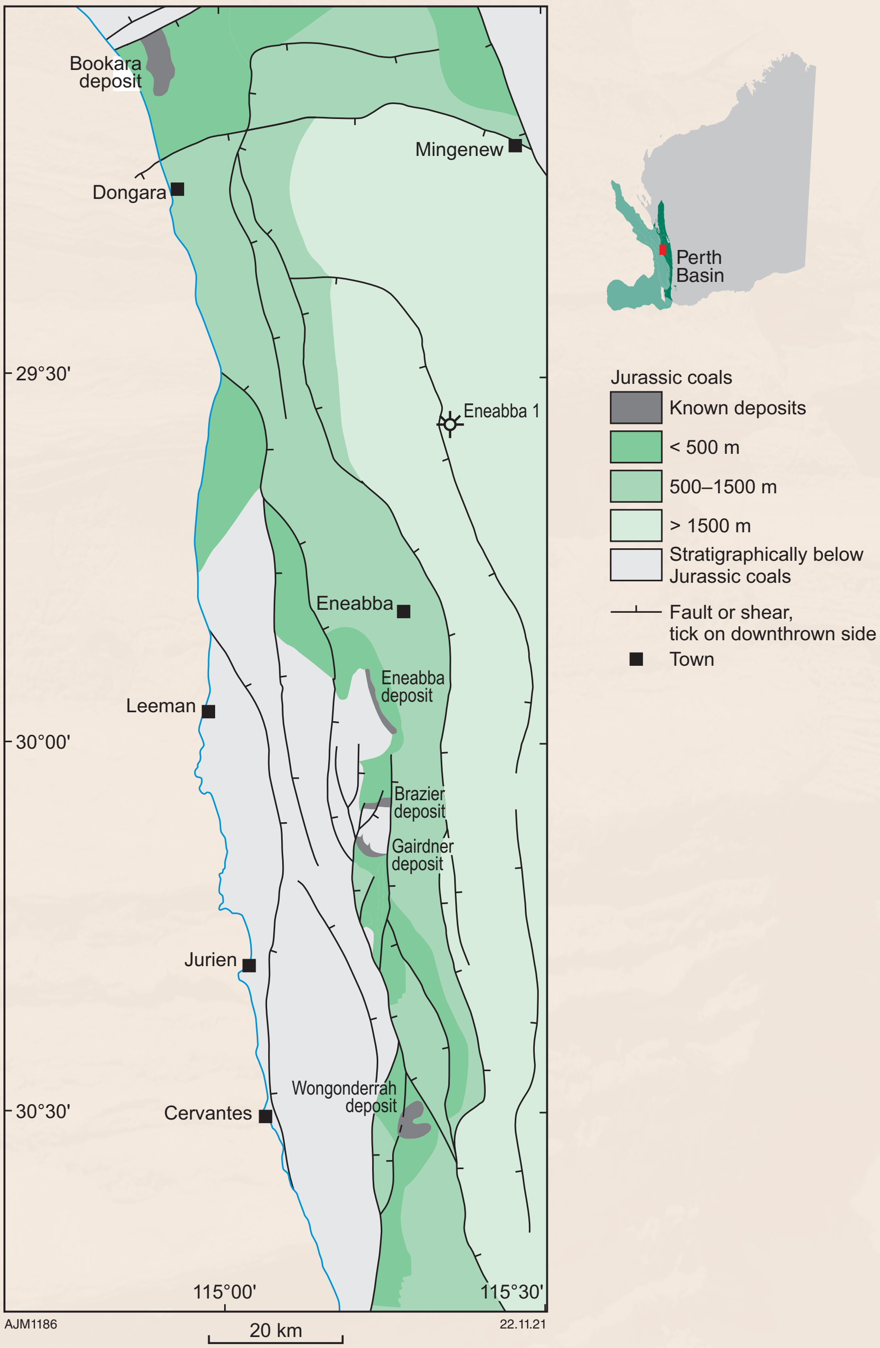
Coal — buried ancient swamps

The first finds of supposed Mesozoic coal, during the late 1840s along the Fitzgerald River, were quickly shown to be worthless carbonaceous Cenozoic substances with some bitumen. Although possible Jurassic coal was found in the late 1880s at Fly Brook, a tributary of the Donnelly River, mapping in the 1960s showed that the seam is thin and oxidized, so its age and quality remain uncertain. To date, the most substantial Mesozoic coal deposits are in the northern Perth Basin where all defined resources lie within the Lower Jurassic Cattamarra Coal Measures along the Cadda Terrace or Greenough Shelf. All other commercial (or potentially commercial) coals in the State are Permian. Other coals within the Cretaceous and Jurassic in the southern Perth Basin, or near the coast within the Canning Basin, are either too thin, too deep or of too low quality to warrant additional investigation. Similarly, the depth, and distance from the coast, of Middle Triassic to Jurassic seams in offshore petroleum exploration wells renders them uneconomic, although some may have generated gas.

All Jurassic coals in the State are sub-bituminous

In the northern Perth Basin, coal was intersected in WAPET exploration well Eneabba 1 in 1961 (and Bookara 3 in 1967), with the first find encouraging the company to investigate Jurassic outcrops in the Hill River area. However, by late 1963, poor coal quality and structural complexity dissuaded further exploration. It was not until the 1970s to early 1980s that shallow coal below the Cenozoic heavy mineral sand deposits near Eneabba prompted a reinvestigation of the region. Exploration led by Conzinc Riotinto of Australia (CRA), between Gairdner Range and Cowalla Peak within the Cadda Terrace, outlined in excess of 500 Mt of coal over five adjacent deposits, of which about 90 Mt was judged to be accessible by open-cut mining. The maximum cumulative coal thickness is 16 m, with 5–11 m in the principal seam. The seams formed from telmatic peat deposited in forested swamps across a brackish upper–lower delta plain with minor marine influence. Coal rank throughout the main deposits, in the Gairdner Range – Cowalla Peak, Eneabba and Bookara areas, is largely sub-bituminous, i.e. suitable for thermal electricity generation. The coals are vitrinite- and inertinite-rich and generally low in liptinite. Vitrinite reflectance ranges from 0.3% at Bookara and Eneabba to 0.5% in Gairdner Range. About half of the defined 'in situ resource' is now within Lesueur National Park, which was gazetted in 1992 shortly before CRA relinquished its tenements over the area.

The most recent evaluation of the Eneabba deposit (renamed 'Central West Coal Project' by Aviva Corporation) cites total reserves of 89.7 Mt at depths of up to 130 m. The project stalled due to a perceived lack of additional demand across the South West electricity grid and objections on environmental grounds; the company's option for the coal rights expired in late 2009. Exploration near Bookara on the Greenough Shelf began in the early 1980s with limited success. A subsequent evaluation for coal seam gas by Eneabba Gas Limited indicated low rank and low to non-existent gas content. A later re-evaluation for underground coal gasification delineated a resource of 205 Mt — the project has been abandoned and the tenements surrendered.

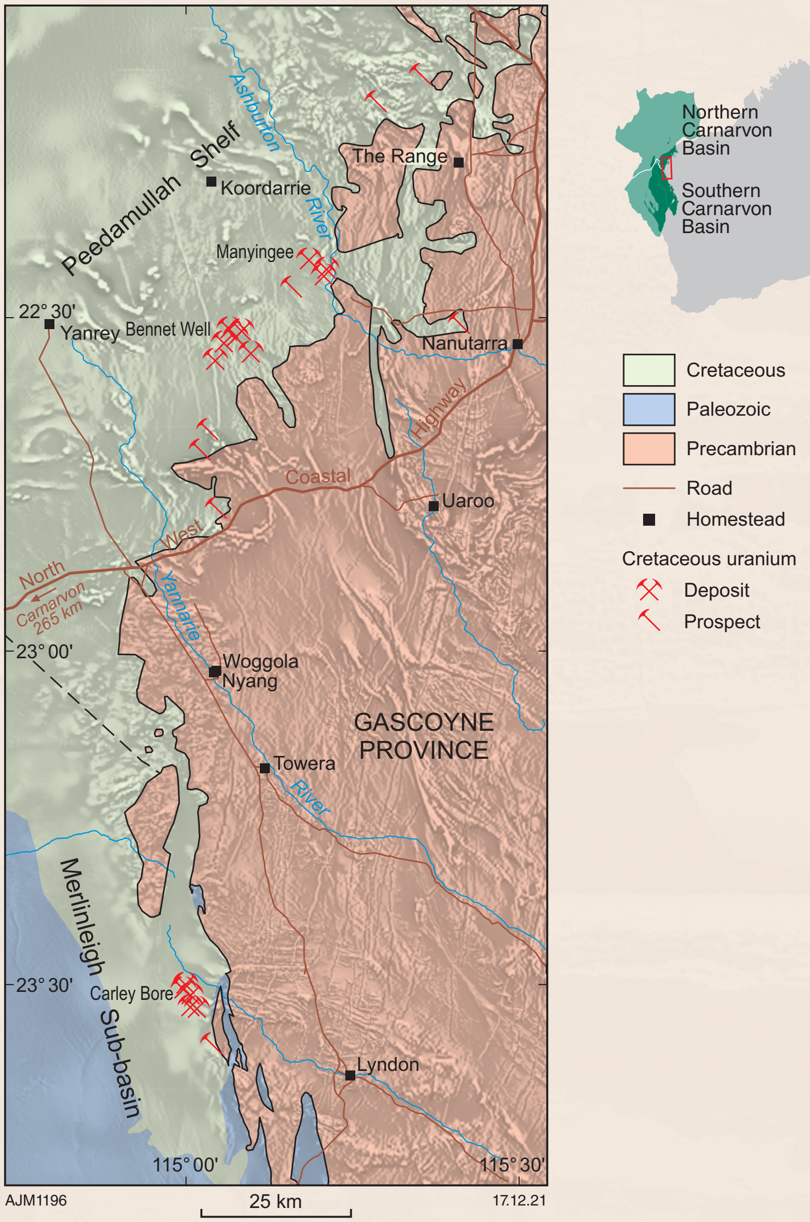


Distribution of Lower Jurassic coal deposits, northern Perth Basin

Uranium — a glowing future

Western Australia is well endowed with uranium, the feedstock for nuclear power that can generate a reliable electricity baseload with carbon emissions comparable to solar and hydro-power over the life of such projects. The State has total resources and reserves of 258 000 tonnes of U_3O_8 contained in 475 Mt of ore. The majority of these deposits are in Cenozoic paleochannels or surficial calcrete, with about one-third within Carboniferous to Cenozoic sandstone units. Emplacement of such ores, however, is considerably younger than the host strata.

All uranium prospects within Mesozoic rocks in the State are roll-front deposits within Lower Cretaceous paleochannels draining basement rocks along the eastern margins of the Peedamullah Shelf and the northern Merlinleigh Sub-basin. The ore lies within the Birdrong Sandstone, typically 50–150 m below ground level in zones 40–70 m thick, and locally overlies up to 40 m of conglomerate and weathered granite. Three prospects have JORC Code 2012 (Australasian Joint Ore Reserves Committee) resources: Bennet Well, Manyingee and Carley Bore (Table 1). These deposits are suitable for in situ leaching/recovery using oxidising fluids to extract the uranium as a solution thereby minimizing the environmental impact otherwise associated with shallow mining methods. However, those deposits are not as large as those that have (or had) environmental approval for mining: Mulga Rock, Wiluna and Yeelirrie in Cenozoic sediment over the Yilgarn Craton, and the unconformity-hosted Proterozoic Kintyre deposit in the East Pilbara. Of these, only Mulga Rock is currently under consideration for development.



