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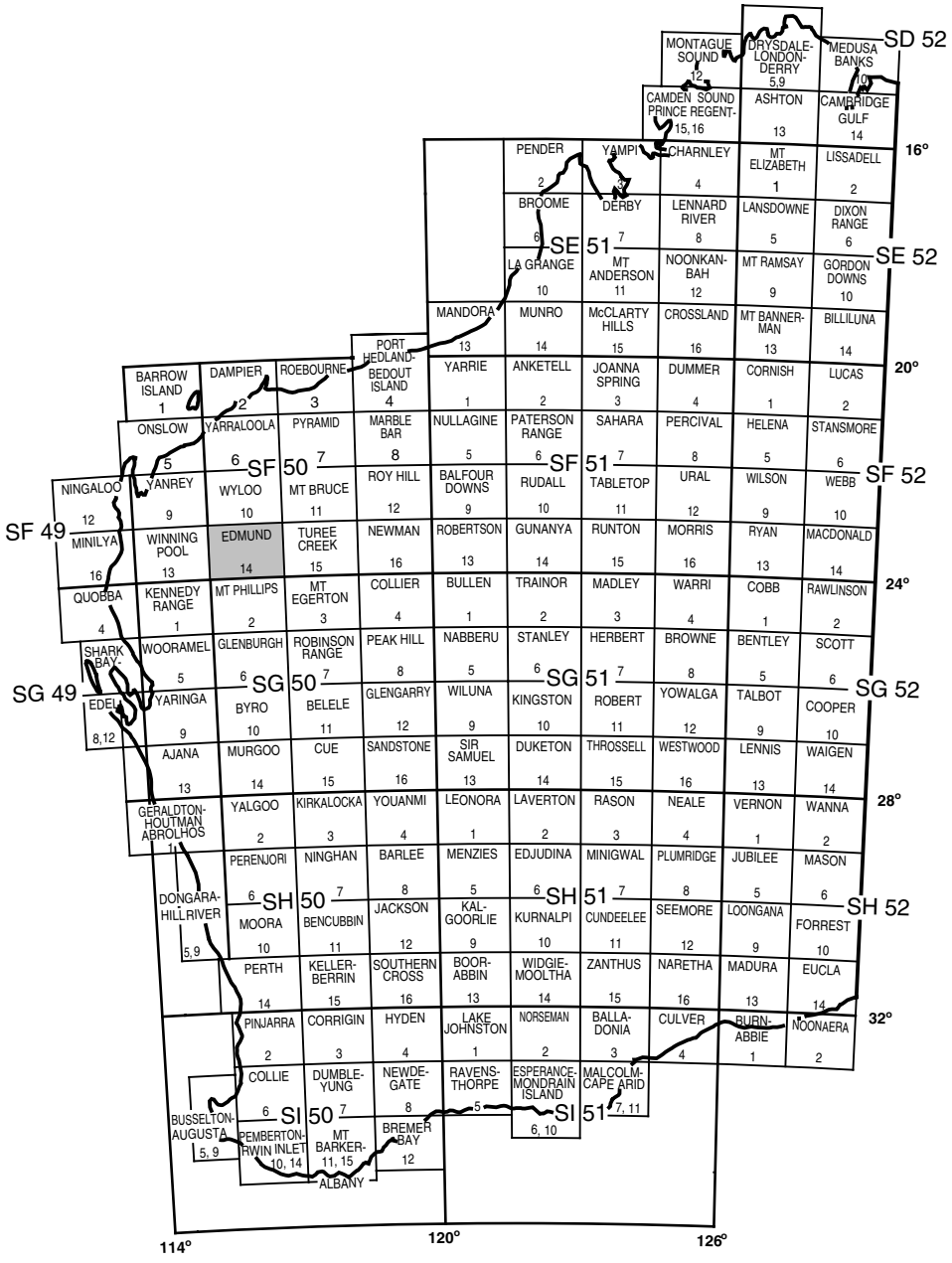
EXPLANATORY NOTES

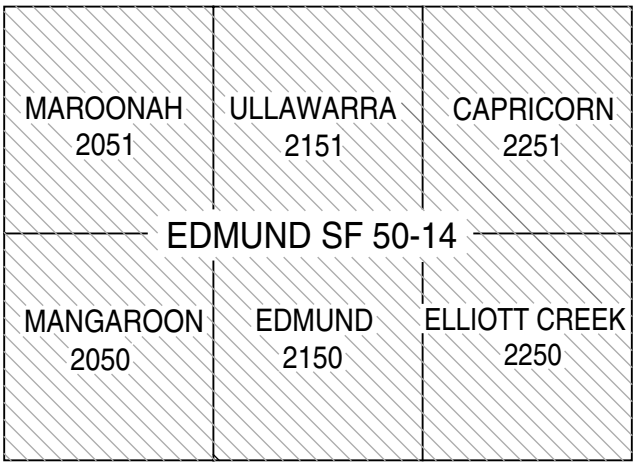
GEOLOGY OF THE MAROONAH, ULLAWARRA, CAPRICORN, MANGAROON, EDMUND, AND ELLIOTT CREEK 1:100 000 SHEETS

by D. McB. Martin, S. Sheppard, and A. M. Thorne

1:100 000 GEOLOGICAL SERIES

Geological Survey of Western Australia





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GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

GEOLOGY OF THE MAROONAH, ULLAWARRA, CAPRICORN, MANGAROON, EDMUND, AND ELLIOTT CREEK 1:100 000 SHEETS

by
D. McB. Martin, S. Sheppard, and A. M. Thorne

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Cover photograph:
Stromatolitic and brecciated dolostone lithofacies, Irregully Formation, Edmund Group. Irregully Gorge, southwestern Capricorn 1:100 000 map sheet.

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Geology of the Maroonah, Ullawarra, Capricorn, Mangaroon, Edmund, and Elliott Creek 1:00 000 sheets

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D. McB. Martin, S. Sheppard, and A. M. Thorne

Abstract

The study area forms part of the Capricorn Orogen, a major tectonic zone between the Archaean Yilgarn and Pilbara Cratons. The Capricorn Orogen here comprises Palaeoproterozoic rocks of the Ashburton and Blair Basins and Gascoyne Complex, Late Palaeoproterozoic to Mesoproterozoic rocks of the Edmund Basin, and Mesoproterozoic rocks of the Collier Basin.

The Ashburton Basin corresponds to the present day outcrop of the 2446–1786 Ma Wyloo Group. It comprises low-grade, metasedimentary and metavolcanic rocks. The unconformably overlying Blair Basin is represented by c. 1804 Ma metasedimentary and metavolcanic rocks of the Capricorn Group.

The Gascoyne Complex is composed of Palaeoproterozoic metasedimentary and meta-igneous rocks, which are extensively intruded by large volumes of granite. Within the study three tectonic zones are recognized: the Boora Boora, Mangaroon, and Limejuice Zones. The Boora Boora and Limejuice Zones both contain metasedimentary rocks that were intruded by granites of the Moorarie Supersuite during the 1830–1780 Ma Capricorn Orogeny. The Mangaroon Zone is composed of metasedimentary rocks (Pooranoo Metamorphics) that were deformed and metamorphosed at medium to high grade during the Mangaroon Orogeny at 1680–1620 Ma. Granite plutons of the 1680–1620 Ma Durlacher Supersuite intruded a wide area of the Gascoyne Complex.

Rocks of the Ashburton and Blair Basins and the Boora Boora and Limejuice Zones of the Gascoyne Complex have been extensively deformed during the Palaeoproterozoic Capricorn Orogeny. Deformation, low- to medium-grade metamorphism and voluminous granite intrusion across the Gascoyne Complex took place between 1830 Ma and 1780 Ma. The Wyloo and Capricorn Groups record two major deformation events, D_{1a} and D_{2a}. D_1 and D_2 structures in the Boora Boora Zone are comparable in age with D_{1a} and D_{2a} in the Wyloo Group.

The 1680–1620 Ma Mangaroon Orogeny in the Gascoyne Complex encompasses complex and progressive deformation and metamorphism. In the Mangaroon Zone, two deformation and regional metamorphic 'events' (D_{1m}/M_{1m}, D_{2m}/M_{2m}), which are broadly associated with intrusion of early (1680–1660 Ma) voluminous granite plutons of the Durlacher Supersuite, are recognized. High-grade contact metamorphism, including hornfels migmatites, is also seen to overprint the regional metamorphic fabrics. Less intensive granite intrusion and deformation continued until c. 1620 Ma.

The Edmund and Collier Basins correspond to the present day outcrop of the Edmund and Collier Groups that together make up the Bangemall Supergroup. The Late Palaeoproterozoic to Mesoproterozoic Edmund Group is at least 4 km thick and consists of mostly fine-grained siliciclastic and carbonate sedimentary rocks. The Edmund Group is younger than 1620 Ma granites in the underlying Gascoyne Complex, and older than c. 1465 Ma dolerite sills that intrude it. The 2–2.5 km thick Collier Group disconformably overlies the Edmund Group and consists largely of siliciclastic sedimentary rock. The age of the Collier Group is about 1400–1070 Ma. The extensive system of dolerite sills that intrude the Collier Group probably relate to the 1078–1070 Ma Warakurna Large Igneous Province.

The 1070–755 Ma Edmundian Orogeny is an intracratonic event that deformed the Bangemall Supergroup, and either formed or reactivated structures in the basement. It resulted in two main periods of deformation and low-grade metamorphism, D_{1e}/M_{1e} and D_{2e}/M_{2e}.

Rocks of the Capricorn Orogen are cut by northeast trending dolerite dykes belonging to the 755 Ma Mundine Well dyke swarm, north-northwesterly trending dolerite dykes that pre- or post-date the Mundine Well dyke swarm, and by quartz veins of various orientations. In addition, ferruginous veins and linear alteration zones cut the Gascoyne Complex and Bangemall Supergroup.

The physiography and Cainozoic deposits of the region are described in relation to three main topographic zones, the Ashburton Valley, Bangemall, and Maroonah Plains Geomorphological Provinces. These correspond to outcrop areas of the Wyloo and Capricorn Groups, Bangemall Supergroup, and Gascoyne Complex respectively.

Occurences of gold, copper, lead, silver, zinc, barite, uranium and diamonds in particular are discussed in terms of tectonic setting and mineralization style.

KEYWORDS: Ashburton Basin, Blair Basin, Edmund Basin, Collier Basin, Gascoyne Complex, Bangemall Supergroup, Edmund Group, Collier Group, Capricorn Group, Wyloo Group, Moorarie Supersuite, Durlacher Supersuite, Pooranoo Metamorphics, Capricorn Orogen.

Introduction

These Explanatory Notes complement the 'Western Capricorn Orogen 1:100 000 Geological Information Series' data package available from the Geological Survey of Western Australia. The package contains Geological Series maps and base layers covering geology, mineralization and exploration, topography and georeferenced images for the six 1:100 000 maps. The contents of the data package are outlined in Appendix 1.

Location, access, and previous work

The study area coincides with the EDMUND* 1:250 000 sheet area (SF 50-14) and is bounded by latitudes 23°S and 24°S and by longitudes 115°30'E and 117°E. The centre of the sheet area is located about 900 km north of the state capital Perth, and about 300 km northeast of the coastal town of Carnarvon. The only commercial activity on EDMUND consists of beef-cattle grazing. Within the sheet area there are a number of homesteads (Maroonah, Mangaroon, Ullawarra, Edmund, and Gifford Creek) but no towns or other permanent settlements. The nearest township, Gascoyne Junction, is located about 150 km south-southwest by road of EDMUND. The southern and northeastern parts of the sheet area are traversed by several unsealed roads maintained by the local shires; the roads may be closed after rain. The bulk of EDMUND is accessed by a network of station tracks that provide year-round access.