Distribution of uranium deposits in the Lower Cretaceous Birdrong Sandstone along the eastern margin of the Merlinleigh Sub-basin and Peedamullah Shelf, Carnarvon Basin; geology superimposed on first vertical derivative magnetic image

Table 1. Uranium resources from Cretaceous formations next to the West Australian Craton

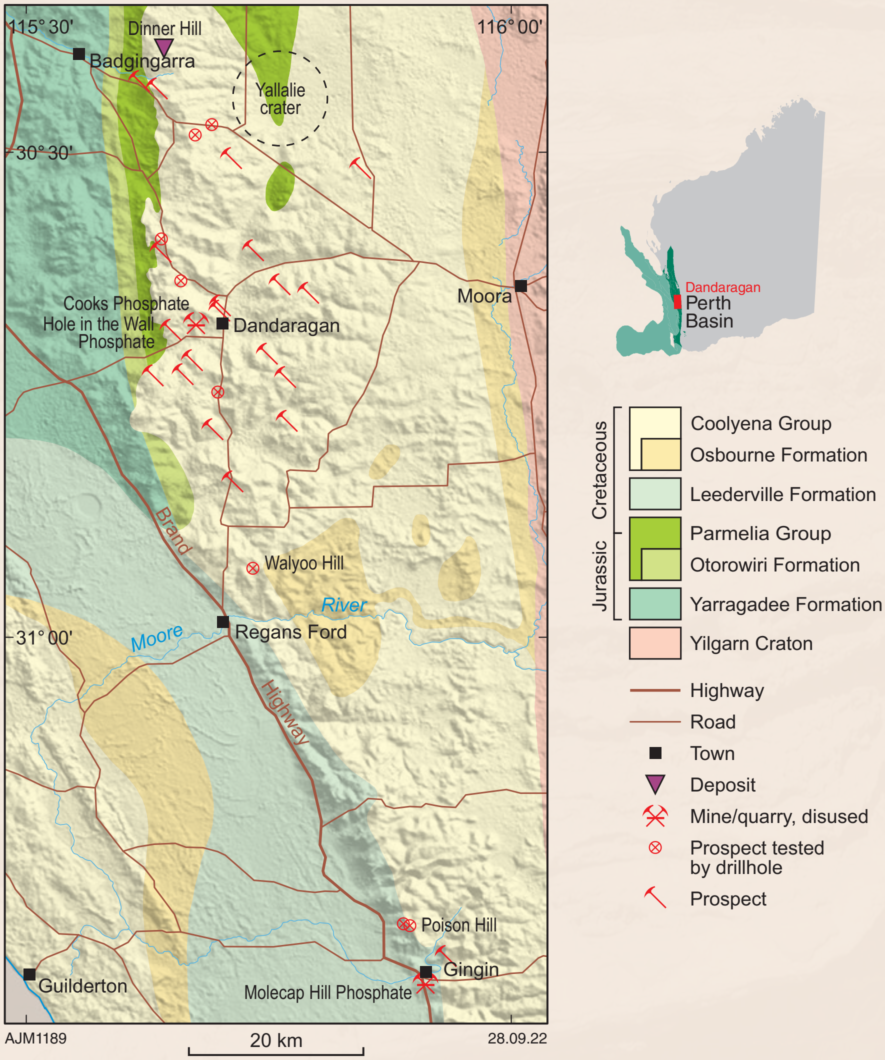
Deposit	*JORC Code 2012 indicated plus inferred Resource (Mt)*	*Average grade (ppm)*	*Cut-off grade (ppm)*	*Contained U_3O_8 (t)*	*Company*
Manyingee	13.78	850	250	11 740	Paladin Energy Ltd
Bennet Well	38.9	360	150	13 990	Cauldren Energy Ltd
Carley Bore	5.4	280	150	4 808	Paladin Energy Ltd

Greensands — fertilizer and fossils

Greensands contain glauconite, a green iron-potassium phyllosilicate (mica group) clay mineral that typically forms authigenically under low-oxygen marine conditions where the rate of deposition is slow with locally elevated concentrations of phosphate. Most greensands in the State are Cretaceous in age and lie within the Perth, Southern and Northern Carnarvon, Bight and Canning Basins, although only those in the Perth Basin have been evaluated for commercial development. Between 1932 and 1962, greensand from the small quarry at Molecap Hill, 1.2 km south of Gingin, was used as a water-softening agent. Phosphate nodules from near Dandaragan were analysed in the 1940s but little further work was done until the 1980s. Renewed interest in potash (a source of potassium) and phosphorous salts — vital components of fertilizers and cathodes in lithium iron phosphate ($LiFePO_4$) batteries — has seen the identification of many prospects at depths of up to 40 m from Gingin to east of Badgingarra. Of these, only Dinner Hill has resource calculations (250 Mt P_2O_5, average grade 2.9% with a cut-off of 1.5%; 195 Mt K_2O, average grade 3.8%, with a cut-off of 1%). Factors impeding development include low grades, access issues and complex extraction involving crushing, magnetic separation, and several phases of acid leaching and salt precipitation. By comparison, extraction from deposits in Cenozoic paleochannels and lakes over Precambrian terranes (e.g. Beyondie Lakes, Lake Mackay and Lake Way) is simpler as it involves just solution mining and precipitation, and the Mardie Project on the northeastern side of Exmouth Gulf requires only solar evaporation of seawater in the supratidal zone. Phosphate sources in the Mesozoic also include Cretaceous and Jurassic nodules in the Southern Carnarvon and Canning Basins, respectively, but these are much smaller in comparison.

Molecap Hill quarry, Gingin, showing contact between the greensand and overlying Gingin Chalk in 1987 (from the Australian Heritage Photographic Library, taken by TE Perrigo)

Although deposited in Late Cretaceous shallow seas, macrofossils are rare in greensands within the Perth Basin. Nevertheless, the Molecap Greensand contains bivalves, belemnites, fish (including shark teeth) and isolated bones and bony fragments from marine reptiles such as ichthyosaurs, plesiosaurs and mosasaurs. In comparison, the Poison Hill Greensand seemingly has no macrofossils, although invertebrate trace fossils are present. Mosasaur bones from the Molecap Greensand cannot be identified to genus or species level, but appear related to *Platecarpus* from the Lower Cretaceous of Kansas in the United States and would have been from individuals up to 2.6 m long (see ***Macrofaunas***, p. 14; and *Yallalie* in ***Impact structures***, p. 58). In the Canning Basin, the Lower Triassic Blina Shale contains thin beds of phosphatic lingulids as well as vertebrate remains (see ***Macrofaunas***, p. 14).



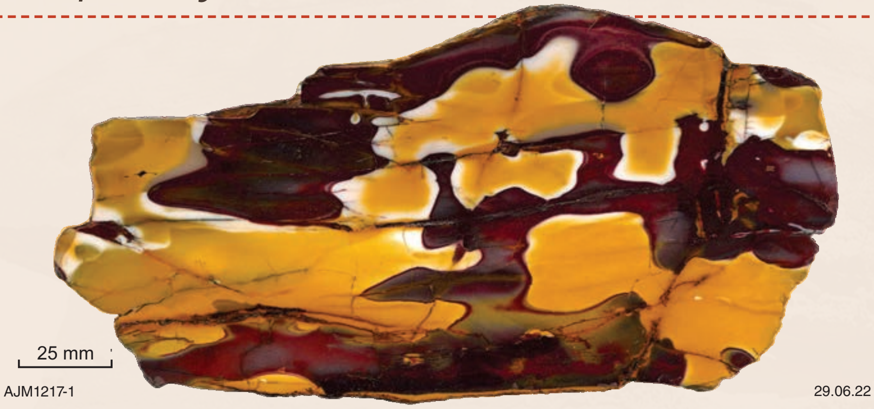
Cretaceous greensand prospects between Badgingarra and Gingin,, northern Perth Basin

Gemstones and lapidary materials

Nearly all of the State's Mesozoic gemstones are silicified semiprecious deposits within the Southern Carnarvon Basin. The exception is the Wandagee 'diamond province', although so far that area has yielded just three microdiamonds.

Mookaite

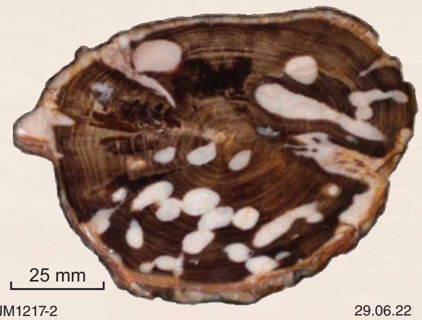
'Mookaite' is a commercial name for varicoloured porcellanite from the Lower Cretaceous Windalia Radiolarite in the Southern Carnarvon Basin. The name is from the former Mooka Station on the southwestern side of Kennedy Range where nearly all unit outcrops are. It is a popular lapidary material with desirable qualities including being very fine grained, with a wide variety of colours and attractive, mottled patterns; a general lack of directional weakness; and adequate hardness. Although the radiolarite is regionally extensive, porcellanite (which may be opalized) within this unit is typically present near fault zones, which facilitated surface and near-surface secondary silicification. Mottled or blotchy iron staining is from the later influence of meteoric waters.



Polished mookaite slab from Mooka Creek, southwestern Kennedy Range, Lower Cretaceous Windalia Radiolarite, Southern Carnarvon Basin

Fossil wood

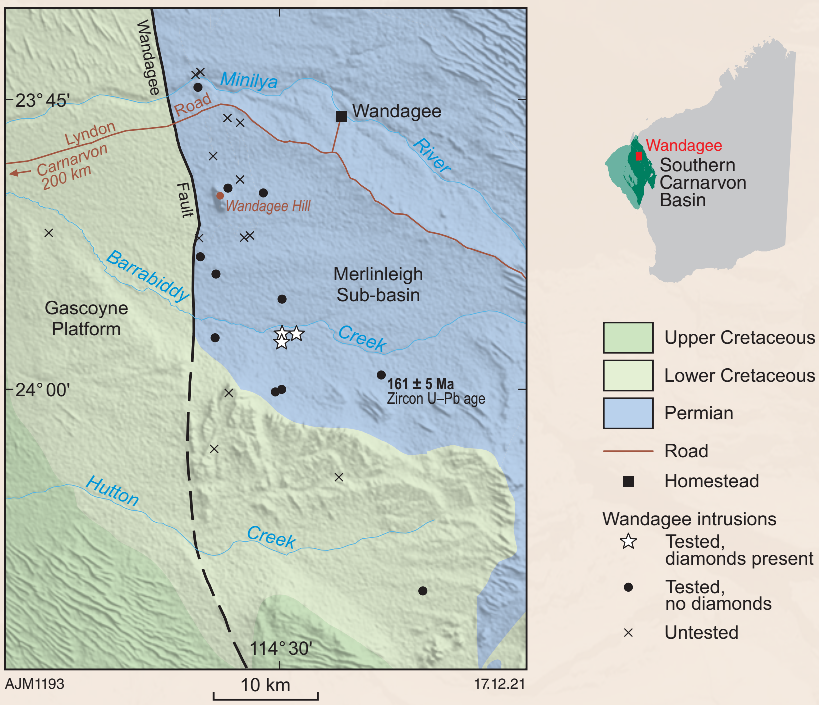
Jurassic and Cretaceous petrified woods in Western Australia show prominent growth rings and anatomical features of evergreen podocarpacean and araucarian conifers (see ***Flora — greening Western Australia***, p. 16). Several sites in the Southern Carnarvon Basin yield lapidary-grade specimens from rocks of these ages, of which the majority are from extensive exposures of the Lower Cretaceous Windalia Radiolarite along the western flanks of Kennedy Range. Many of these contain 'peanut wood', formed where borings by bivalves similar to shipworms of the families Teredinidae or Pholadidae were subsequently infilled by now-white, radiolarian-rich mud. High-grade lapidary material formed following burial when chalcedonic and opaline silica replaced wood and burrows.



'Peanut wood', from the western side of Kennedy Range (courtesy Glenn Archer, Australian Outback Mining Pty Ltd)

Wandagee diamonds

Small kimberlite-like Jurassic intrusions in the Wandagee 'diamond province', approximately 125 km northeast of Carnarvon in the Southern Carnarvon Basin, have yielded just three microscopic diamonds — no commercial-sized diamonds were recovered from the bulk samples. The diatremes intrude the Permian but not the overlying Lower Cretaceous Winning Group — five of the intrusions lie below up to 160 m of Cretaceous strata and xenocrystalline zircons from one of the intrusions have yielded a U–Pb radiometric date of 161 ± 5 Ma. All but one of the 25 diatremes identified are restricted to a 15 × 50 km belt in the Merlinleigh Sub-basin immediately east of the Wandagee Ridge. Fifteen of the intrusions identified are diatremes filled with pyroclastic deposits without magmatic phases, three are alkali picrite dykes and seven are sills.



Wandagee 'diamond province', Southern Carnarvon Basin, showing intrusions initially located from aeromagnetic imagery

Other

Agates and chalcedony collected from Bunbury during land reclamation and dredging of the harbour in the 1970s were attributed to the Lower Cretaceous Bunbury Basalt. Evidence for such an origin is uncertain as the only place where these minerals are possibly associated with the basalt is overburden in a disused part of the Gelorup quarry south of Bunbury (see ***Construction materials — society's building blocks***, p. 54).

Construction materials — society's building blocks

The use of basic raw materials for construction, and to a lesser extent industrial processes, from Mesozoic sources is relatively minor compared to those from Cenozoic deposits and Precambrian rocks in the State; however, the division between Mesozoic and Cenozoic deposits can be difficult to pick, especially if the latter are derived from, or sitting directly on, the former. This is apparently the case for some semiplastic clay deposits, overlying the Lower Cretaceous Leederville and Osborne Formations near Perth, used to manufacture bricks, vitrified pipes and roofing tiles, whereas east of Muchea the Osborne Formation is excavated directly for this purpose. The remoteness of the refractory clay in the Upper Jurassic Jarlemai Siltstone in the Canning Basin, near Dampier Downs homestead, renders it sub-economic. Various clay deposits within lateritic profiles across the Yilgarn Craton possibly first developed in the Cretaceous (see ***Duricrusts***, p. 33). As with heavy mineral sands, sand resources principally come from Cenozoic deposits on the Swan Coastal Plain, derived in the majority of cases from Jurassic sources. Nevertheless, there are a few areas where such sand may be excavated directly from the Jurassic, such as southeast of Geraldton. In the Southern Carnarvon Basin, the Cretaceous Windalia Radiolarite contains minor high-grade silica and cristobalite–tridymite resources, with the latter presumably generated by late hydrothermal activity along faults.

White Peak Quarry, 1926, in Lower Jurassic sandstone 18 km north of Geraldton (photo by A. C. Burns)

Quarries exploiting the Lower Cretaceous Bunbury Basalt near Gelorup, about 8 km south of Bunbury, are mostly for road aggregate. To the south-southwest, numerous small quarries in the eponymous sandstone surrounding Donnybrook have supplied dimension stone for many buildings in Perth. Examples include Old Parliament House (1902–04), the AMP building (1911–12), the General Post Office (1914–23), Winthrop Hall at The University of Western Australia (1929–32) and the renovation of St Mary's Cathedral (2006–09). However, the Cretaceous age assigned to the Donnybrook Sandstone is poorly constrained. Other examples of Mesozoic dimension stone include the Lower Cretaceous Melligo Sandstone, which is actively quarried on the Dampier Peninsula near the Cold Duck heavy mineral sand prospect 33 km north of the Great Northern Highway (see ***Heavy mineral sands — ancient shorelines***, p. 46). Blocks from that location are marketed as 'Kimberley Sandstone' and used for paving and wall cladding and have been used extensively in Perth's Elizabeth Quay and, along with Donnybrook Sandstone, in central Melbourne's Federation Square. Also quarried from the Melligo Sandstone just south of the highway is the silicified 'Nillibubbacca Quartzite', some of which has been used for sculptures but is mostly crushed for road use and concrete. Near Geraldton, now-abandoned small quarries within the Lower Jurassic Greenough Sandstone provided stone for the city's historic Saint John's Uniting Church (1894) and Saint Francis Xavier Cathedral (1916–38).

Cladding of Lower Cretaceous Melligo Sandstone from the Dampier Peninsula, Canning Basin, at Elizabeth Quay in Perth

Channel cutting into deformed floodplain facies of the Upper Jurassic Yarragadee Formation, Irwin River, 12 km west-northwest of Mingenew, northern Perth Basin

Geothermal potential — deep heat

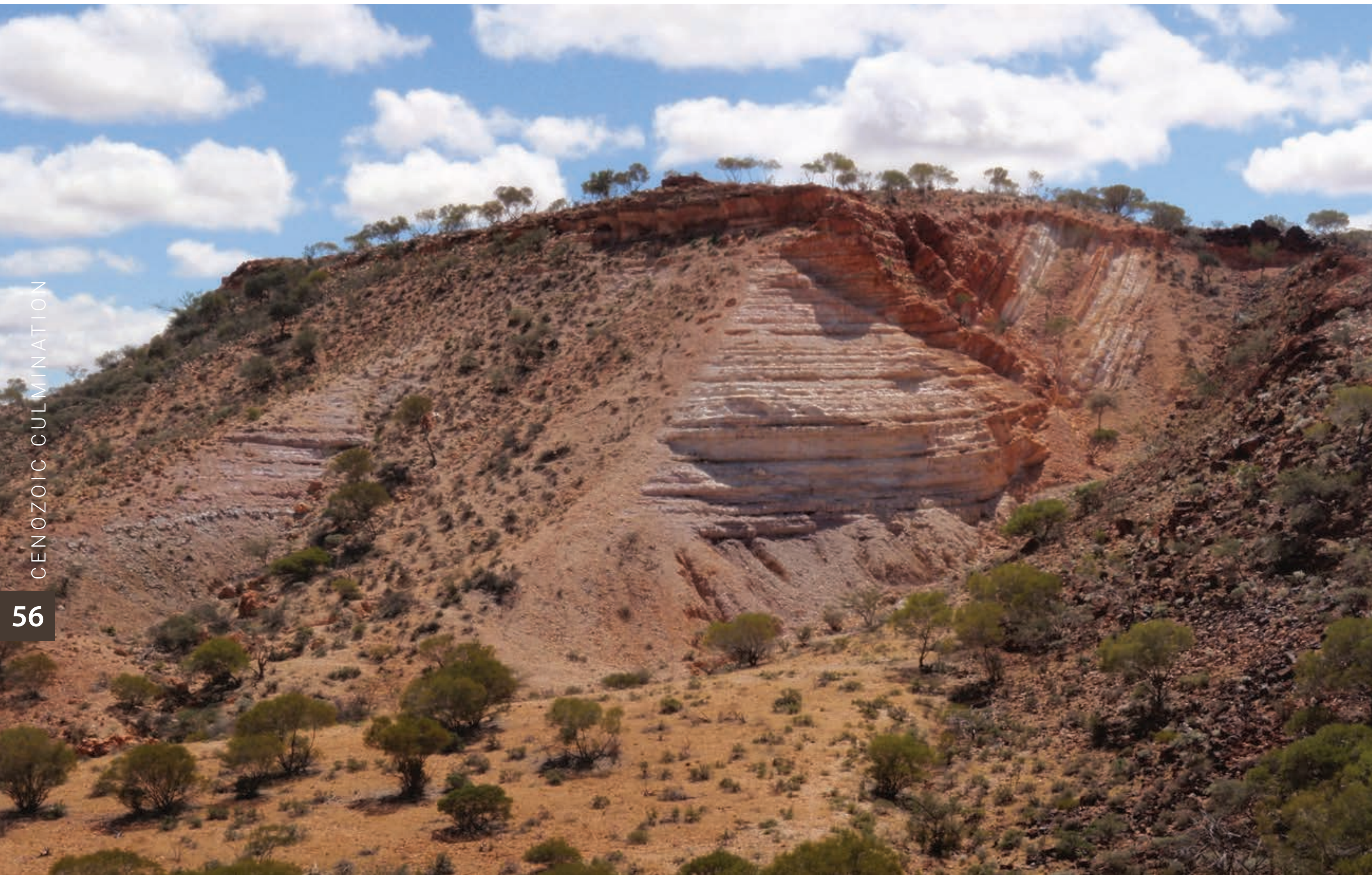
Geothermal resources in Western Australian basins are used for heating and cooling, desalination and dehumidification applications. In the Perth metropolitan area, only low-enthalpy geothermal applications are economically feasible at present; these exploit relatively shallow aquifers that have moderate to high permeability and excellent water quality within the Upper Jurassic – lowermost Cretaceous Parmelia Group. Historical geothermal direct-use heating, since early in the twentieth century, included the reptile enclosure in the South Perth Zoological Gardens, the Claremont laundry, for drying wool in Jandakot and at the Crawley baths. Modern direct-use heating typically involves extraction of groundwater, circulating it through heat exchangers, then re-injection of heat-depleted water into a shallower aquifer to maintain a neutral water balance. Present examples include heating for the swimming pools at Challenge Stadium and several aquatic centres utilizing bores that are up to 1000 m deep, and cooling buildings from shallow aquifers. These aquifers also may be used to dissipate heat, as is the case for the Pawsey Supercomputer Centre in Kensington.

Data from onshore petroleum wells in the Canning, Northern Carnarvon and Perth Basins show an average temperature gradient to 3 km of 20 to 36.5 °C/km. Whereas temperatures of 110 to 130 °C are more than sufficient to generate electricity with current technology, this depends on the economics of deep drilling and being able to extract sufficient hot water from a relatively thick reservoir — which requires one with adequate porosity and permeability extending over an area that can support widely spaced wells. If feasible, geothermal power stations in the State are likely to rely on deep reservoir facies or fractured Precambrian rock. The northern Perth Basin is one of the most prospective regions for geothermal power generation in the State but from Permian rather than Mesozoic facies.

Cenozoic culmination/postscript

Near the end of the Cretaceous, sedimentation changed dramatically as prograding carbonate platform successions began to surround the continent, with the final separation of Antarctica from Australia eventually allowing unfettered circum-continental oceanic circulation at ~40 Ma in the Eocene. Burial beneath several kilometres of carbonate across the North West Shelf increased the thermal maturity of the underlying Mesozoic, and was instrumental in inducing hydrocarbon generation and migration into numerous traps, which include giant gasfields and large oilfields. By comparison, marine incursions onshore were episodic, thereby allowing Cenozoic supergene, regolith, nearshore or lake processes to concentrate, precipitate or enrich minerals from Precambrian bedrock or Paleozoic strata. Examples of deposits formed by these processes include iron ore, gold, bauxite, nickel, heavy minerals, rare earth elements, potash, manganese, cobalt, lithium and uranium. Extensive onshore Cenozoic surficial deposits are generally thin, not deformed or related to tectonic activity and have not been deeply buried — accordingly they should not be considered part of sedimentary basins. The exceptions are folded Paleocene–Miocene carbonates within the Northern and Southern Carnarvon Basins, Quaternary sediment in sunklands, especially between Miocene anticlines across the Southern Carnarvon Basin, and Eocene–Pliocene carbonate platform facies of the Eucla Basin.