The first systematic work conducted on EDMUND consisted of regional mapping by J. L. Daniels in 1965. The first edition EDMUND 1:250 000 sheet and explanatory notes (Daniels, 1967, 1969) contained a stratigraphy for the Bangemall Group (now Supergroup), but showed only a two-fold subdivision of the Gascoyne Complex: 'Precambrian undetermined' and 'Granite and granodiorite'. On the WINNING POOL – MINILYA and MOUNT PHILLIPS 1:250 000 sheets to the west and south of EDMUND, the distribution of the main rock types in the Gascoyne Complex was identified, and a structural and metamorphic history established (Williams et al., 1983; Hocking et al., 1985). Reconnaissance mapping and sampling by S. J. Williams on EDMUND was incorporated into his summary report on the Gascoyne Complex (Williams, 1986). The stratigraphy of the Bangemall Supergroup, including that on EDMUND, was revised by Muhling and Brakel (1985). The petrology and geochemistry of alkaline dykes in the southern central part of EDMUND was examined by Pearson (1996), Pearson and Taylor (1996), and Pearson et al. (1996).

Vegetation

Regional vegetation surveys at 1:1 000 000 scale covering EDMUND are described in Beard (1975; 1981; 1990). Western Australia has been divided up into three main botanical provinces (Eremaean, Northern and South-West Provinces), and a South-Western Interzone (Beard, 1990). Each of the provinces comprise several natural regions, each with characteristic features of climate, geology, landforms, soils, and vegetation. EDMUND falls within the northwestern part of the Gascoyne Region, which is part of the Eremaean Province. The boundary with the Pilbara Region, which lies to the north, is marked '…by a major biogeographical boundary, the Acacia-Triodia line, to the north of which spinifex vegetation is predominant and to the south woody Acacia-dominated vegetation' (Beard, 1990).

The Gascoyne Region is dominated by mulga, commonly with snakewood and other acacia species '…as scrub on the hills and as low woodland on the plains' (Beard, 1990). The exception consists of Bangemall Supergroup rocks over much of MAROONAH, which are covered by hummock grasslands consisting of spinifex. Spinifex is present on Gascoyne Complex rocks only in the far northwestern corner of MAROONAH. Metasedimentary rocks of the Ashburton and Blair Basins on northeastern EDMUND commonly are sparsely vegetated with low shrubs (<1 m tall), principally species of Cassia and Eremophila (Beard, 1990). Tall trees, comprising mainly species of Eucalyptus and Melaleuca, are confined to rivers and major creeks on EDMUND.

Climate

EDMUND has an arid climate (i.e. <350 mm annual rainfall, as classified by the Commonwealth Bureau of Meteorology <http://www.bom.gov.au/index.shtml>) with hot, dry summers (average daily maximum temperatures of 41°C in January for both Nyang Homestead, located about 70 km west of Maroonah Homestead, and Gascoyne Junction) and mild winters (average daily maximum temperatures of 26°C and 23°C in June for, respectively, Nyang Homestead and Gascoyne Junction). Median annual rainfall for the mapped area is between 290 mm (Nyang Homestead) and 200 mm (Gascoyne Junction). Rainfall in the summer months (November to April) is provided by rain-bearing depressions from the northwest, which represent degraded cyclones, and more localized thunderstorms. In the winter months, rain is produced by the interaction of tropical cloud bands from the north-northwest with strong cold fronts approaching from the southwest. All the creeks on Edmund are ephemeral, and the major rivers flow only after heavy rain. Scattered rock pools may be fed by permanent springs or soaks.

Proterozoic Capricorn Orogen

The study area is located in the northwestern part of the Capricorn Orogen, a major zone of Proterozoic deformation, metamorphism, and magmatism between the Archaean Yilgarn and Pilbara Cratons (Gee, 1979; Cawood and Tyler, 2004; Fig. 1). The orogen includes metamorphic and igneous rocks of the Gascoyne Complex, a number of sedimentary basins, as well as the

* Capitalized names refer to standard map sheets. Where 1:100 000 and 1:250 000 sheets have the same name, the 1:250 000 sheets is implied unless otherwise indicated.

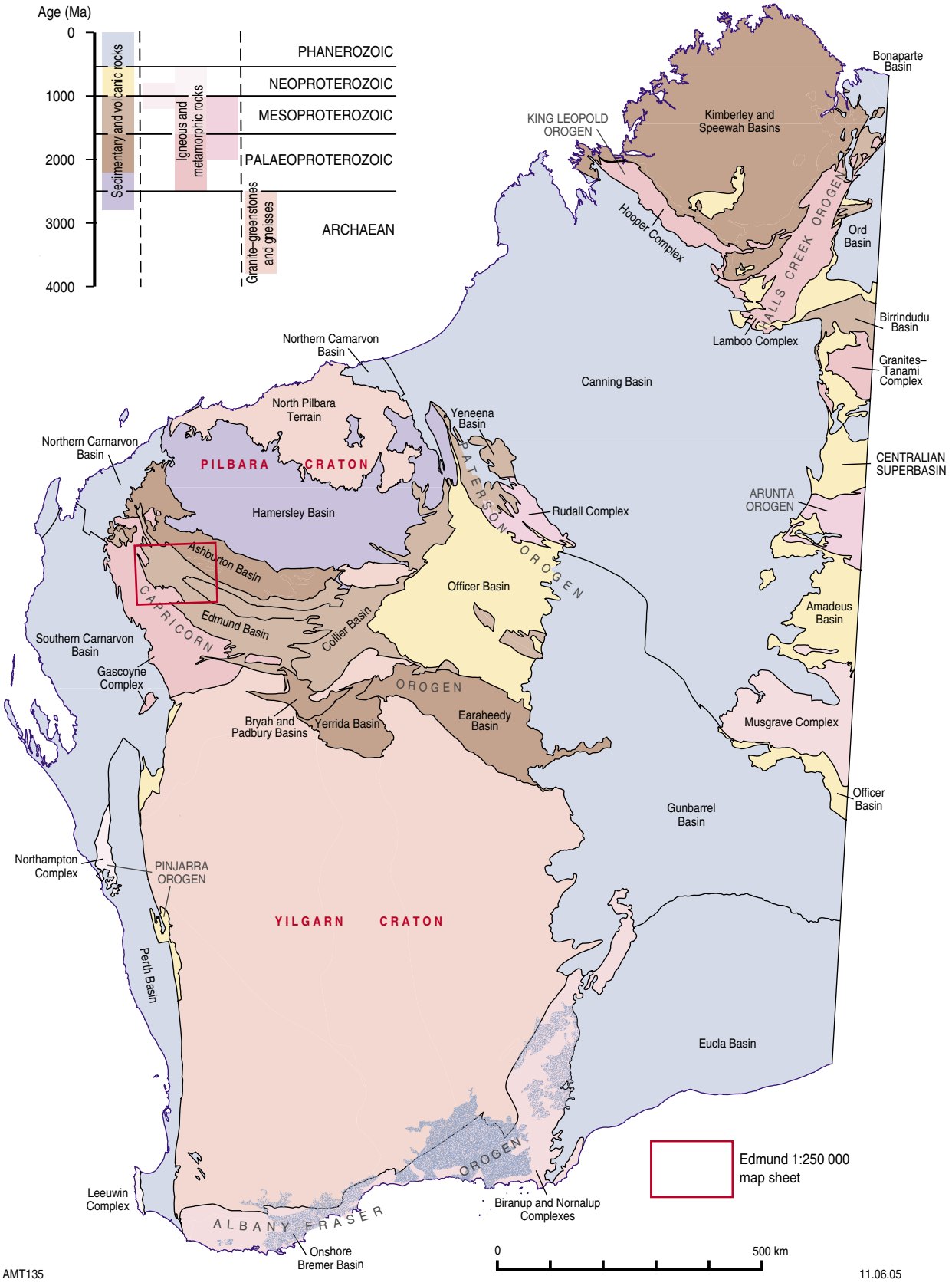


Figure 1. Location of the EDMUND map sheet in relation to the major tectonic units of Western Australia

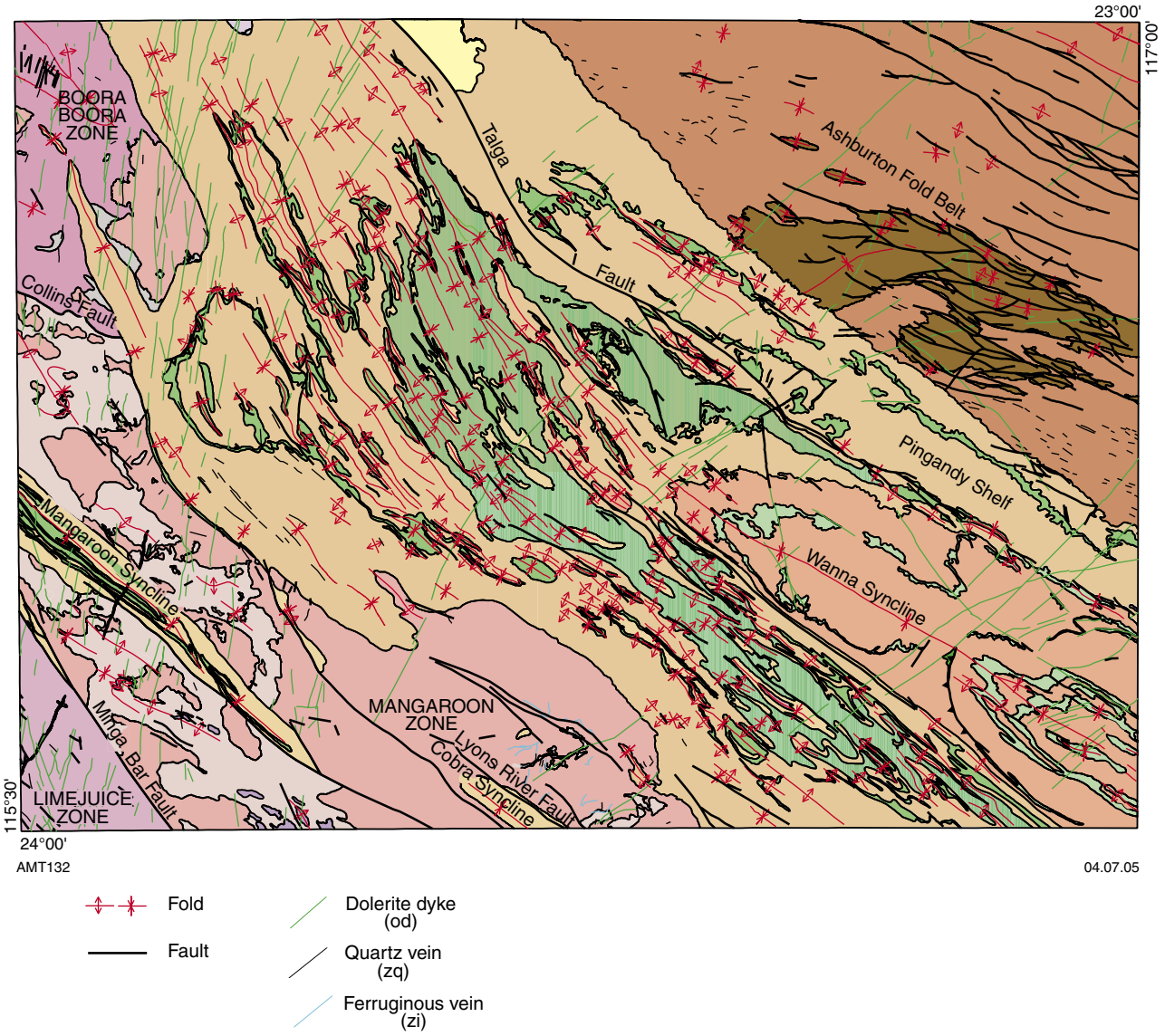
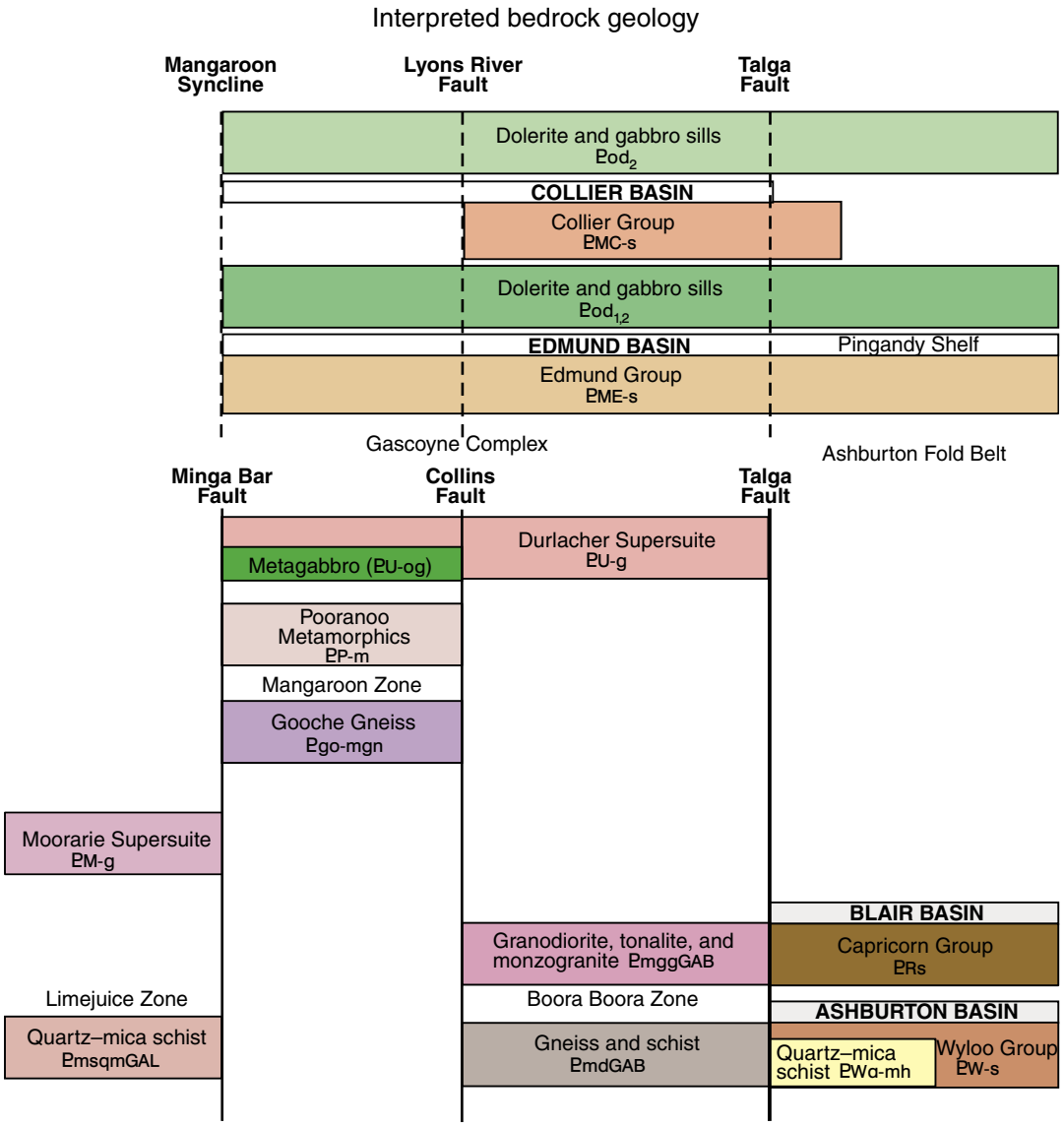


Figure 2. Simplified geological map of the area covered by the Edmund map sheet

deformed margins of the Yilgarn and Pilbara Cratons. Within the study area, Capricorn Orogen rocks comprise Palaeoproterozoic rocks of the Ashburton and Blair Basins and Gascoyne Complex, Late Palaeoproterozoic to Mesoproterozoic rocks of the Edmund Basin, and Mesoproterozoic rocks of the Collier Basin (Fig. 2 and Plate 1).

Palaeoproterozoic Ashburton Basin

The Ashburton Basin (Thorne, 1990a; Thorne and Seymour, 1991) corresponds to the present day outcrop of the Wyloo Group. It is exposed in a broad west-northwesterly trending belt in the northeastern part of the study area and comprises a 12 km-thick succession of low-grade, metasedimentary and metavolcanic rocks (Fig. 2 and Plate 1). Tyler and Thorne (1990) and Thorne and Seymour (1991) interpreted the Ashburton Basin stratigraphy as a response to the transition from an active tectonic margin to a foreland basin, during the convergence of the Pilbara and Yilgarn Cratons. The strongly diachronous nature of sedimentation during the foreland basin stage was highlighted by Evans et al. (2003) in their comparison of geochronological data from the upper Wyloo Group and the overlying Capricorn Group. Krapez (1999) considered the Ashburton Basin fill in terms of two megasequences that record the opening and closure of an Atlantic-type ocean. Other workers have suggested that the lower part of the Ashburton Basin succession, along with the underlying Turee Creek Group of the Mount Bruce Supergroup, were deposited in the McGrath Trough (Horwitz, 1982; Blake and Barley, 1992; Powell and Horwitz, 1994; Martin et al., 2000), a foreland basin related to the development of the Ophthalmia Fold Belt (Cawood and Tyler, 2004).



Wyloo Group (*PW-s*)

The Wyloo Group was informally established and subdivided by MacLeod et al. (1963) and subsequently revised by Trendall (1979), Horwitz (1980), and Thorne and Seymour (1991). It has also been discussed in the context of a sequence stratigraphic framework by Krapez (1999). The Wyloo Group unconformably overlies Archaean granite–greenstone and Archaean to Palaeoproterozoic supracrustal rocks of the Pilbara Craton along the northern margin of the Capricorn Orogen. It is unconformably overlain by the Proterozoic rocks of the Blair, Bresnahan, and Edmund Basins and by the Phanerozoic cover of the Carnarvon Basin. The Wyloo Group is subdivided into a lower succession consisting of the Beasley River Quartzite and the overlying Cheela Springs Basalt, and an upper succession comprising the Mount McGrath Formation, Duck Creek Dolomite, June Hill Volcanics, and Ashburton Formation (Thorne and Seymour, 1991).

The age of the Wyloo Group is poorly constrained. The youngest population of detrital zircons in a sandstone from the Beasley River Quartzite gives a maximum sensitive high-resolution ion microprobe (SHRIMP) U–Pb age for this unit of 2446 ± 8 Ma (Geological Survey of Western Australia, 2005; GSWA 169084). Martin et al. (1998) provide a maximum SHRIMP U–Pb zircon age of 2209 ± 15 Ma for a volcaniclastic breccia in the overlying Cheela Springs Basalt. The age of the upper part of the Wyloo Group is more closely fixed by data from volcaniclastic units within the June Hill Volcanics and overlying Ashburton Formation. Evans et al. (2003) obtained SHRIMP U–Pb zircon ages of 1799 ± 8 Ma and 1786 ± 11 Ma from a pumice-breccia sandstone within the locally developed June Hill Volcanics on Wyloo, whereas a thick felsic volcaniclastic sandstone and siltstone unit within the Ashburton Formation on northeast EDMUND has yielded a SHRIMP U–Pb zircon age of 1806 ± 9 Ma (Geological Survey of Western Australia, 2005; GSWA 148922). These dates are slightly younger than the SHRIMP U–Pb age of 1819 Ma from the youngest zircon

population in Ashburton Formation sandstones reported by K. N. Sircombe (2002, written comm.) and the SHRIMP U–Pb zircon age of 1829 ± 5 Ma obtained from a felsic volcaniclastic rock within the Ashburton Formation on Turee Creek (Sircombe, 2003). The younger age limit for the Wyloo Group is also constrained by the SHRIMP U–Pb age of 1786 ± 5 Ma for the Boolaloo Granodiorite (Krapez and McNaughton, 1999), that intrudes the Ashburton Formation on Wyloo.

The only Wyloo Group units exposed within the study area are the Duck Creek Dolomite and Ashburton Formation of the upper Wyloo Group.

Duck Creek Dolomite (Ewd-k)

The Duck Creek Dolomite (Thorne and Seymour, 1991) rests conformably on the Mount McGrath Formation (not exposed in the study area) and is conformably overlain by the Ashburton Formation. It has a maximum thickness of 1 km on adjacent Wyloo, however only the uppermost part of the formation is exposed in the study area, where it forms a series of small outcrops in the northeastern part of Edmund (around MGA 496000E 7454000N).

The maximum age for the Duck Creek Dolomite is poorly constrained by the SHRIMP U–Pb zircon age of 2209 ± 15 Ma from the underlying Cheela Springs Basalt (Martin et al., 1998). The younger age limit is fixed by the 1806–1786 Ma ages from the overlying June Hill Volcanics and Ashburton Formation (Evans et al., 2003; Geological Survey of Western Australia, 2005; GSWA 148922).

The formation consists of thin- to thick-bedded, buff, grey, or mauve laminated dolostone interlayered with thin- to very thick bedded dolostone breccia. Silicification is locally intense. Thin-bedded dolostones are planar to undulose laminated and often contain layers and nodules of red or black chert. Beds are generally interstratified with thin horizons of chloritic or ferruginous mudstone, and may contain synsedimentary folds. Thin-bedded dolostone is transitional into nodular dolostone, the texture of which ranges from a gentle pinch-and-swell in the dolostone layers to a complex network of interlocking nodules. Thin- to very thick beds of both clast- and matrix-supported, pebble- to boulder-dolostone breccia consist of a chaotic mixture of dolostone fragments set in a matrix of mudstone, coarsely crystalline dolomite or sparry quartz.

Thorne and Seymour (1991) interpreted the upper part of the Duck Creek Dolomite as an assemblage of shelf-slope carbonates.

Ashburton Formation (EWa-s, EWa-st, EWa-sc, EWa-f, EWa-mh)

The Ashburton Formation, the uppermost stratigraphic unit of the Wyloo Group, conformably overlies the Duck Creek Dolomite and is unconformably overlain by the Capricorn, Bresnahan, and Edmund Groups. It outcrops in a broad southeast-trending belt in the northeastern part of Edmund and has an estimated thickness of 5 to 12 km (Thorne and Seymour, 1991).