Lower Cretaceous Winning Group faulted against Permian strata on Middalya Station, northern Kennedy Range, Merlinleigh Sub-basin, Southern Carnarvon Basin



South West gold — abandoned mines

Most of the gold discovered near the South West town of Donnybrook by Richard Hunter in 1897 was mined during 1898–1903 when about 34.5 kg (1110 troy ounces) was extracted from approximately 1700 tonnes of ore. By comparison, total gold production reported for the State in 1903 was 61 tonnes (not surpassed until 1987 and peaking at 238 tonnes in 1997). Several of the mines near Donnybrook were worked in the 1930s and 1940s when an additional 3.2 kg (102 troy ounces) were recovered. The majority of the workings in the area are now infilled or obscured by agricultural activities, but some require remediation due to safety concerns. Panning near the old workings (with the permission of landowners and tenement holders) has yielded small amounts of gold dust, but nuggets are rare.

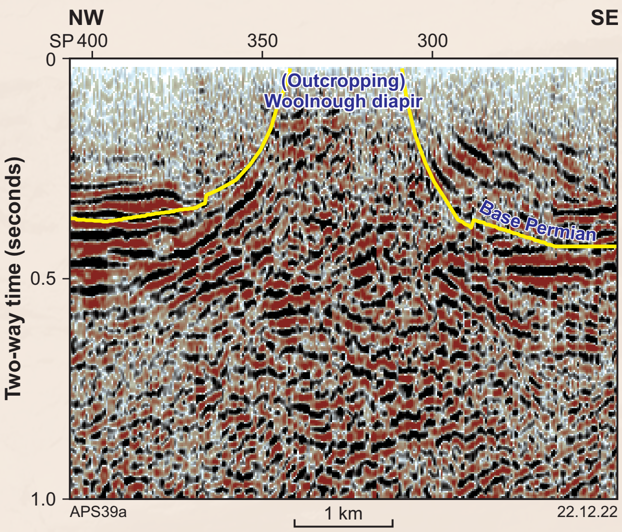
The main zone of mineralization and early workings follows a 3 km north-northwesterly trend extending from 2.6 km south to 5.4 km south-southwest of the town. In the three westernmost mines (Queen of the South, Empress Helena, Arc of Gold) between Precambrian outcrop to the east and the Darling Fault to the west, mineralization extended into sandstone, according to 1900–1940 reports, whereas in the remainder the gold is hosted entirely in Archean gneiss and amphibolite. Although 1980s exploration drilling in the immediate area failed to find gold, the core yielded both Cretaceous and Permian palynomorphs; however, the age of most sandstone outcrops remains ambiguous. Of the exposures near Donnybrook, only those about 2 km south-southwest of the town (next to Goodwood Road) are indisputably Cretaceous. It is unclear if this is the same unit quarried or mapped as Donnybrook Sandstone; similarly, it is uncertain if remobilization of gold via epithermal fluids from the Archean is temporally related to emplacement of the Bunbury Basalt (see ***Late Jurassic – Early Cretaceous breakup and separation,*** p. 31) even though both appear associated with the Darling Fault in some manner.

Gold-encrusted grain from Donnybrook (photo by Rod Martin)

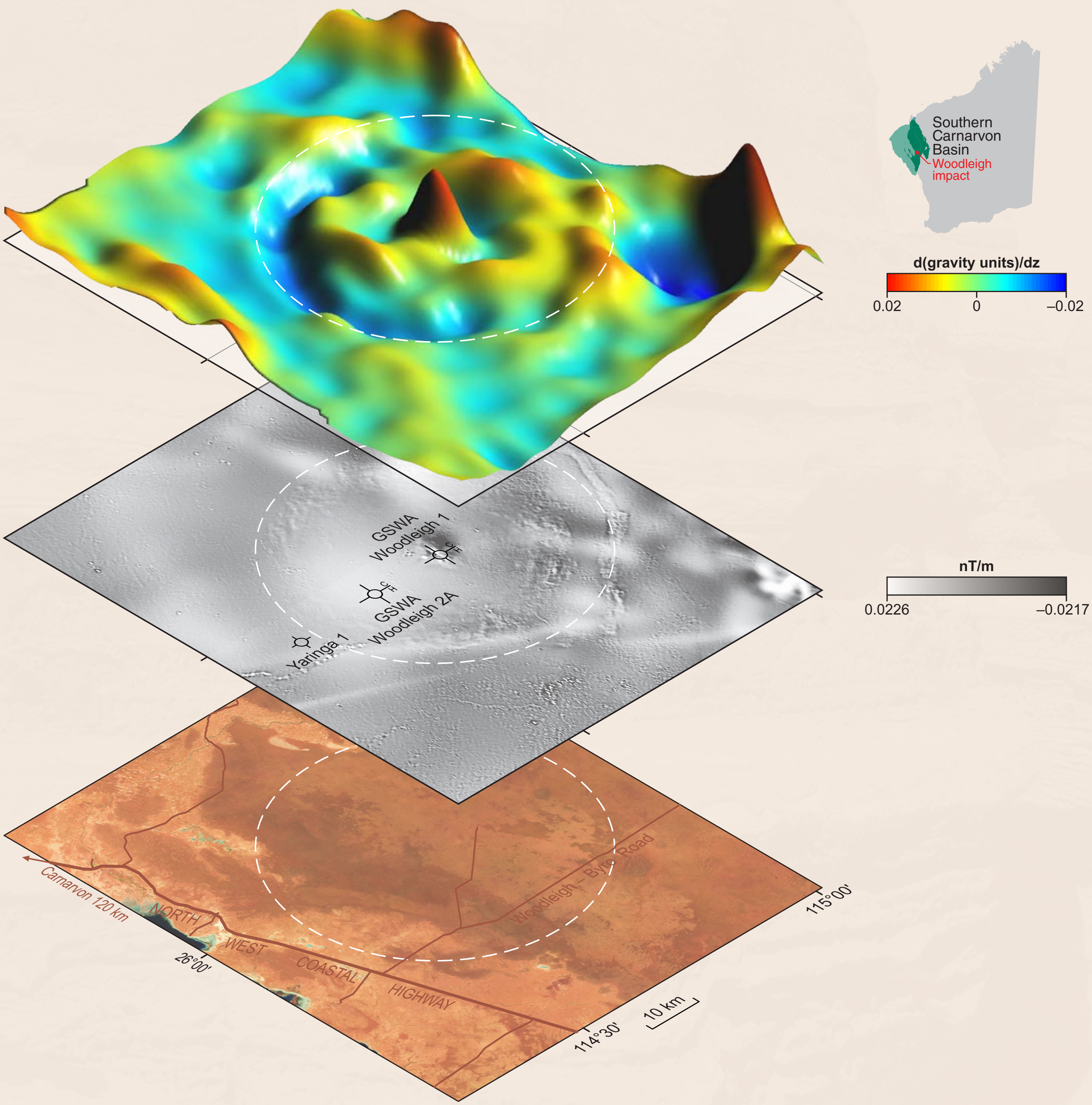
Salt structures — Mesozoic mobilization

Although there are no significant salt deposits of Mesozoic age, salt accumulations, originating from the Ordovician–?Devonian in the Bonaparte and northern–central Canning Basins or the Neoproterozoic Officer Basin below the southern Canning Basin, appear to have moved during the Mesozoic. Because of its low mechanical strength and density, which does not increase with burial, relatively minor sediment loading or mild external structural events can mobilize salt. However, dating such episodes can be difficult as the latest movements typically mask earlier ones.

Seismic reflection profiles from the southwestern Canning Basin show folds in the Permian below the Fitzroy Unconformity have larger amplitudes than in either the underlying Lower–Middle Ordovician or overlying Upper Jurassic and Cretaceous successions. This relationship implies mobilization or dissolution of Upper Ordovician – Silurian salt during the Triassic – Middle Jurassic, although the same sections also indicate some later salt movements of likely Cretaceous–Cenozoic age. Similarly, in the northern part of the basin (near Frome Rocks 1), deformations of the mid-Jurassic Wallal Sandstone probably are due to late adjustments following salt mobilization during the Late Triassic to mid-Jurassic Fitzroy Transpression. By comparison, folded or highly tilted Permian and Lower Cretaceous formations adjacent to the Browne, Madley and Woolnough diapirs in the southeast of the basin indicate a Late Cretaceous – Cenozoic age for at least the latest salt movement. Salt diapirs on the western side of the Vulcan Graben (near Paqualin 1 and Swan 1) in the Bonaparte Basin appear to have been active from the Late Jurassic into the Cenozoic following burial below thick prograding carbonate platform and the collision of the Australian and Indonesian Plates in the Miocene. In the southeastern part of the basin, salt diapirs were probably mobile through at least part of the Mesozoic and into the Cenozoic. The Silurian of the Southern Carnarvon Basin includes the only other noteworthy salt deposits in the State, but shows little or no signs of mobilization, perhaps because they are relatively thin.



Seismic section across the Woolnough diapir, Officer–Canning Basins



Isometric views of the Woodleigh impact structure, Southern Carnarvon Basin: a) first vertical derivative of the Bouguer gravity image; b) first vertical derivative of the total magnetic anomaly; and c) satellite imagery showing the lack of surface expression. The southwestern edge spans ~120 km

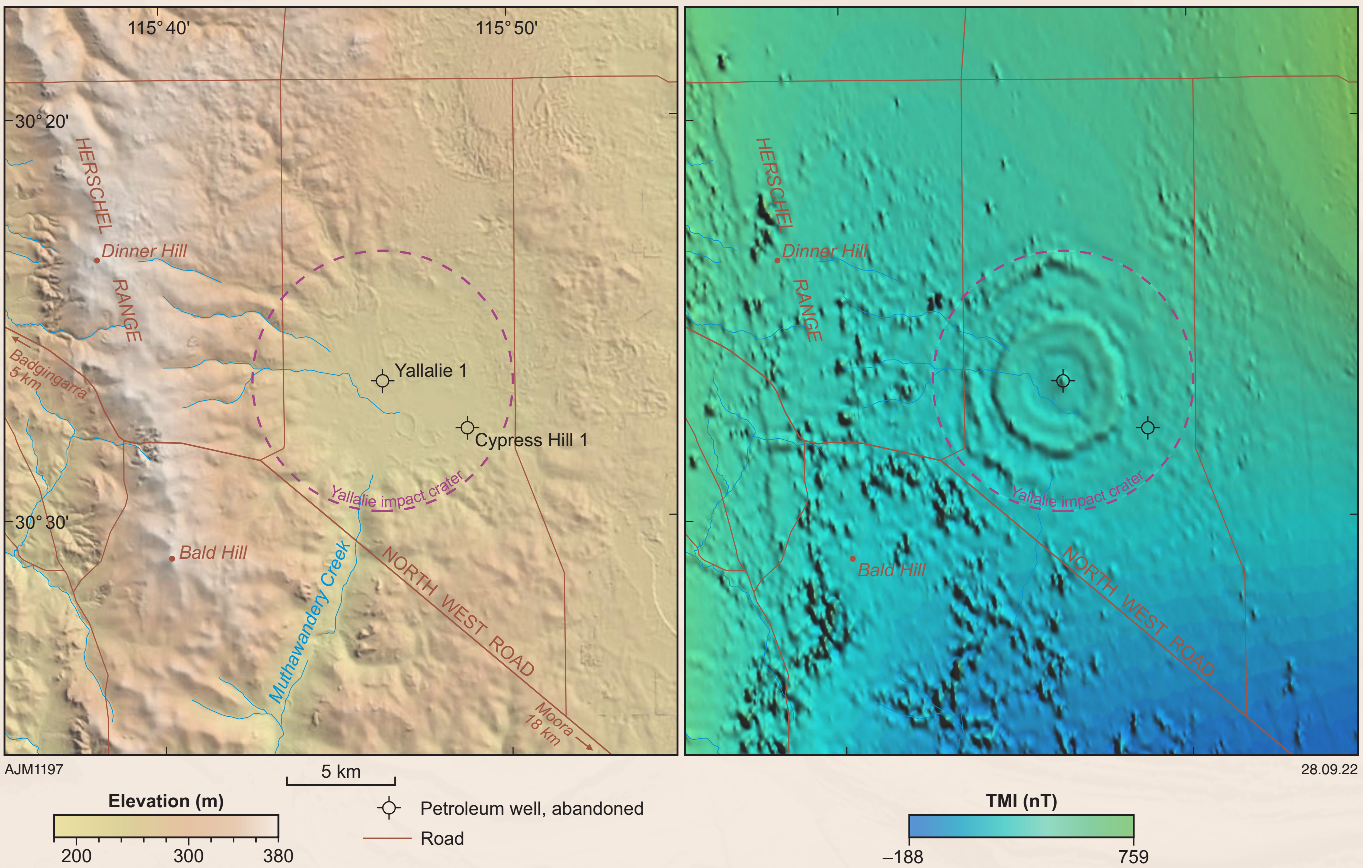
Of all the impact structures identified in Western Australia, only Woodleigh, east of Shark Bay, is unequivocally Mesozoic. Any remaining crater morphology of this feature, if preserved, is confined to the subsurface below Lower Jurassic and Cretaceous sedimentary deposits. The Yallalie crater within Mesozoic strata midway between Moora and Dandaragan has been modified by erosion, but may be younger than Cretaceous. Mesozoic ages attributed to other impact features are either ambiguous or poorly constrained.