The age of the Ashburton Formation is fixed by SHRIMP U–Pb data from volcanic and sandstone units within the formation, from volcanics in the underlying June Hill Volcanics and the overlying Capricorn Group, and from the Boolaloo Granodiorite. Evans et al. (2003) obtained SHRIMP U–Pb zircon ages of 1799 ± 8 Ma and 1786 ± 11 Ma from a pumice-breccia sandstone within the locally developed June Hill Volcanics on Wyloo, whereas a thick felsic volcaniclastic sandstone and siltstone unit within the Ashburton Formation on northeast Edmund has yielded a SHRIMP U–Pb zircon age of 1806 ± 9 Ma (Geological Survey of Western Australia, 2005; GSWA 148922). These dates are slightly younger than the SHRIMP U–Pb age of c. 1819 Ma reported from the youngest zircon population in seven Ashburton Formation sandstones (Sircombe, K. N., 2002, written comm.) and the SHRIMP U–Pb age of 1829 ± 5 Ma obtained from a felsic volcaniclastic unit within the Ashburton Formation (Sircombe, 2003). Hall et al. (2002) reported a SHRIMP U–Pb age of 1804 ± 7 Ma for a felsic volcanic unit in the unconformably overlying Capricorn Formation (now Capricorn Group). The younger age limit for the Ashburton Formation is also constrained by the SHRIMP U–Pb age of 1786 ± 5 Ma for the Boolaloo Granodiorite that intrudes these rocks on Wyloo (Krapez and McNaughton, 1999). The contradictory nature of some of this age data may reflect markedly diachronous foreland basin sedimentation during the Capricorn Orogeny (Tyler and Thorne, 1990; Thorne and Seymour, 1991; Evans et al., 2003).

The Ashburton Formation (*EWa-s*) is composed of mudstone, siltstone, and immature sandstone, interbedded with minor amounts of conglomerate and volcanic rock. Mudstone and siltstone make up an estimated 65% of the formation and are most abundant in middle and upper parts of the stratigraphy. Chloritic and ferruginous mudstones occur as layers, a few millimetres to several metres thick that are interbedded with sandstone, conglomerate, or chemical deposits; they also occur in mudstone-dominated units up to several hundreds of metres thick. Mudstones are either structureless or parallel laminated. Chloritic siltstones occur as beds within thick mudstone units, or as a capping thin- to medium-bedded sandstone. Their internal structure consists of parallel lamination or climbing ripple cross-lamination. In many cases, primary structure is modified by soft-sediment deformation.

Feldspathic and lithic quartz sandstone (*EWa-st*) make up approximately 30% of the Ashburton Formation. It is the most abundant rock type in the lower part of the stratigraphy. Two varieties of arenaceous deposit are recognized; thin- to medium-bedded sandstone and massive sandstone. Thin to medium thickness sandstone beds are laterally continuous, normally graded, and display partial or complete development of the Bouma sequences of sedimentary structures. Massive sandstone is generally medium- to coarse-grained or pebbly, and occurs in tabular or lenticular beds, up to 5 m thick. Palaeocurrent data from Ashburton Formation sandstones in the study area suggest sediment transport was either toward the west-northwest or towards the northeast (Thorne and Seymour, 1991).

Clast- and matrix-supported conglomerate (*EWa-sc*) outcrops in lenticular or tabular beds up to 40 m thick.

These beds are commonly interlayered with sandstone and mudstone. Many conglomerate beds are parallel-stratified and may show either normal or reverse grading. Others, particularly the coarser grained conglomerates, are massive. Clasts consist of vein quartz, with smaller amounts of jaspilitic chert, felsic volcanic rock, and silicified sandstone.

Thin units of felsic volcaniclastic rock (*PWa-f*) occur interbedded with other Ashburton Formation sedimentary rocks. They are particularly well exposed in the area northeast of Stockyard Creek (MGA 495397E 7411035N). Here, the thickest volcaniclastic unit is about 45 m thick and outcrops over a strike length of at least 7 km, close to the unconformity with the overlying Capricorn Group. It has a gradational contact with the underlying Ashburton Formation siltstone and sandstone, these rocks become more siliceous as the base of the felsic volcaniclastic unit is approached. The lowermost 1–2 m of the volcaniclastic unit is thinly tabular bedded, whereas the overlying 20 m is characterized by tabular to sublenticular, thick to very thick, weakly defined bedding, that is cut by a pervasive network of joints. This part of the unit has a sand-sized clastic appearance on weathered surfaces, but no internal detail other than diffuse, irregular undulose, porcelanous lamination. The top 20 m of the felsic volcaniclastic unit is composed of thin- to medium-bedded, sand-sized volcaniclastic material, interbedded, with thin siltstone layers. Some ripple cross-lamination is present in the volcaniclastic beds. The upper contact with the overlying Ashburton Formation succession is very poorly exposed, but it appears transitional. It is characterized by an increase in the proportion of siltstone, which becomes less siliceous upwards. Felsic volcaniclastic units, other than the ones exposed northeast of Stockyard Creek, are mostly 1–20 m thick, thin- to thick-bedded, and are composed of fine- to coarse-grained felsic volcanic sandstone. Accretionary lapilli are recorded in a volcaniclastic unit north of Woolshed Outcamp (SITEID DBS1844B, MGA 461070E 7449570N).

In the northwestern part of Ullawarra, Ashburton Formation rocks are metamorphosed to upper greenschist–lower amphibolite facies. Pelitic, semi-pelitic, and psammitic schist (*PWa-mh*) forms a series of small outcrops north of 12 Mile Well (MGA 406643E 7452471N). These rocks are lateral equivalents of metamorphosed Ashburton Formation siltstone and sandstone that outcrop extensively on the southern part of Wyloo, immediately to the north. The metamorphosed Ashburton Formation rocks are unconformably overlain by the basal units of the Edmund Group. Pelitic rocks are now represented by a coarse-grained metamorphic mineralogy that obscures all primary sedimentary structures. Psammitic units are tabular, thin- to very thick bedded, and may preserve evidence of former sedimentary grading locally. In thin section, most of the schists comprise varying proportions of quartz, muscovite, and biotite, together with porphyroblasts of biotite, andalusite, cordierite, and garnet.

Thorne and Seymour (1991) interpret the Ashburton Formation as a linear submarine fan system developed in a foreland basin setting.

Blair Basin

The Blair Basin (Thorne, 1990b; Thorne and Seymour, 1991) corresponds to the present day outcrop of the Capricorn Group. It forms a broad west-northwesterly trending outcrop in the northeastern part of the study area and comprises a 1.5 to 3 km succession of low-grade metasedimentary and metavolcanic rocks. Tyler and Thorne (1990), Thorne and Seymour (1991), Hall et al. (2001), and Cawood and Tyler (2004) interpreted the Blair Basin stratigraphy as having been deposited during the final stages of foreland basin evolution that accompanied convergence of the Pilbara and Yilgarn Cratons. The strongly diachronous nature of sedimentation during this foreland basin stage was highlighted by Evans et al. (2003) in their comparison of geochronological data from the upper Wyloo Group and the Capricorn Group. An alternative view was put forward by Krapez (1999) who interpreted the Blair Basin as the eroded remnant of a retroarc satellite basin, formed as a result of southeasterly dipping subduction beneath the Capricorn hinterland.

Capricorn Group (*PR-s*)

Rocks assigned to the Capricorn Group have been included within the Wyloo Group (e.g. Horwitz, 1980; Seymour et al., 1988). Subsequently, Thorne and Seymour (1991) regarded these rocks as a separate, younger formation because of a marked angular unconformity that separates them from the underlying Ashburton Formation. The Capricorn Formation was then raised to group level as a result of work carried out during this present study. This redefinition is based on the recognition of two lithostratigraphic units, the lower Bywash Formation (named after Bywash Bore on central Capricorn), and the upper Mooline Formation (named after Mooline Well on central Capricorn). In addition, a third named stratigraphic unit, the Koonong Member (named after Koonong Pool on southeastern Capricorn) has been identified at the top of the Bywash Formation. The type section for the Capricorn Group is the same as that proposed for the Capricorn Formation by Thorne and Seymour (1991) and is exposed along a northward draining creek that cuts the basal unconformity northeast of Stockyard Creek (MGA 493160E 7412160N). Here the Capricorn Group has an estimated mimimum thickness of about 1.5 km, although this estimate is made difficult by the faulted nature of the upper part of the section and the fact that the top of the Capricorn Group is not exposed. In the western Capricorn Range, a thickness estimate based on more limited dip information suggests the Capricorn Group has a minimum thickness of about 2.5–3 km in the area east of Irregully Creek (around MGA 464628E 7419600N). These thickness estimates are considerably more than the 0.8 km figure suggested by Thorne and Seymour (1991), but are less than the 6 km value quoted by Barnes (1998).

Within the study area the Capricorn Group is exposed in the Capricorn Range, west of Irregully Creek (around MGA 450000E 7424000N), and at Mount Dawson (around MGA 453000E 7439500N). It is unconformably overlain by the Edmund Group. The Capricorn Group consists of sandstone, siltstone and mudstone, and small amounts of conglomerate, dolostone, and felsic volcanic rock

and was deposited in the interval between two episodes of post-Wyloo Group deformation (D_{1a} and D_{2a}) (see **Palaeoproterozoic Capricorn Orogeny** section).

The age of the Capricorn Group is fixed by SHRIMP U–Pb zircon data from lower and upper parts of the succession. Hall et al. (2002) reported an age of 1804 ± 7 Ma for a felsic volcanic unit (Koonong Member) in the Bywash Formation, whereas the youngest population of detrital zircons in a coarse-grained lithic sandstone from the overlying Mooline Formation indicates this unit has a maximum age of 1801 ± 14 Ma (Geological Survey of Western Australia 2005; GSWA 148925). These results are within error of the 1799 ± 8 Ma and 1806 ± 9 Ma ages obtained respectively from the June Hill Volcanics (Evans et al., 2003) and Ashburton Formation (Geological Survey of Western Australia, 2005; GSWA 148922) in the underlying Wyloo Group.

Bywash Formation (*ERb-s*)

The Bywash Formation (*ERb-s*) is the lowermost stratigraphic unit of the Capricorn Group and has an estimated thickness range of 400–550 m. The formation outcrops extensively in the Capricorn Range (around MGA 472000E 7422000N), west of Irregully Creek (around MGA 449000E 7424000N), in small outliers at Mount Dawson (around MGA 453000E 7439500N) and south of Bywash Bore (MGA 458800E 7434500N). It unconformably overlies the Ashburton Formation and is conformably overlain by the Mooline Formation. The Bywash Formation is composed of thin- to very thick bedded sandstone, dolomitic sandstone, dolostone, siltstone, and felsic volcanic rock.

Fine- to coarse-grained, thin- to very thick bedded quartz sandstone, dolomitic sandstone, and lithic sandstone are commonly ferruginous and micaceous. A prominent 1.5 – 4 m-thick, trough cross-stratified quartz sandstone unit forms the base of the formation in the central Capricorn Range (e.g. around MGA 492030E 7418650N) and records a northeasterly directed palaeoflow. The overlying dolomitic sandstones and lithic sandstones display a range of sedimentary structures that include parallel stratification, trough and tabular cross-stratification, ripple cross-lamination, sole markings, and ball-and-pillow structures. Most of the sandstones are poorly to moderately sorted lithic quartz arenites and wackes. Lithic clasts form up to 10% of the rock and include siltstone, very fine grained quartzite, chert, phyllite, and rare fine-grained quartz–tourmaline composites. The main accessory minerals are often concentrated within specific laminae and include opaque minerals, sericite, feldspar, tourmaline, and zircon. Alignment of sericite may also form a distinct foliation throughout the rock.