Woodleigh

The Woodleigh structure, with a diameter of about 50 km, has its centre 43 km east of Shark Bay on the eponymous station within the Southern Carnarvon Basin. Its impact origin and Early Jurassic age are based on drilling and geophysical data as it lies below 140–200 m of flat-lying Lower Jurassic, Cretaceous and Cenozoic sedimentary rock, none of which outcrops close to the structure. Erosion between the Early Jurassic and Early Cretaceous probably removed much of the original crater and at least some of its Jurassic fill.

Drilling at the centre of the structure (at 26°03′19″ S, 114°39′56″ E) intersected deformed Proterozoic Pinjarra Orogen granitic basement directly beneath a thin Lower Cretaceous sedimentary succession. The granitic rock contains abundant shock-induced planar deformation features in quartz, feldspar transformed into glass by high-pressure vitrification, and penetrative glassy veining (pseudotachylite). The chemical composition of the veins points to injection of meteoritic components and chemical fractionation by shock volatilization. All available radiometric ages are older than the age deduced from stratigraphic relationships — zircons from the granitic basement of the central uplift, for example, retain a pre-impact 850 Ma age despite having shock-induced fractures.

Up to 300 m of the lowermost Jurassic Woodleigh Formation, interpreted as lacustrine crater fill, extends about 25 km beyond, but not over, the central basement high. Below this unit within the annular depression surrounding the central peak is an unnamed massive paraconglomerate containing shocked granite clasts in a matrix of shocked sand grains overlying a thin dolomitic breccia made up of angular clasts from the underlying Silurian (cored in GSWA Woodleigh 2A where it is 66 m thick). The paraconglomerate and breccia are inferred to have been deposited during a single event almost immediately after the impact but have so far yielded nothing that can be dated apart from Permian palynomorphs in a presumably reworked clast. The diameter of the original crater, and an impact age close to the Triassic–Jurassic boundary (201 Ma), are deduced from the near coincidence of the Woodleigh Formation with a circular aeromagnetic anomaly and concentric gravity features, and palynomorphs in this formation. In addition, seismic line 11GA-SC1 along the Woodleigh–Byro Road crosses the outer quarter of the structure and reveals its outer western margin corresponds to a zone of down-to-the-east normal faults, which probably developed on the outer margin of the crater. Other partial or weakly concentric features previously interpreted as the outer edge of the structure include diverted drainage associated with the Wooramel River, the terminations of the Ajana and Wandagee Ridges shown by gravity data, and an arcuate aeromagnetic feature to the east near the



Yallalie crater northwest of Moora, northern Perth Basin: a) digital elevation model and b) first vertical derivative of the total magnetic anomaly

Impact structures *continued*

edge of the Coolcalalaya Sub-basin. These features may have been reactivated by the impact, or by Cretaceous or younger structural events, but are unlikely to have been a direct consequence of the event judging from their depths and distances from the centre of the structure. Ejecta from the impact have not been located, possibly because the nearest sections across the Triassic–Jurassic boundary lie 350 km to the south within the northern Perth Basin, in which the preservation potential of a thin bed in non-marine facies is low.

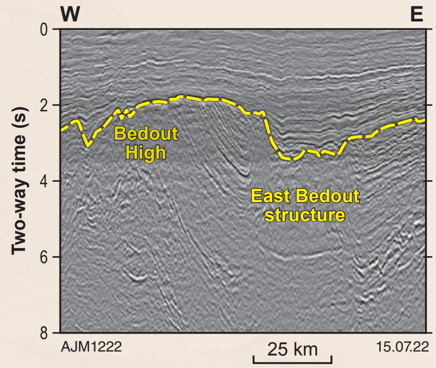
Yallalie

This crater forms a surface depression about 12 km across within the Perth Basin, in an area surrounded by Cretaceous outcrop 30 km northwest of Moora (at 30°26′36″ S, 115°46′22″ E). The depression shows inwards radial drainage breached to the south by Muthawandery Creek, which feeds southwards into Minyulo Brook near Cataby. Coincident with the depression is a central magnetic peak surrounded by concentric positive magnetic anomalies, which presumably coincide with arcuate, inward-dipping faults imaged in two dimensions on seismic profiles — these faults are no longer evident at ground level due to erosion. Overall, the geophysical signature is similar to that for craters formed in low-strength, water-saturated rocks, implying a subaqueous impact. Neither of the petroleum wells drilled within the crater (Yallalie 1 on the central uplift and Cyprus Hill 1 near the southeastern margin) encountered hydrocarbons.

About 4 km from the southwestern rim of the crater, ridges of polymictic, allochthonous breccia contain siltstone clasts up to 1 m across from Upper Jurassic to Upper Cretaceous formations. The pronounced flow of bedding around more competent clasts suggests fluidized surges during deposition. Most quartz grains within the breccia show prismatic cleavage indicative, though not diagnostic, of low shock. By comparison, breccia 6 km west of the crater contains grains with planar fractures and planar deformation features consistent with shock compression in the order of 5–20 GPa and an ejecta origin. Greensand clasts within the breccia presumably are from the Cenomanian – lower Santonian Molecap Greensand as there are none of the Santonian–Campanian Gingin Chalk — this implies an age near the Santonian–Campanian boundary for the impact. If this age is correct, an impact-generated tsunami may explain the lack of bedding in the Molecap Greensand, its mixed fossil assemblage and irregular contact with the overlying Gingin Chalk in outcrop near Gingin. However, a younger age for the impact is feasible given the stratigraphic gap between the Lower Cretaceous and Pliocene sediment in the three water bores and two petroleum wells within the crater. A comparison of the relative positions of these drillholes within the crater with other impact structures suggests that the most complete crater-fill succession should be near Agaton 2 (2.75 km north-northeast of the crater's centre); unfortunately, no samples from that water bore are available.

Other impact features of possible Mesozoic age

A buried impact structure, about 11 km across, at Lake Raeside, 37 km west-northwest of Leonora on the Yilgarn Craton, is interpreted from aeromagnetic data and shock features in a breccia underlying a Cenozoic paleochannel. As with the 5 km-wide impact feature east of Ora Banda and about 47 km northwest of Kalgoorlie, its age is poorly constrained between the early Permian and Eocene. Other less well-dated and deeply eroded impact structures in the State that are possibly Mesozoic



Seismic section across the Bedout High and East Bedout structures. Both are onlapped by Triassic strata

are Glikson (14 km across) in the Little Sandy Desert, Connolly Basin (9 km) in the Gibson Desert and Piccaninny (7 km) in the East Kimberley. Connolly is purportedly Paleogene, but nearby Aptian–Albian deposits seemingly provide a maximum age for this structure. Similarly, only maximum ages are available for the Glikson (<508 Ma) and Piccaninny (<360 Ma) structures.

Contested or speculative Mesozoic impact features

A postulated impact origin near the end of the Permian for the Bedout structure centred below Bedout 1 in the offshore Roebuck Basin has been disputed, with a volcanic origin proposed instead, albeit based mostly on geophysical data. A 25 km-diameter circular structure interpreted from seismic reflection data directly east of this feature, also claimed to be of impact origin with a possible age close to the Permian–Triassic boundary, could equally well be an igneous intrusion. Similarly, the suggested impact origin of the 'Gnargoo structure' near the northern end of the Gascoyne Platform of the Southern Carnarvon Basin, with a presumed diameter of 75 km and an age supposedly constrained between mid-Permian and lower Cretaceous formations, is not obvious from aeromagnetic data acquired since such an origin was proposed. Moreover, the structure is questionable based on available gravity and seismic data, there are no drillholes deeper than the Cretaceous near its centre and there is no evidence of high-pressure alteration in wells within its claimed extent. In the southeastern Exmouth Plateau, the 'Mercury structure' originally was interpreted as about 30 km across and of late Cretaceous age from a 2D seismic line. No further work has been done on this speculative feature even though the coordinates provided (19°40′ S, 114°20′ E) are about 7.5 km northwest of Jansz 2 and the supposed extent is now largely covered by 3D seismic surveys.

Silver and sulphides

Within the Southern Carnarvon Basin, minor silver and zinc–lead sulphides, associated with manganese and limonitic minerals, are mostly restricted to nodules formed by burrows and coprolites in the mid-Cretaceous Gearle Siltstone along the Giralia anticline about 130 km south of Exmouth on Cardabia Station. The mineralization is attributed to fluid movement on faults extending into Precambrian basement and is possibly related to anomalous heat flow (detected from groundwater temperatures). However, the highest Ag, Zn and Pb assay values are low (up to 847, 1750 and 1500 ppm, respectively), as is the likelihood of an economic deposit. Similar results from coprolites at the same stratigraphic level on Hill Springs Station west of Kennedy Range are probably due to organic sulfides having scavenged heavy metals from the enclosing carbonaceous siltstone.

Abbreviations used

B	billion (10^9)
bbl	barrels (1 bbl = 0.1589787 kL)
Bm^3	billion cubic metres (gas)
CBM	coal-bed methane (also called 'coal seam gas')
FLNG	floating liquefied natural gas (facility)
FPSO	floating production storage and offloading (facility)
GL	gigalitres (1 GL = 10^9 litres liquids)
GPa	gigapascals (1 GPa = 10^9 pascals)
HMS	heavy mineral sands
J	Jurassic
JORC	Australasian Joint Ore Reserves Committee
K	Cretaceous
kL	kilolitres (1 kL = 6.28981 bbl)
LNG	liquefied natural gas
m^3	cubic metres (1 m^3 = 35.314667 cubic feet)
Ma	million years
MMB	million barrels
MSL	mean sea level
Mt	million tonnes
MTPA	million tonnes per annum
nT	nanotesla (1 nT = 10^{-9} tesla)
ppm	parts per million
t	tonnes
TL	trillion litres (= 10^{12} litres)
TOC	total organic carbon
TR	Triassic
TWT	two-way time (in seconds)

Useful links

Australian Petroleum Production and Exploration Association

www.appea.com.au

Geological Survey of Western Australia

www.dmirs.wa.gov.au/gswa

Interactive geological map (GeoVIEW.WA)

www.dmirs.wa.gov.au/geoview

Mineral exploration reports (WAMEX)

www.dmirs.wa.gov.au/wamex

Petroleum & Geothermal Information Management System (WAPIMS)

www.dmirs.wa.gov.au/wapims

Geoscience Australia

www.ga.gov.au/scientific-topics/energy

National Offshore Petroleum Information Management System

www.ga.gov.au/nopims

Petroleum Exploration Society of Australia

https://pesa.com.au

Flat-lying Lower Cretaceous Nanutarra Formation, eastern Peedamullah Shelf, Northern Carnarvon Basin

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In addition, the reader can find regularly updated information from Geoscience Australia at <www.ga.gov.au/scientific-topics/energy/province-sedimentary-basin-geology/petroleum>.

Mount Augustus, an inselberg rising up to 700 m above the surrounding plain in the Gascoyne region, possibly formed during Mesozoic erosion of the Paleoproterozoic sandstone

Mid-Jurassic sandstone and ferrugenized carbonate displaced by a small fault at Ellendale Pool, Greenough River, 36 km east-southeast of Geraldton, northern Perth Basin

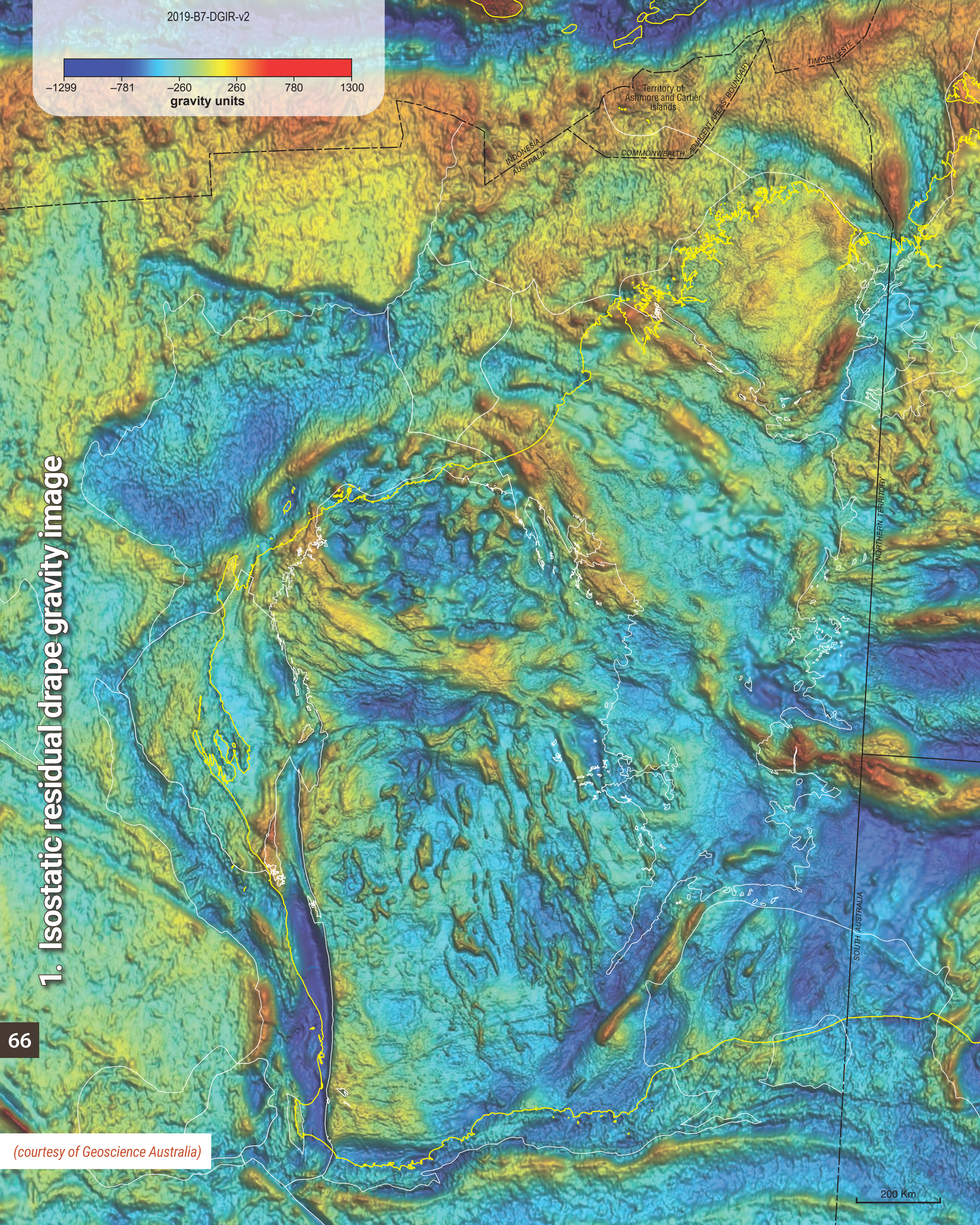
Looking west over Upper Cretaceous outcrops, mostly of the Toolonga Calcarenite, at Yalthoo Field, Murchison House station, 12 km east-northeast of Kalbarri, Southern Carnarvon Basin

Maps of Western Australia

1. Isostatic residual drape gravity image (courtesy of Geoscience Australia)
2. First vertical derivative image from aerial and ship-borne magnetic data
3. Localities mentioned in text superimposed on topography and bathymetry images, with index (bathymetry courtesy of Geoscience Australia)
4. Mesozoic hydrocarbon fields and mineral deposits
5. SEEBASE (Geognostics) depth-to-basement image
6. Location of wells used to generate isopach images

Flat-lying Lower Cretaceous Nanutarra Formation onlapping basement near the eastern edge of the Peedamullah Shelf, Northern Carnarvon Basin

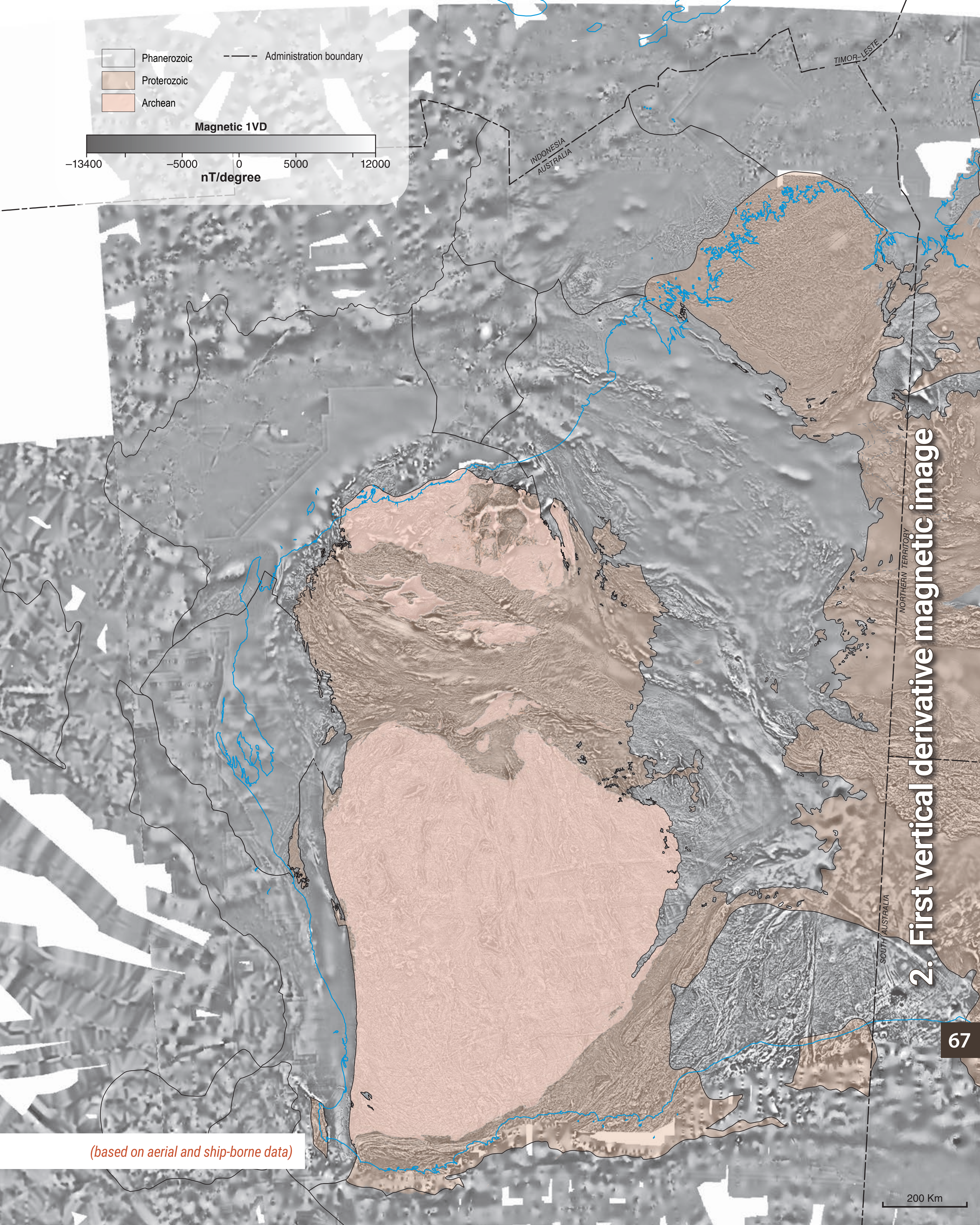
1. Isostatic residual drape gravity image

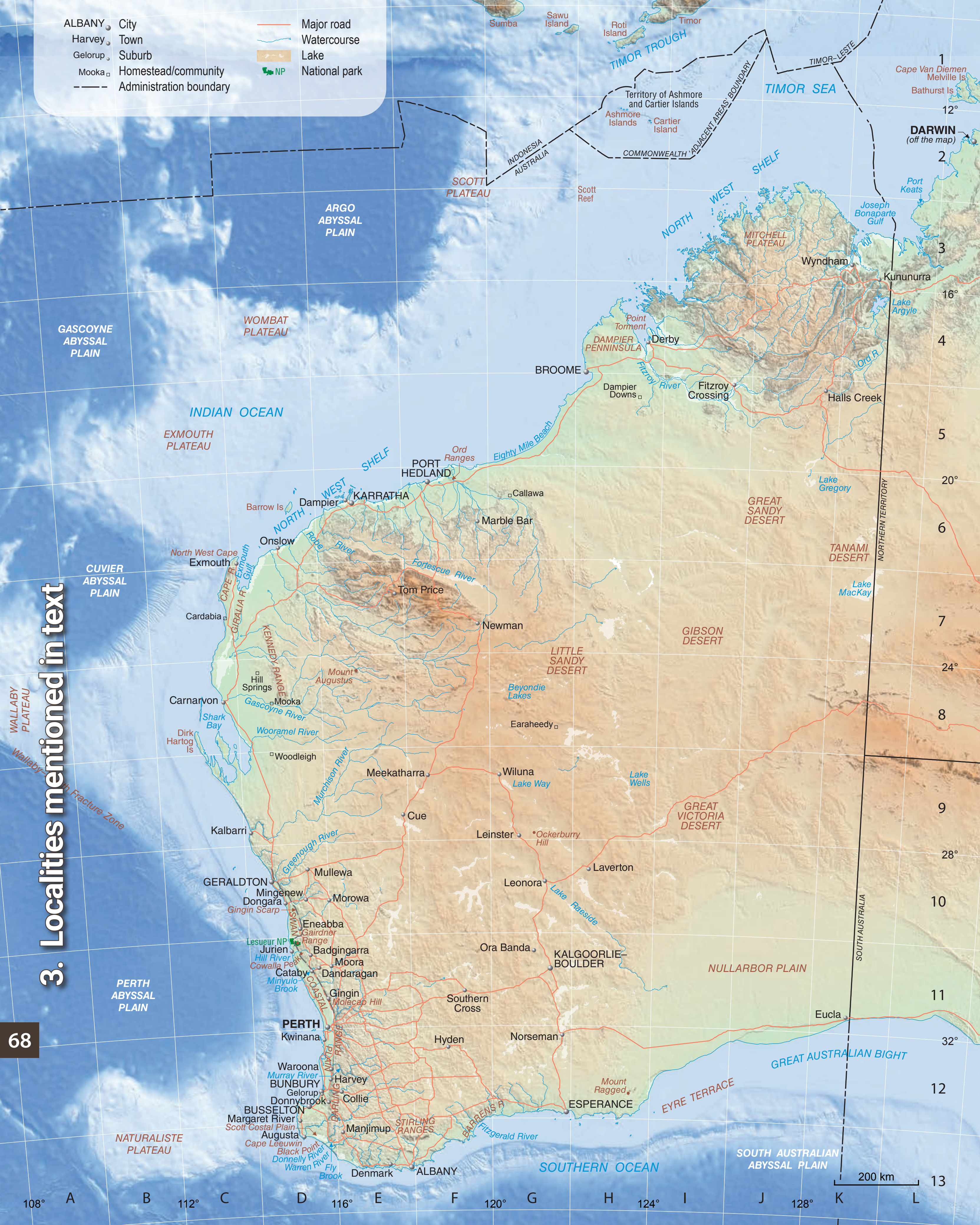


(courtesy of Geoscience Australia)