Lenticular units of interbedded siltstone, fine- to medium-grained sandstone, and dolostone (*ERb-sl*) outcrop in the northwestern Capricorn Range (e.g. around MGA 473160E 7427890N). Siltstones and sandstones are planar laminated or ripple cross-laminated. Dolostone units are about 1–2 m thick and consist of cross-stratified, coarse-grained dolomitic grainstone. Locally small (5 cm scale) domical stromatolites are present but the internal detail is very poorly preserved. Mudstone and siltstone are generally ferruginous and micaceous. Mudstones are either massive or parallel-laminated; siltstones are parallel-laminated or else display a variety of ripple profiles and bedforms. Thin (approximately 1 m thick) units of cross-stratified dolomitic grainstone with rare, poorly preserved domical stromatolites are interbedded with siliciclastic units in the northwestern Capricorn Range (WAROX SITEID AMT638, MGA 473160E 7427890N).

Thin units of felsic volcanic rock are interbedded with non-volcanic sedimentary rocks in the Bywash Formation. The most prominent of these, the Koonong Member (*ERbk-f*), occurs at the top of the formation and has yielded a SHRIMP U–Pb age of 1804 ± 7 Ma (Hall et al., 2001). The Koonong Member ranges in thickness up to 20 m and comprises tabular beds of silicified, massive or parallel-planar stratified, felsic volcaniclastic sandstone and accretionary lapilli tuff. Locally it contains deformed clasts of sedimentary rock. The Koonong Member is well exposed in a northward-draining creek 2 km northwest of Koonong Pool (MGA 492480E 7418340N). Here, the lowermost 6 m of this member consists of 0.1–0.5 m bedded, massive or planar laminated felsic volcaniclastic sandstone and vitric sandstone. These sandstones display small dish structures and fine-grained irregular siliceous lapilli. The overlying 2 to 3 m are dominated by tabular beds of siliceous, accretionary lapilli tuff. The lapilli are 2–8 mm in diameter and are packed into parallel-planar stratified beds that show normal grading locally. The upper 1.5 m of the member consists of very fine grained siliceous volcaniclastic sandstone and the topmost contact is marked by a 0.5 – 1 m-thick unit of dolomitic sandstone breccia that contains angular felsic volcanic clasts.

The felsic volcanic units are composed of recrystallized, felsic, vitric volcaniclastic sandstone and siltstone. Clasts consist of diffuse, recrystallized and sericitized vitric lapilli; often defined by fine-grained granular iron oxide inclusions, angular and broken sericitized feldspar, millimetre-sized anhedral irregular aggregates of chlorite, muscovite, and both angular and rounded fragments of beta quartz. Accessory zircon and apatite are also present. The clasts are set in a fine-grained, wispy laminated, recrystallized quartz–feldspar–sericite matrix.

Thorne and Seymour (1991) interpret the lower part of the Capricorn Group, including the Bywash Formation, as an assemblage of braided-fluvial and shallow-marine (or lacustrine) deposits. They were deposited in a rapidly subsiding basin, located to the north of a tectonically active upland area that occupied the central part of the Capricorn Orogen.

Mooline Formation (*ERm-s*)

The Mooline Formation (*ERm-s*), the uppermost stratigraphic unit of the Capricorn Group, outcrops throughout the Capricorn Range where it conformably overlies the Bywash Formation. Attempts to estimate the preserved thickness of the Mooline Formation are made difficult by the nature of Ashburton Fold Belt D_{2a} and D_{3a} faulting and folding. Estimates range from about 1.1 km

in the area south of Koonong Pool to about 2–2.5 km in the western Capricorn Range (around MGA 464628E 7419600N). The Mooline Formation is composed of thin- to very thick bedded sandstone, dolomitic sandstone, siltstone, dolostone, conglomerate, and minor felsic volcaniclastic sandstone.

Thin- to very thick bedded sandstone units are composed of fine- to very coarse grained or pebbly sandstone. They are commonly micaceous or dolomitic, and are often interbedded with variable amounts of siltstone. Fine- to medium-grained quartz sandstone or lithic quartz sandstone is thin- to medium-bedded and displays a range of internal structures including parallel-planar lamination, low-angle planar cross-lamination, undulatory lamination, and ripple cross-lamination. Linsen or flaser laminated fine-grained sandstone beds are sometimes associated with mixed sandstone and siltstone units. Medium- to very coarse grained or pebbly lithic sandstone and quartz sandstone occur in medium- to very thick bedded tabular to lenticular units. Internal structure is dominated by stacked sets of medium- to large-scale trough or planar tabular cross-stratification, interlayered with parallel-planar or undulatory stratification. Trough axes generally record a broad, northward palaeocurrent flow. Soft sediment deformation, in the form of ball-and-pillow structures or convolute lamination, may modify the primary internal structure. Petrographically the lithic sandstones are poorly sorted and contain a diverse suite of rock fragments including sedimentary and metasedimentary rock, altered felsic volcanic rock, and chlorite-rich rock. Single crystal quartz grains may form a relatively minor (20–25%) component of the rock and many are derived from a felsic volcanic source. Accessory minerals include disseminated, ragged limonite and leucoxene, and rare grains of tourmaline and fractured zircon.

The Mooline Formation includes three 100–250 m-thick units of siltstone and fine- to coarse-grained sandstone, interbedded with minor amounts of dolostone and felsic volcanic rock (*ERm-sl*). The lowest of these units generally occurs at the base of the formation, directly overlying the Koonong Member. This contact is marked by a 0.5 – 1 m-thick bed of dolomitic sandstone breccia, that contains angular clasts of felsic volcanic rock. The succession overlying the dolomitic sandstone breccia consists of siltstone interbedded with subordinate dolostone. The siltstone has the appearance of fine-grained felsic volcaniclastic rock in places, especially close to its lower contact; however, most of the unit is black and carbonaceous, with parallel-planar lamination. Much of the dolostone consists of fine- to coarse-grained dolarenite with irregular scouring and undulatory lamination. Some fine-pebble dolorudite is also present. Sandstones that occur interbedded with siltstone throughout the overlying parts of the siltstone and sandstone unit are either normally graded or non-graded, and may show parallel-planar lamination, ripple cross-lamination, or trough cross-stratification.

Approximately 220 m of thin- to very thick bedded dolostone, dolomitic sandstone, dololutite, dolorudite, and quartz sandstone (*ERm-kd*) outcrops in the northern Capricorn Range, southeast of Police Camp Yard (around MGA 478200E 7425000N). Based on present outcrop geometry, the mixed carbonate–siliciclastic unit appears to be a lenticular body that overlies the lowermost siltstone and sandstone unit (*ERm-sl*) in the Mooline Formation. Dolostone units comprise thin to very thick bedded, massive or stratified dolarenite and dolorudite interbedded with dololutite and dolomitic sandstone. Some dolostone beds show faint traces of small (<1 cm wide) columnar stromatolites. Dolomitic sandstone and medium- to very coarse grained quartz sandstone show parallel- or low-angle planar lamination and medium- to very large scale trough cross-stratification, with over-steepened laminae locally.

Two or three lenticular units of polymictic, clast- and matrix-supported pebble- to cobble-conglomerate, pebbly sandstone, coarse-grained sandstone, dolomitic sandstone, and dolostone (*ERm-sc*) are present in the upper part of the Mooline Formation around Koonong Pool. The most prominent of these units is estimated to be 150 m thick. Most of the conglomerates are massive and very poorly sorted with clast diameters generally in the range 5–200 mm, although boulders up to 0.8 m diameter are recorded. Clasts are composed of dolostone, sandstone, chert (commonly jaspilitic), vein quartz, felsic volcanic rock, granular iron-formation, and mudstone. Lenticular beds of coarse-grained to pebbly lithic sandstone, dolomitic sandstone, and quartz sandstone are generally massive, although normal grading is observed in places. Dolostone beds are also lenticular; they are generally composed of coarse-grained dolarenite or dolorudite with angular to rounded clasts.

Thin beds and laminae of felsic volcaniclastic sandstone occur interlayered with non-volcanic sandstone and siltstone units within the Mooline Formation. The thickest volcaniclastic sandstone bed is 1.2 m and is characterized by a massive internal structure. Thinner beds consist of fine- to medium-grained felsic volcaniclastic sandstone and display parallel planar or undulatory lamination or ripple cross-lamination.

Thorne and Seymour (1991) interpret the middle to upper part of the Capricorn Group, including the Mooline Formation, as an assemblage of predominantly shallow-marine (or lacustrine) deposits. They were deposited in a rapidly subsiding basin, located to the north of a tectonically active upland area that occupied the central part of the Capricorn Orogen. In the latter stages of the basin's evolution, source area uplift was accompanied by braided fluvial progradation. Finally, localized proximal fan-delta deposits, containing a high proportion of carbonate and felsic volcanic material were introduced from the south.

Palaeoproterozoic Gascoyne Complex

The Gascoyne Complex is composed of Palaeoproterozoic metasedimentary and meta-igneous rocks, which are extensively intruded by large volumes of granite. The southern part of the Gascoyne Complex comprises late Archaean to Palaeoproterozoic foliated and gneissic

granitic and metasedimentary rock, collectively referred to as the Glenburgh Terrane. The Glenburgh Terrane is dominated by 2005–1970 Ma granitic gneiss and granite that formed at an Andean-type margin before accretion to the Yilgarn Craton at c. 1960 Ma (Occhipinti et al., 1999; Sheppard et al., 1999). Late Archaean granitic rocks (Halfway Gneiss) of the terrane probably form basement (Occhipinti and Sheppard, 2001). The relationship of the Glenburgh Terrane to the remainder of the Gascoyne Complex is unclear; the Glenburgh Terrane may either extend underneath the northern part of the complex, or have been accreted to it (Sheppard, 2004). The Glenburgh Terrane is not within the study area, and so it is not discussed further.

The boundary between the Gascoyne Complex and Yilgarn Craton to the south is marked by the Errabiddy Shear Zone. This shear zone contains deformed metasedimentary and mafic meta-igneous rocks of the Camel Hills Metamorphics with protolith ages between c. 2025 and c. 1970 Ma.

The Palaeoproterozoic geology of the northern Gascoyne Complex can be described in terms of three zones: the Boora Boora, Mangaroon, and Limejuice Zones (Fig. 2 and Plate 1). The Boora Boora and Limejuice Zones, which flank the Mangaroon Zone, contain metasedimentary rock successions that were intruded by granitic rocks during the Capricorn Orogeny; these granites have been grouped into the 1830–1780 Ma Moorarie Supersuite (Occhipinti and Myers, 1999; Sheppard and Swager, 1999). Deformation and metamorphism related to the Capricorn Orogeny affected the entire Gascoyne Complex, and granites of the Moorarie Supersuite were intruded throughout the complex (Occhipinti et al., 1998; Krapez and McNaughton, 1999; Occhipinti and Sheppard, 2001; Sheppard et al., 2003). Rocks of the Limejuice Zone are present only in the southwest corner of MANGAROON, but rocks of the Mangaroon and Boora Boora Zones outcrop extensively on MANGAROON, MAROONAH, and EDMUND (1:100 000 sheet).