2. First vertical derivative magnetic image

(based on aerial and ship-borne data)





ALBANY City
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Gelorup Suburb
Mooka Homestead/community
Administration boundary
Major road
Watercourse
Lake
NP National park
Sumba
Sawu Island
Roti Island
Timor
TIMOR TROUGH
TIMOR SEA
TIMOR–LESTE
Cape Van Diemen
Melville Is
Bathurst Is
DARWIN (off the map)
Territory of Ashmore and Cartier Islands
Ashmore Islands
Cartier Island
COMMONWEALTH 'ADJACENT AREAS' BOUNDARY
INDONESIA
AUSTRALIA
SCOTT PLATEAU
Scott Reef
ARGO ABYSSAL PLAIN
NORTH WEST SHELF
MITCHELL PLATEAU
Joseph Bonaparte Gulf
Port Keats
Wyndham
Kununurra
Lake Argyle
GASCOYNE ABYSSAL PLAIN
WOMBAT PLATEAU
Point Torment
DAMPIER PENNINSULA
Derby
Ord R
BROOME
Dampier Downs
Fitzroy River
Fitzroy Crossing
Halls Creek
INDIAN OCEAN
EXMOUTH PLATEAU
Eighty Mile Beach
Ord Ranges
PORT HEDLAND
Lake Gregory
Callawa
Barrow Is
Dampier
KARRATHA
Marble Bar
GREAT SANDY DESERT
TANAMI DESERT
NORTHERN TERRITORY
North West Cape
Exmouth
Exmouth Gulf
Onslow
Robe River
Fortescue River
CUVIER ABYSSAL PLAIN
CAPE R
GIRALIA R
Tom Price
Lake MacKay
Cardabia
Newman
KENNEDY RANGE
GIBSON DESERT
LITTLE SANDY DESERT
Mount Augustus
Hill Springs
Beyondie Lakes
WALLABY PLATEAU
Carnarvon
Mooka
Gascoyne River
Shark Bay
Earaheedy
Dirk Hartog Is
Wooramel River
Woodleigh
Wallaby–Zenith Fracture Zone
Murchison River
Meekatharra
Wiluna
Lake Way
Lake Wells
GREAT VICTORIA DESERT
Cue
Kalbarri
Leinster
Ockerburry Hill
Greenough River
Laverton
Mullewa
GERALDTON
Leonora
Mingenew
Morowa
Dongara
Gingin Scarp
Lake Raeside
SOUTH AUSTRALIA
Eneabba
Gairdner Range
Lesueur NP
Jurien
Badgingarra
Hill River
Cowalla Peak
Moora
Ora Banda
KALGOORLIE–BOULDER
NULLARBOR PLAIN
Cataby
Dandaragan
Minyulo Brook
PERTH ABYSSAL PLAIN
SWAN COASTAL PLAIN
Gingin
Molecap Hill
Southern Cross
Eucla
PERTH
Kwinana
DARLING RANGE
Hyden
Norseman
GREAT AUSTRALIAN BIGHT
Waroona
Murray River
Harvey
BUNBURY
Gelorup
Collie
Donnybrook
Mount Ragged
EYRE TERRACE
BUSSELTON
Margaret River
Scott Costal Plain
ESPERANCE
BARRENS R
Manjimup
STIRLING RANGES
Augusta
NATURALISTE PLATEAU
Cape Leeuwin
Black Point
Donnelly River
Fitzgerald River
Warren River
Fly Brook
Denmark
ALBANY
SOUTHERN OCEAN
SOUTH AUSTRALIAN ABYSSAL PLAIN
200 km
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16°
20°
24°
28°
32°
108°
112°
116°
120°
124°
128°
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Ashmore Islands		I2
Augusta	town	D13
Badgingarra	town	D11
Barrens Range		F12
Barrow Island		D6
Bathurst Island		L1
Beyondie Lakes		G8
Black Point		D13
Broome	city	H4
Bunbury	city	D12
Busselton	city	D12
Callawa	homestead	G6
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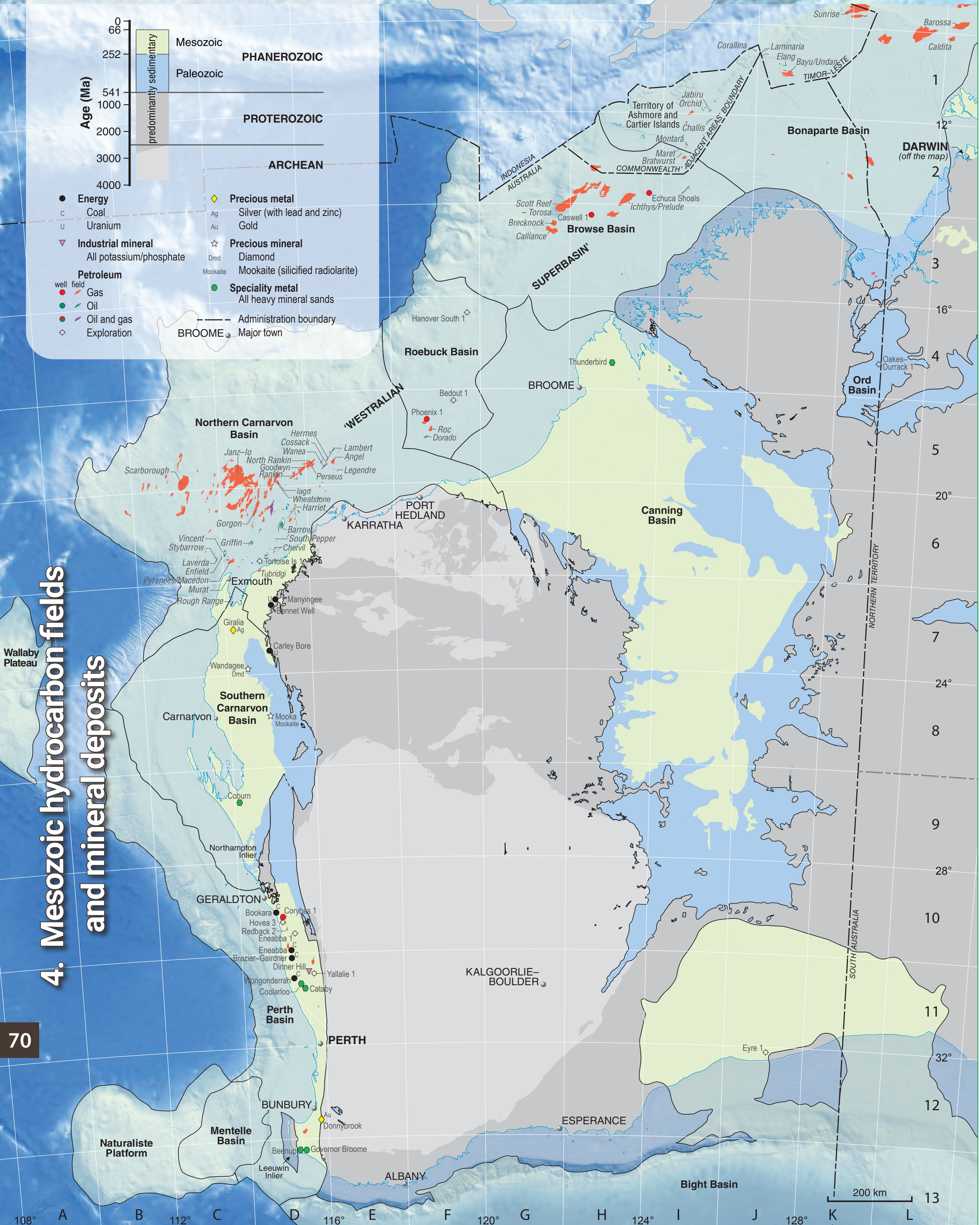
Gingin Scarp		D10
Giralia Range		D7
Great Australian Bight		K12
Great Sandy Desert		J6
Great Victoria Desert		I9
Greenough River		D10
Halls Creek	town	J5
Harvey	town	D12
Hill River		D11
Hill Springs	homestead	D8
Hyden	town	F12
Indian Ocean		C5
Joseph Bonaparte Gulf		K3
Jurien	town	D11
Kalbarri	town	D9
Kalgoorlie–Boulder	city	G11
Karratha	city	E6
Kennedy Range		D8
Kununurra	town	K3
Kwinana	town	D12
Lake Argyle		K4
Lake Gregory		J6
Lake MacKay		K7
Lake Raeside		G10
Lake Way		G9
Lake Wells		H9
Laverton	town	H10
Leinster	town	G9
Leonora	town	G10
Lesueur National Park		D11
Little Sandy Desert		G8
Manjimup	town	E13
Marble Bar	town	F6
Margaret River	town	D12
Meekatharra	town	F9
Melville Island		L1
Mingenew	town	D10
Minyulo Brook		D11
Mitchell Plateau		J3
Molecap Hill		D11
Mooka	homestead	D8
Moora	town	E11
Morowa	town	E10
Mount Augustus		E8
Mount Ragged		H12
Mullewa	town	D10
Murchison River		E9
Murray River		E12
Naturaliste Plateau		B13
Newman	town	F7
Norseman	town	G12
North West Cape		D6
North West Shelf		D6–L1
Nullarbor Plain		J11
Ockerburry Hill		G9
Onslow	town	D6
Ora Banda	townsite	G11
Ord Ranges		F6
Ord River		K4
Perth	city	D11
Perth Abyssal Plain		B11
Point Torment		H4
Port Hedland	city	F6
Port Keats		K3
Robe River		E6
Roti	island	H1
Sawu	islands	G1
Scott Costal Plain		D13
Scott Plateau		F2
Scott Reef		G3
Shark Bay		C8
South Australian Abyssal Plain		J13
Southern Cross	town	F11
Southern Ocean		H13
Stirling Ranges		E13
Sumba	island	G1
Swan Coastal Plain		D11
Tanami Desert		K6
Timor	island	H1
Timor Sea		J11
Timor Trough		H1
Tom Price	town	E7
Wallaby – Zenith Fracture Zone		A9
Wallaby Plateau		A8
Waroona	town	D12
Warren River		D13
Wiluna	town	G9
Wombat Plateau		D4
Woodleigh	homestead	D9
Wooramel River		D8
Wyndham	town	K3

4. Mesozoic hydrocarbon fields and mineral deposits



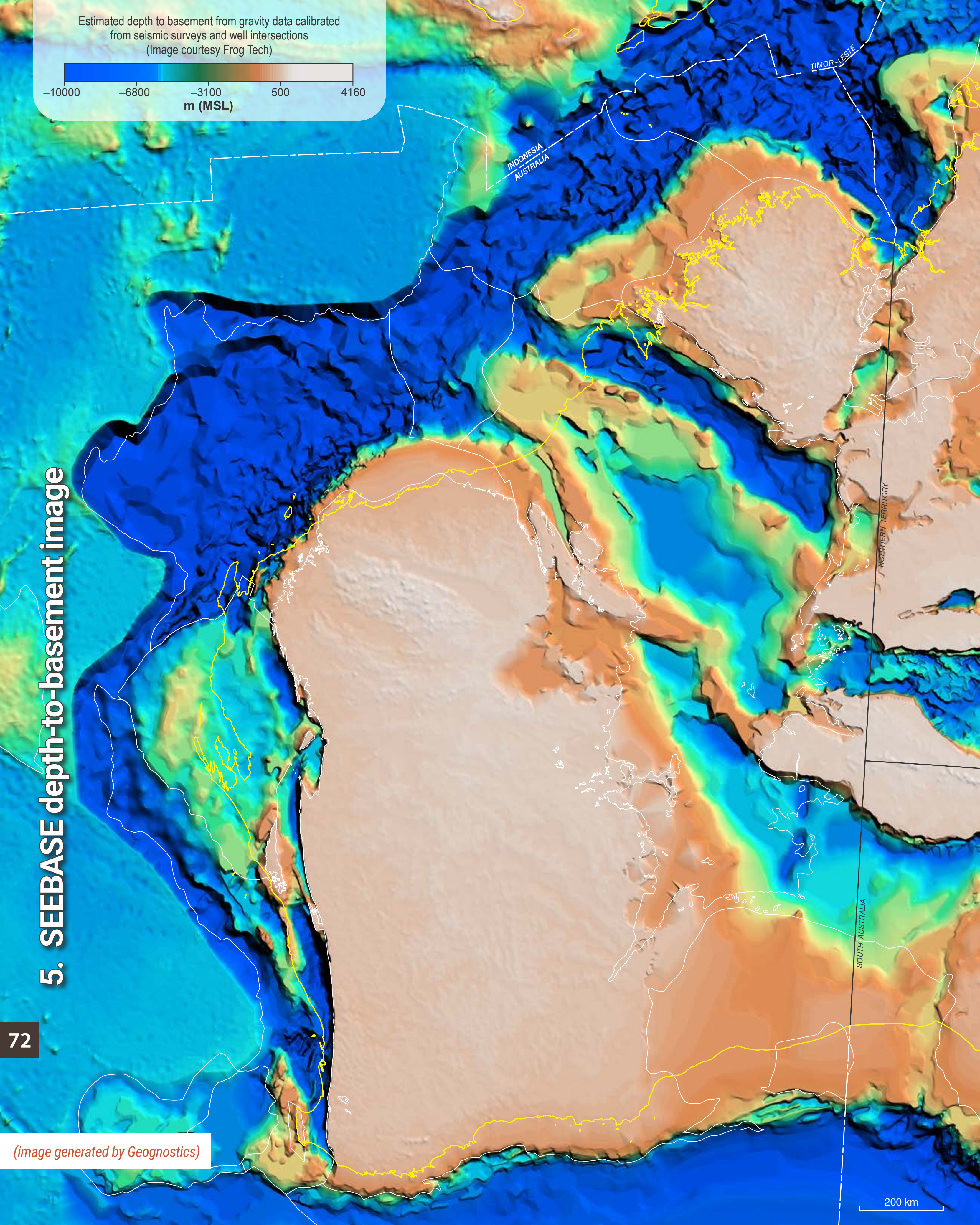
Index to Map 4

Site	Category	Commodity	Ref.
Angel	field	gas	E5
Barossa	field	gas	L1
Barrow	field	oil	D6
Bayu/Undan	field	gas and oil	J1
Bedout 1	well (P&A)	exploration	F5
Beenup	rehabilitated mine	heavy mineral sands	D13
Bennet Well	deposit	uranium	D7
Bookara	deposit	coal	D10
Bratwurst	field	gas	I2
Brazier–Gairdner	deposit	coal	D11
Brecknock	field	gas	G3
Caldita	field	gas	L1
Calliance	field	gas	G3
Carley Bore	deposit	uranium	D7
Caswell 1	well (P&A)	gas	H3
Cataby	mine	heavy mineral sands	D11
Challis	decommissioned field	oil	I2
Chervil	field	oil	D6
Coburn	mine under development	heavy mineral sands	D9
Cooljarloo	mine	heavy mineral sands	D11
Corallina	field	oil	I1
Corybas 1	well (shut in)	gas	D10
Cossack	field	oil and gas	E5
Dinner Hill	deposit	glauconite/phosphate	D11
Donnybrook	quarries	dimension stone	D12
Donnybrook	historic mines	gold	D12
Dorado	field	oil	F5
Echuca Shoals	field	gas	H2
Elang	field	oil and gas	J1
Eneabba	deposit	coal	D10
Eneabba 1	well (P&A)	exploration	D10
Enfield	field	oil	C6
Eyre 1	well (P&A)	exploration	J12
Giralia	deposit	silver	D7
Goodwyn	field	gas	D5
Gorgon	field	gas and condensate	D6
Governor Broome	deposit	HMS	D13
Griffin	depleted field	oil	D6
Hanover South 1	well (P&A)	exploration	F4
Harriet	shut-in field	oil	D6

Note: P&A, plugged and abandoned

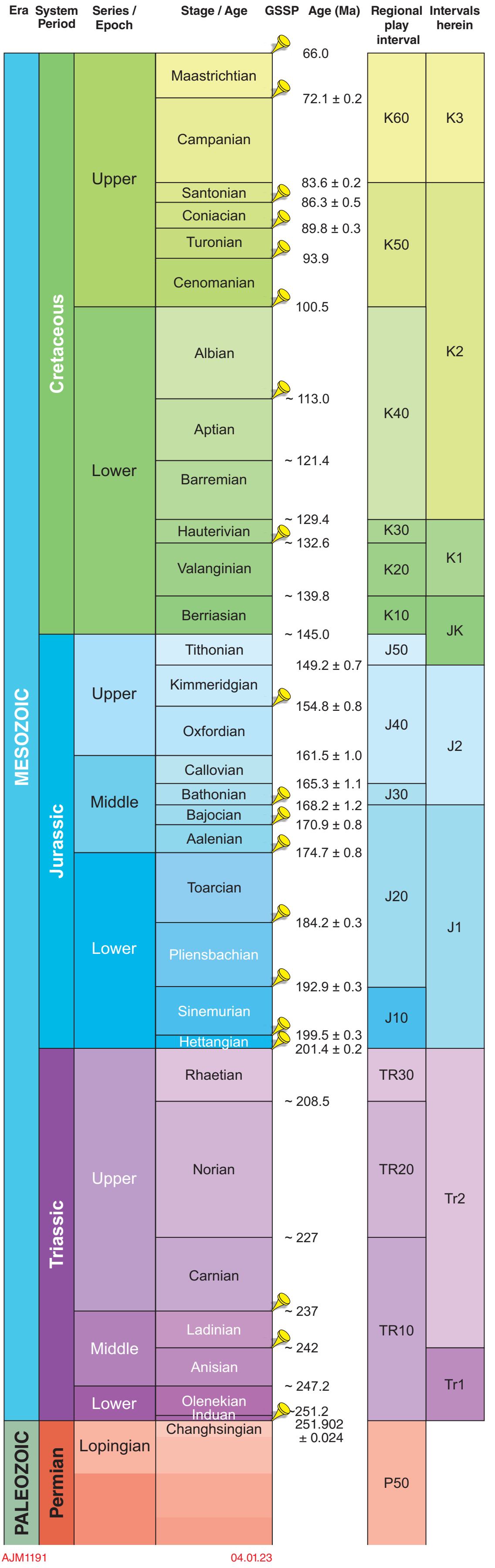
Site	Category	Commodity	Ref.
Hermes	field	oil	E5
Hovea 3	well (P&A)	exploration	D10
Iago	field	gas	D5
Ichthys/Prelude	field	gas	H2
Jabiru	decommissioned field	oil and gas	I1
Janz–Io	field	gas	D5
Lambert	shut-in field	oil and gas	E5
Laminaria	field	oil and gas	J1
Laverda	field	oil and gas	C6
Legendre	shut-in field	oil	E5
Manyingee	deposit	uranium	D7
Maret	field	oil	I2
Montara	field	oil	I2
Mooka	mine	semiprecious stone	D8
Murat	field	gas	D6
North Rankin	field	gas	E5
Oakes-Durrack 1	well (abandoned)	exploration	K4
Orchid	field	oil and gas	I1
Perseus	field	gas	E5
Phoenix 1	well	gas	F5
Pyrenees/Macedon	field	oil and gas	D6
Rankin	field	gas	D5
Redback 2	well	gas	D10
Roc	field	oil	F5
Rough Range	shut-in field	oil	D7
Scarborough	field	gas	C5
Scott Reef – Torosa	field	gas	H2
South Pepper	depleted field	oil	D6
Stybarrow	field	oil	C6
Sunrise	field	gas	K1
Thunderbird	mine under development	heavy mineral sands	H4
Tortoise Is 1	well (P&A)	exploration	D6
Tubridgi	depleted field	gas	D6
Vincent	field	oil	D6
Wandagee	occurrence	diamond	D7
Wanea	field	oil and gas	E5
Wheatstone	field	gas	D5
Wongonderrah	deposit	coal	D11
Yallalie 1	well (P&A)	exploration	D11

5. SEEBASE depth-to-basement image



(image generated by Geognostics)

6. Location of wells used to generate isopach images



Mid-Permian–Cretaceous IUGS timescale including regional 'play intervals' and those used for isopach–paleogeographic images in this book; based on an IUGS chronostratigraphic chart v 2022/10, and Marshall and Lang (2013)

About this book

Mesozoic transformation of Western Australia spans 252 to 66 Ma, an era represented by sedimentary deposits that cover about 23% of the onshore part of the State and virtually all offshore basins, with Upper Jurassic – Cretaceous deposits extending beyond the continent onto oceanic crust. These sedimentary successions are up to 15 km thick in offshore depocentres and the Perth Basin, and contain only minor igneous rocks apart from areas near the continent–ocean boundary where intrusions are abundant. Because of subdued tectonic events, the major resources within the Mesozoic are hydrocarbons in the offshore basins whereas, onshore, the most significant resources in, or uses of, Mesozoic strata are heavy mineral sand deposits on the Dampier Peninsula, water resources and gas storage. The Mesozoic depositional and structural history of the State and its surrounding waters is illustrated with a series of statewide paleogeographic reconstructions paired with isopach images — which represent 'time slices' derived from regional correlations largely based on biostratigraphic studies. The four main phases of basin evolution are: Triassic intracratonic rifting, Early–Middle Jurassic rifting, Late Jurassic – Early Cretaceous breakup and separation, and lastly trailing-edge rifting and marginal sag. However, these phases are not synchronous, as there are differences between some areas in their timing, especially with the progressive breaking away of continental fragments from north to south.





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

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