Most of the Gascoyne Complex rocks on MANGAROON and EDMUND (1:100 000 sheet) belong to the Mangaroon Zone. This zone is composed of sedimentary rocks deposited after c. 1680 Ma that were deformed and metamorphosed at medium to high grade during the Mangaroon Orogeny at 1680–1620 Ma. These metamorphic rocks are part of the newly defined Pooranoo Metamorphics. Granite plutons of the Durlacher Supersuite were largely intruded at 1680–1660 Ma during and shortly after the peak of regional metamorphism. This work has confirmed the presence of granitic magmatism of this age first identified by Pearson (1996), and has further delineated the extent of this magmatism and the associated orogenic event. Smaller volumes of granite of the Durlacher Supersuite were emplaced until as late as c. 1620 Ma throughout the Gascoyne Complex. Intrusion of granite plutons at c. 1620 Ma into the Yarlarweelor Gneiss Complex adjacent to the southeastern edge of the Gascoyne Complex was known previously (Sheppard and Swager, 1999; Geological Survey of Western Australia, 2005), but the extent of this magmatism and its relationship to tectonothermal events was unclear.

Williams (1986) suggested that metasedimentary rocks in the northern Gascoyne Complex passed northwards, with decreasing metamorphic grade, into low-grade metasedimentary rocks of the upper Wyloo Group. SHRIMP U–Pb dating of samples collected during mapping show that the protoliths to rocks of the Pooranoo Metamorphics are younger than sedimentary rocks of the Ashburton Formation (see **Late Palaeoproterozoic Pooranoo Metamorphics**), although metasedimentary rocks of the Boora Boora Zone (and the Limejuice Zone) appear to have been deposited at the same time as the Ashburton Formation (Fig. 2).

The Gascoyne Complex is unconformably overlain by late Palaeoproterozoic to Mesoproterozoic sedimentary rocks of the Bangemall Supergroup to the east, and by Phanerozoic sedimentary rocks of the Carnarvon Basin to the west. Gascoyne Complex rocks are exposed as a series of inliers within the sedimentary rocks to the east and west.

Boora Boora Zone

The Boora Boora Zone consists of metasedimentary schists and gneisses that were initially deformed and metamorphosed during the Capricorn Orogeny, and intruded by granites of the Moorarie Supersuite between c. 1805 and c. 1785 Ma. These metasedimentary rocks are about 100 m.y. older than protoliths to the Pooranoo Metamorphics in the Mangaroon Zone to the south.

Palaeoproterozoic supracrustal rocks

In the western part of MAROONAH north of Collins Well (MGA 350999E 7417181N), metasedimentary and minor meta-igneous rocks of the Boora Boora Zone are extensively intruded by foliated and gneissic granites. These supracrustal rocks are about the same age as the Ashburton Formation of the upper Wyloo Group to the north and metasedimentary rocks in the Limejuice Zone on the MOUNT PHILLIPS 1:100 000 sheet area to the south (Fig. 2).

Amphibolite and mafic schist (EmwaGAB)

Amphibolite and actinolite–plagioclase–epidote schist are tectonically interleaved with foliated and gneissic granites. The mafic rocks form lenses typically less than 2 m thick and less than 50 m long, most of which are too small to show on the map. However, in the northwestern corner of MAROONAH, composite layers up to 100 m thick and 3 km long are exposed. Amphibolite is commonly heterogeneous, ranging from a medium-grained rock with a granoblastic texture to a porphyritic leucogabbro with a relict igneous texture.

For many of the mafic rocks it is difficult to determine an intrusive or extrusive origin, as contacts are not exposed, or are faulted. In the area about 6 km northeast of Boora Boora Bore (MGA 357080E 7455280N), layered metagabbro, including porphyritic meta-leucogabbro, is exposed. The contact with the enclosing granitic gneiss is faulted, but the coarse porphyritic and fractionated nature of some metagabbro layers suggests

that they may be intrusive. About 5 km east-northeast of Minga Springs (MGA 361480E 7444890N) inclusions of massive actinolite–clinozoisite–quartz rock in granodiorite gneiss (*EmggGAB*) are exposed. In a creek pavement about 6 km east-southeast of Mundong Well (MGA 361310E 7438650N) fine-grained amphibolite layers less than 0.5 m thick truncate gneissic layering in granitic gneiss at a low angle. Amphibolite also contains rare inclusions of granitic gneiss attesting to an intrusive origin.

Most of the mafic rocks consist of fine- to medium-grained epidote amphibolite or actinolite gneiss. Typically, the rocks comprise bluish-green actinolite or green actinolitic hornblende, clinozoisite, and quartz, with minor titanite. Porphyritic leucogabbro contains plagioclase phenocrysts up to 1 cm in diameter pseudomorphed by granular clinozoisite, sericite, and sodic plagioclase, with interstitial actinolitic hornblende, clinozoisite, and sericite.

Calc-silicate gneiss and schist (EmkqGAB)

Calc-silicate gneiss and schist are a minor component of the supracrustal rocks in the Boora Boora Zone. The main exposure of this rock unit is as a near-continuous layer up to about 120 m thick that defines a megascopic refolded fold centred on Boora Boora Bore. Otherwise, calc-silicate rocks form layers less than a few metres thick and a few tens of metres long. Calc-silicate gneiss is composed of medium- to fine-grained diopside–zoisite–titanite–plagioclase–quartz with thin layers of zoisite–quartz–titanite(–diopside). Calc-silicate schist shows extensive tremolite replacement of diopside, and albite–oligoclase after original plagioclase. Calc-silicate rocks also include cream to pale green marble.

Metamorphosed iron formation (EmiGAB)

Metamorphosed banded and granular iron formation (*EmiGAB*) is confined to the northwestern corner of Maroonah, where it outcrops as rubbly strike ridges. It forms semi-continuous layers or lenses up to 30 m thick, either interlayered with calc-silicate gneiss (*EmkqGAB*) or tectonically interleaved with foliated and gneissic granodiorite and tonalite (*EmggGAB*) west of Boora Boora Bore. Most of the iron formation is granular, but locally it contains chert bands 3–7 mm thick. Metamorphosed iron formation comprises magnetite, grunerite, and quartz, with secondary hematite and goethite.

Pelitic and psammitic schist (EmlsGAB)

Pelitic and psammitic schist (*EmlsGAB*) outcrop in an east-southeasterly trending belt about 12 km wide along the southern edge of the Boora Boora Zone. The rocks form large rafts and screens within foliated and gneissic granodiorite and tonalite (*EmggGAB*). Pelitic and psammitic schist outcrop as low, rough strike ridges and hills. These metasedimentary rocks are typically strongly weathered and ferruginous close to the unconformity with the overlying Edmund Group.

The pelitic and psammitic rocks are locally gneissic, although in the area about 6 km east of Middle Bore, the unit consists of interbedded metamorphosed siltstone and feldspathic pebbly sandstone. In this area the rocks have been metamorphosed at low grade and graded bedding is preserved. Sandstone beds are 0.3–1.0 m thick and contain clasts of quartz and lesser feldspar up to 1 cm in diameter, but mostly 2–6 mm. Some feldspar clasts are tabular. Immediately west of Horse Well (MGA 354630E 7428520N) blocks and lenses of fine-grained quartzite are included within foliated and gneissic granodiorite and tonalite (*EmggGAB*).

No geochronological data are available directly from the pelitic and psammitic schist. However, pelitic and psammitic schist is intruded by foliated and gneissic granites, one of which near Mundong Well (GSWA 169088) is dated at 1806 ± 7 Ma (Geological Survey of Western Australia, 2005). Although many of the schists look similar to pelitic and psammitic gneiss (*EP-mln*) of the Pooranoo Metamorphics, the schists are considerably older; protoliths to the Pooranoo Metamorphics have a maximum age of c. 1680 Ma (see **Late Palaeoproterozoic Pooranoo Metamorphics**).

Most of the schists comprise varying proportions of muscovite, quartz, plagioclase, biotite, andalusite, and garnet. Near the western edge of Maroonah, the rocks include muscovite–quartz–biotite–plagioclase(–sillimanite) schist. In the area around the Laura U–Cu–Pb prospect (MGA 361549E 7424474N) layers up to 1 m thick of finely laminated quartz–tourmaline–muscovite–siderite rock are present. In places, these tourmaline bearing rocks are transitional to tourmaline-rich pelitic schist. Details of the metamorphic assemblages and grades are discussed in the sections dealing with the various orogenic events (see below).

Limejuice Zone

The Limejuice Zone consists of metasedimentary schist that is intruded by granites of the Moorarie Supersuite. These metasedimentary rocks are of markedly lower grade (and were deposited more than 100 m.y. earlier) than metasedimentary rocks of the Pooranoo Metamorphics in the Mangaroon Zone. The Limejuice Zone may have a tectonic history similar to that of the Boora Boora Zone, and this crust may be contiguous underneath the intervening Mangaroon Zone.

Palaeoproterozoic supracrustal rocks

Quartz–mica schist and metamorphosed sandstone (EmsqmGAL)

Quartz–mica schist and metamorphosed fine-grained sandstone are present as rare rafts and scattered inclusions within granites of the Moorarie Supersuite. Two rafts 600–700 m long and about 150 m wide outcrop 7 km north-northwest and 3 km north of Diamond Well within medium-grained porphyritic biotite monzogranite (*EM-gmp*). Exposures consist of schist with up to 50% sand-sized grains of quartz and a few percent of quartz granules in a muscovite- and chlorite-rich matrix.

Palaeoproterozoic Moorarie Supersuite

Palaeoproterozoic granitic rocks in the Limejuice Zone belong to the 1830–1780 Ma Moorarie Supersuite. This supersuite is developed across the entire width of the Gascoyne Complex and also intrudes the upper Wyloo Group to the north (Krapez and McNaughton, 1999) and the northern edge of the Yilgarn Craton to the south (Occhipinti et al., 1998; Occhipinti and Myers, 1999; Sheppard and Swager, 1999; Sheppard et al., 2003). In the Boora Boora Zone to the north of MANGAROON, foliated and gneissic granites (*EmggGAB*, *EmgmGAB*) have igneous crystallization ages indistinguishable from granites of the Moorarie Supersuite. These foliated and gneissic rocks are interpreted to be deformed and metamorphosed granites of the Moorarie Supersuite. Foliated granite and augen gneiss of the Gooche Gneiss (*Pgo-mgn*), which forms basement to the Mangaroon Zone, is also part of the supersuite.

Foliated and gneissic granodiorite and tonalite (EmggGAB)

Foliated and gneissic granodiorite and tonalite (*EmggGAB*) comprises the bulk of the Boora Boora Zone on MAROONAH. The most common rock type is a medium- to fine-grained grey foliated or gneissic granodiorite. Most rocks are weakly pegmatite banded, but locally they are strongly pegmatite banded. The granodiorite is interleaved with lesser amounts of foliated to gneissic fine-grained, dark grey tonalite, and foliated and gneissic monzogranite (*EmgmGAB*). The unit also includes dykes of pale-grey biotite monzogranite that intrude the gneissic layering at a low angle, but which are also deformed. The dykes are widespread, although not abundant, and up to 2 m wide.

The foliated and gneissic granodiorite and tonalite outcrops as low rounded hills covered in boulders and tors, with some pavements. In the northern part of the zone on MAROONAH the rocks are commonly fresh, but farther south, closer to the unconformity with the overlying Edmund Group, the rocks are ferruginous and strongly weathered. Here they can be difficult to distinguish from metasedimentary rocks — particularly high-grade metamorphosed feldspathic sandstone (*EP-mtf*) — of the Pooranoo Metamorphics.

Foliated, equigranular to porphyritic biotite granodiorite with sparse pegmatite veins was sampled 6 km west-northwest of Minga Springs for SHRIMP U–Pb zircon geochronology. The sample (GSWA 169087) is from a low-strain domain and is representative of the main rock type comprising the unit. Sixteen analyses of 16 zircon grains in the sample gave an igneous crystallization age of 1794 ± 9 Ma (Geological Survey of Western Australia, 2005). In addition, eight xenocrysts have ages between c. 2280 Ma and c. 1850 Ma. A monzogranite dyke from about 5 km northwest of Boora Boora Bore was also sampled for SHRIMP U–Pb geochronology (GSWA 169086). The dyke has an igneous foliation, and cuts gneissic layering (S_1) in the gneissic granodiorite, and intrudes an F_2 fold along the axial surface. The dyke has an igneous crystallization age of 1784 ± 5 Ma (Geological Survey of Western Australia, 2005).

Low-strain areas of the granodiorite comprise a medium- to coarse-grained rock that is equigranular to weakly porphyritic. In places the granodiorite contains inclusions of biotite tonalite (MGA 349400E 7443890N) or fine-grained monzogranite (MGA 349850E 7444390N). Where little affected by low-grade metamorphism, the granodiorite has an anhedral granular or amoeboid texture with mafic minerals consisting of biotite, or biotite and minor muscovite. Microcline or microperthite is a minor component. Accessory minerals include zircon, apatite, and allanite. The tonalite differs from the granodiorite in containing less K-feldspar and more biotite. There is no evidence of igneous hornblende in the granodiorite or tonalite.

Foliated and gneissic monzogranite (EmgmGAB)

Pale-grey, foliated and gneissic monzogranite (*EmgmGAB*) is tectonically interleaved with foliated and gneissic granodiorite and tonalite (*EmggGAB*) over a wide area on northwestern MAROONAH. However, it is predominant only in the area southwest of Boora Boora Bore. Here it forms a layer, which is probably folded, up to 700 m thick and more than 9 km long that extends onto the TOWERA 1:100 000 sheet area to the west. Low-strain areas consist of a medium-grained, even-textured biotite monzogranite with minor pegmatite veining. In places the monzogranite contains up to 10% oval-shaped K-feldspar phenocrysts about 1 cm in diameter. The monzogranite was sampled from pavements in the Telfer River at Mundong Well for SHRIMP U–Pb zircon geochronology. The sample (GSWA 169088) gave an igneous crystallization age of 1806 ± 7 Ma (Geological Survey of Western Australia, 2005). In places (e.g. MGA 349670E 7453520N) the monzogranite contains lenticular inclusions of fine-grained, dark-grey quartz diorite or tonalite.

Gooche Gneiss (Pgo-mgn)

The Gooche Gneiss (*Pgo-mgn*) was defined on EDMUND (Martin et al., 2002), where it forms several elongate rafts (each <2 km^2) in the Pimbyana Granite. On MANGAROON the gneiss outcrops over a wide area in the Mangaroon Zone between the Minga Bar Fault and the Mangaroon Syncline as a series of small (<2 km^2 and mostly <1 km^2) inliers amongst pelitic gneiss and granofels (*EP-mln*) and metamorphosed feldspathic sandstone (*EP-mtf*) of the Pooranoo Metamorphics. Contacts between the Gooche Gneiss and rocks of the Pooranoo Metamorphics are tectonic. The Gooche Gneiss ranges from a foliated, porphyritic biotite granodiorite or monzogranite, to a pegmatite-banded augen gneiss. Phenocrysts of K-feldspar are round and up to 3 cm in diameter. The gneiss is typically weathered, but is commonly well exposed as whalebacks and pavements.

A sample of augen gneiss (GSWA 169058) from the Gooche Gneiss on EDMUND (1:100 000 sheet), gave a SHRIMP U–Pb zircon age of 1776 ± 8 Ma, which is interpreted as the age of igneous crystallization of the precursor granite (Geological Survey of Western Australia, 2005). The sample is incorrectly described as a 'sheared quartzofeldspathic gneiss breccia'. The precursor granite is at least 30–40 m.y. older than sedimentary protoliths to the

Pooranoo Metamorphics, to which it probably comprises basement.

Medium- to coarse-grained tonalite (PM-gti)

Massive, medium- to coarse-grained tonalite, and lesser medium-grained granodiorite, outcrop over an area of more than 150 km^2 in the southwestern corner of MANGAROON. The unit forms low rounded hills covered in boulders and tors, as well as a sandy, gently undulating land surface with boulders and tors. Adjacent to thicker dolerite dykes, the tonalite is hornfelsed and forms long ridges up to approximately 25 m high.

About 3 km west-southwest of Minga Well (MGA 349960E 7350180N), a sample of coarse-grained tonalite (GSWA 178024) gave a SHRIMP U–Pb zircon age of 1783 ± 5 Ma (Geological Survey of Western Australia, 2005). In the far southwest corner of MANGAROON (MGA 348530E 7345970N), tonalite is intruded by dykes of medium- to coarse-grained strongly porphyritic biotite monzogranite (*PM-gmp*). The tonalite, as well as other granite plutons in the Minnie Creek batholith, is intruded by numerous dykes of fine-grained, leucocratic biotite granite (*PM-gma*).

The main tonalite phase is a medium- to coarse-grained, even-textured biotite tonalite with numerous clots of mafic rock and locally abundant rounded inclusions of quartz diorite. The tonalite contains about 15–20% biotite, and locally has prominent oval-shaped quartz crystals 5–7 mm in diameter. The northern margin of the intrusion consists of medium-grained tonalite and granodiorite that grade into the coarse-grained tonalite. However, in the area about 5 km west-southwest of Diamond Well (MGA 34890E 7357840N), the tonalite comprises angular blocks within granodiorite. The granodiorite is a lighter coloured rock than the tonalite, and contains much fewer mafic clots and inclusions of quartz diorite. The tonalite and granodiorite are commonly pale green owing to the presence of abundant epidote. Epidote is more abundant near dolerite dykes.

Quartz diorite inclusions are typically 5–30 cm long but may be up to 2 m in diameter. Inclusions are fine or fine to medium grained and typically sparsely to moderately plagioclase porphyritic; phenocrysts commonly have the same shape and texture as plagioclase crystals in the enclosing tonalite.

Equigranular medium-grained biotite(–muscovite) granodiorite (PM-gge)

Equigranular to sparsely porphyritic biotite(–muscovite) granodiorite outcrops over less than 2 km^2 in the far southwestern corner of EDMUND; most of the intrusion is exposed on MOUNT PHILLIPS to the south. The rock is massive and pale grey, and contains scattered round mafic inclusions.

Medium-grained porphyritic biotite monzogranite (PM-gmp)

Massive, medium-grained porphyritic biotite monzogranite outcrops over about 80 km^2 west of the Minga Bar Fault in the southwestern corner of MANGAROON. The monzogranite forms boulders, tors, and scattered pavements in a sandy undulating land surface with scattered low hills. Adjacent to thick dolerite dykes, the monzogranite is hornfelsed and forms long, boulder-covered ridges up to 25 m high.

A SHRIMP U–Pb zircon date of 1795 ± 8 Ma was obtained by Evans et al. (2003) for a sample of biotite monzogranite about 3 km north-northwest of Diamond Well (MGA 352850E 7361940N). This age is within error of the age of foliated and gneissic granites in the Boora Boora Zone about 70–80 km to the north. Dykes of porphyritic biotite monzogranite associated with a plug in the southwestern corner of MANGAROON intrude medium- to coarse-grained tonalite (*PM-gti*). The monzogranite contains scattered inclusions of pelitic schist less than 10 cm long, which are locally abundant.

The main rock type is a medium-grained, moderately to strongly porphyritic biotite monzogranite. Oval, or less commonly tabular, phenocrysts of K-feldspar are up to 5 cm long. Along the southern edge of the unit adjacent to the medium- to coarse-grained tonalite, fine- to medium-grained sparsely porphyritic monzogranite predominates. At one locality, about 3 km south of Diamond Well (MGA 354560E 7356320N), medium-grained monzogranite forms a raft within fine-grained monzogranite.

Leucocratic biotite monzogranite (PM-gml)

Massive, medium-grained, equigranular, leucocratic biotite monzogranite forms a north-northwest trending intrusion on the western side of the Minga Bar Fault. The intrusion is located near the southern edge of MANGAROON and extends on to EUDAMULLAH to the south. The monzogranite outcrops as abundant weathered boulders and pavements, and forms a gently undulating landscape. It forms nearly continuous outcrop southwest of Michelles Well (MGA 365100E 7347200N).

Biotite is the sole mafic mineral in the monzogranite, and comprises 5% or less of the rock. The intrusion is homogeneous in texture, and nearly so in composition, although locally it is granodioritic. The unit contains sparse round inclusions of fine-grained metasedimentary rock up to 5 cm in diameter. At the northwestern corner of the intrusion, a few dykes of leucocratic biotite monzogranite intrude medium- to coarse-grained tonalite (*PM-gti*).

Leucocratic biotite micromonzogranite (PM-gma)

Massive, leucocratic biotite micromonzogranite forms a small plug centred about 3.2 km southwest of Diamond Well (MGA 351690E 7357040N). It also forms numerous veins and dykes up to 3 m wide that intrude all other phases of the Moorarie Supersuite on MANGAROON. The micromonzogranite is a sugary and equigranular rock that is almost free of inclusions.

Palaeoproterozoic Capricorn Orogeny

The Capricorn Orogeny has been widely interpreted to reflect oblique collision of the Archaean Yilgarn and Pilbara Cratons (Tyler and Thorne, 1990). The age of

the orogeny was originally poorly defined, but recent work suggests that deformation, low- to medium-grade metamorphism and voluminous granite intrusion across the Gascoyne Complex took place between 1830 and 1780 Ma (Sheppard and Occhipinti, 2000; Occhipinti and Sheppard, 2001; Occhipinti et al., 2001). Deformation and metamorphism in the Wyloo and Capricorn Groups in the Ashburton Fold Belt to the north (Thorne and Seymour, 1991; Krapez and McNaughton, 1999) and high-grade metamorphism, deformation and granite intrusion along the northern margin of the Yilgarn Craton (Yarlarweelor Gneiss Complex; Occhipinti et al., 1998; Occhipinti and Myers, 1999; Sheppard and Swager, 1999; Sheppard et al., 2003) are also related to the Capricorn Orogeny.

Ashburton Fold Belt

The Ashburton Fold Belt formed in response to the Capricorn Orogeny and includes the deformed Wyloo and Capricorn Groups, as well as structurally reworked Archaean and Palaeoproterozoic rocks on the southern margin of the Pilbara Craton. The structural history of the Ashburton Fold Belt has been given by Tyler and Thorne (1990) and Thorne and Seymour (1991) who described two major deformation events, D_{1a} and D_{2a}. In addition, a third deformation event (D_{3a}) has been recognized during the course of this study. The earliest deformation, D_{1a}, took place after deposition of the Ashburton Formation (upper Wyloo Group) but prior to deposition of the Capricorn Group. This deformation was accompanied, or slightly post-dated, by a regional metamorphic event (M_{1a}). The second and third events (D_{2a}/M_{2a} and D_{3a}) took place after deposition of the Capricorn Group and following intrusion of the Boolaloo Granodiorite, but before deposition of the Edmund Group. On the basis of these relationships the timing of D_{1a}/M_{1a} was between about 1806 and 1787 Ma, whereas D_{2a} and D_{3a} took place between c. 1787 and c. 1620 Ma.

Thorne and Seymour (1991) recognized three structural zones within the Ashburton Fold Belt based on the geometry of the D_{2a} structures and the preservation of D_{1a} structures. Zone A is dominated by large-scale open to tight folds and dextral wrench faults, but is not present within the study area. Zones B and C are recognized on northeastern Ullawarra and Capricorn.

Zone B is developed in the Ashburton Formation, northeast of the interpreted fault line linking the points MGA 466400E 7456000N and MGA 500000E 7440000N on Capricorn. It represents a relatively high-strain zone formed during D_{2a}. As a result of this, the recognition of D_{1a} structures within Zone B is generally difficult because strong overprinting by D_{2a} has resulted in the early cleavage (S_{1a}) being coaxial, and often coplanar with the later fabric (S_{2a}).

Zone C occupies the remainder of the Ashburton Fold Belt on Ullawarra and Capricorn, between the southwestern boundary of Zone B and the Edmund Group unconformity. It is distinguished from Zone B by its generally lower level of D_{2a} strain leading to the better preservation of D_{1a} structures and also by the presence of large-scale F_{2a} folds and dextral wrench faults. Zone C also preserves evidence of D_{3a} structures in the western Capricorn Range.

Deformation and metamorphism (D_{1a}/M_{1a})

Most of the evidence for the D_{1a} deformation comes from Zone C and is based on the widespread S_{1a} foliation, the marked angular unconformity between the Ashburton Formation and the Capricorn Group, and rare F_{1a} folds. In many outcrops, evidence for D_{1a} is present in the form of an early S_{1a} cleavage developed subparallel to bedding. This cleavage is often crenulated by S_{2a}, and with the increase in metamorphic grade in southwestern parts of the fold belt, it develops into a metamorphic schistosity. In the Capricorn Range (e.g. localities around MGA 493300E 7412000N), the marked angular unconformity at the base of the Bywash Formation provides clear evidence that the Ashburton Formation was folded prior to deposition of the Capricorn Group. In addition, the Ashburton Formation may show a well-developed S_{1a} penetrative cleavage that is not developed in the overlying Capricorn Group (Thorne and Seymour, 1991). At Mount Blair, on adjacent Turee Creek, the basal unconformity of the Capricorn Group dips north at 50° as a result of D_{2a} folding. The S_{1a} cleavage in the underlying Ashburton Formation dips 15–45° south, while bedding dips (and youngs) southward at 0–30°. Rotation of bedding and S_{1a}, to their pre-D_{2a} orientation indicates that the tight F_1 fold was characterized by a steeply southward-dipping axial surface. An example of F_1 minor folds that have been refolded during D_{2a} is preserved north of Koonong Pool (WAROX SITEID AMT556, MGA 492918E 7418481N). Here, a pair of small-scale F_{1a} folds with 'S' and 'Z' vergence are preserved on the southern and northern limbs respectively of a westerly plunging, downward facing F_{2a} anticline.

Throughout most of the Ashburton Basin, metamorphic grade is low; there is, however, a general increase in grade and schistosity towards the west and southwest. Northeast of the Edmund Group unconformity the nature of the transition is such that it suggests that many psammites and pelites represent metamorphosed Ashburton Formation rocks.

Thorne and Seymour (1991) note that much of the Ashburton Basin is characterized by the mineral assemblage quartz–chlorite–muscovite(–sericite) in pelitic and psammitic rocks. On northern Ullawarra, medium-grade metamorphosed equivalents of the Ashburton Formation are represented by quartz–muscovite–biotite–cordierite–andalusite–garnet schist (*PWa-mh*), that indicate medium-grade metamorphic conditions. Textural evidence suggests that porphyroblastic minerals (biotite, andalusite, cordierite, and garnet) grew during and after the D_{1a} deformation event, overgrowing a quartz, muscovite, and chlorite groundmass. The metamorphic schistosity (S_{1a}) is typically deformed by F_{2a} folds and crenulation cleavage.

Deformation and metamorphism (D_{2a}/M_{2a})

Most obvious folding and faulting in the Ashburton Fold Belt results from the second deformation event, D_{2a}. Within Zone B, D_{2a} deformation has resulted in tight to isoclinal,

non-cylindrical F_{2a} folds, with wavelengths of 5–200 m. Folds trend west to northwest and are associated with a pronounced axial-plane cleavage (S_{2a}) which generally dips 60–90° to the southwest or northeast. Within the main body of Ashburton Formation rocks, faults are generally associated with subparallel quartz veins and are frequently observed to cut out all or part of the northern limb of the F_{2a} folds. This fact, coupled with lack of marker horizons in the Ashburton Formation, and the tight to isoclinal folding, creates a false impression of a simple stratigraphy and southwesterly dipping beds throughout much of Zone B. In such cases, evidence for F_{2a} folding comes from local reversals in younging direction and the presence of isolated F_{2a} fold closures within the otherwise uniformly dipping Ashburton Formation.

F_2 folds in Zone C are large (100–6000 m wavelength), non-cylindrical, and trend west to northwest. Most plunge 10–40° (up to 80° locally) to the southeast or northwest. Axial planes dip steeply to the southwest or northeast. Close to the northern margin of Zone C, folds are open to tight (or locally isoclinal), but are generally more open in central and southwestern parts of the fold belt. S_{2a} is a penetrative slaty cleavage in the more easterly outcrops, but is present as a crenulation cleavage further west.

Numerous west-northwest- to north-northwest-trending wrench faults parallel the F_{2a} fold axes or cross-cut them at a shallow angle. Locally, a dextral displacement of up to 3 km can be measured. In general, however, lack of marker horizons within the Ashburton Formation makes it difficult to assess accurately the amount of relative movement. The northern margin of the Capricorn Range is marked locally by a steep, southward-dipping fracture. Many faults are marked by a line of en echelon quartz veins, dipping 30–90° northeast or southwest. Locally they are associated with a second suite of steeply dipping veins that trend between north-northwest and north-northeast. Most veins consist of equant to prismatic, subhedral to anhedral quartz with irregular goethite vugs (after sulfide). Locally, quartz crystals are kinked as a result of progressive fault movement. Most copper, gold, lead, and silver mineralization discovered to date in the Ashburton Fold Belt is associated with D_{2a} faults and quartz veins.

Low-grade metamorphism accompanied D_{2a} and caused the retrogression of biotite to chlorite and andalusite to sericite and growth of porphyroblastic muscovite.

Deformation (D_{3a})

In the western Capricorn Range (around MGA 467200E 7425600N), the traces of F_{2a} folds in the Capricorn Group are folded such that the regional west-northwest trend swings firstly southwest and then west-northwest again near Irregully Creek (around MGA 449200E 7423200N). Locally the fold limbs are cut by a steep southwesterly dipping fracture cleavage (S_{3a}). The geometry of the F_{3a} fold structure suggests it may have formed in response to a localized late-stage sinistral movement on a pair of wrench faults that occur along the northern margin of the Capricorn Range and beneath the northern edge of the Edmund Group outcrop.

Boora Boora Zone

The supracrustal rocks in the Boora Boora Zone, and the granites that intrude them, were deformed and metamorphosed during the 1830–1780 Ma Capricorn Orogeny. Although fabrics and mineral assemblages related to the Capricorn Orogeny are present across the width of the Capricorn Orogen, it is not clear how the fabrics in the Boora Boora Zone relate to D_1 and D_2 fabrics in the southern part of the orogen (Occhipinti et al., 1998, 2001). However, geochronological work undertaken during remapping indicates that D_1 and D_2 structures in the Boora Boora Zone are comparable in age with D_{1a} and D_{2a} in the Ashburton Fold Belt (Thorne and Seymour, 1991), with which they are correlated.

Deformation and metamorphism (D_{1a}/M_{1a})

The oldest fabric in the metamorphic rocks of the Boora Boora Zone is a regionally extensive foliation or gneissic layering (S_{1a}). This fabric is parallel or subparallel to lithological layering. The gneissic layering is commonly accentuated by minor pegmatite banding. Associated with the gneissic layering are widespread, small-scale isoclinal folds (F_{1a}) that are best developed in the foliated and gneissic granodiorite and tonalite (*EmggGAB*). These are locally refolded by upright F_{2a} folds to form type 3 (Ramsay, 1967) fold interference structures. Around the Monte Carlo mine (MGA 351370E 7450100N), a megascopic, isoclinal F_{1a} fold is refolded about a megascopic F_{2a} fold to form a type 3 interference structure.

A maximum age for D_{1a} in the Boora Boora Zone is constrained by igneous crystallization ages of 1806 ± 7 Ma for a foliated monzogranite (*EmgmGAB*; Geological Survey of Western Australia, 2005; GSWA 169088) and 1794 ± 9 Ma (*EmggGAB*; Geological Survey of Western Australia, 2005; GSWA 169087) for a foliated granodiorite. A minimum age for D_{1a} is provided by an age of 1784 ± 5 Ma for a monzogranite dyke (*EmgmGAB*; Geological Survey of Western Australia, 2005; GSWA 169086) that cuts S_{1a}. In comparison, the D_{1n} fabric in the Yarlarweelor Gneiss Complex (a portion of the Archaean Yilgarn Craton reworked during the Capricorn Orogeny) is dated at c. 1811 Ma, and the sole fabric (S_{1n}) attributed to the Capricorn Orogeny in the Glenburgh Terrane of the southern Gascoyne Complex developed between c. 1810 and c. 1800 Ma (Occhipinti et al., 1998; Occhipinti and Sheppard, 2001).

The grade of M_{1a} is difficult to estimate because most of the metamorphosed rocks are granitic in composition, and because of widespread overprinting by M_{2a} assemblages. Granitic gneisses have locally preserved anhedral granular and amoeboid textures suggesting medium- to high-grade metamorphism. Calc-silicate rocks are composed of augite/diopside, zoisite, titanite, plagioclase, and quartz. Mafic rocks on northern MAROONAH with only a weakly developed S_{2a} fabric, have assemblages of blue-green hornblende, plagioclase and minor quartz, accompanied by polygonal textures. Locally, mafic rocks are epidote amphibolites with plagioclase of oligoclase composition, and no chlorite. Collectively, these assemblages are consistent with

amphibolite or epidote-amphibolite facies metamorphic conditions during M_{1a}.

Metasedimentary rocks in the Boora Boora Zone show a considerable range in M_{1a} metamorphic grade. Metasedimentary rocks at the southern end of a very large pluton of muscovite–biotite granite on MAROONAH show no evidence of having been metamorphosed at more than low or very low grade. However, along strike to the northwest, metasedimentary rocks around the Laura prospect (MGA 361387E 7424532N) contain the M_{1a} assemblage of muscovite, biotite, garnet, ?andalusite, and quartz. Textures indicate that porphyroblasts of garnet and ?andalusite grew at the same time or after S_{1a}, and were partly or wholly replaced by chlorite and sericite during M_{2a}. The M_{1a} assemblages here are consistent with lower amphibolite-facies metamorphic conditions (Spear, 1993). Farther to the northwest, about 8 km northwest of Horse Well (MGA 348340E 7432470N), pelitic rocks contain small domains of biotite, quartz, and muscovite with mats of fibrolite (sillimanite) in the muscovite, implying upper amphibolite-facies conditions (Spear, 1993). The increase in grade to the northwest suggests that the metamorphic isograds are perpendicular to the dominant D_{2a} structural grain, and that the isograds are likely to have been folded.

Deformation and metamorphism (D_{2a}/M_{2a})

The map patterns in the Boora Boora Zone are primarily a function of structures formed during D_{2a}. Metre-scale upright, close to tight folds are developed throughout the zone and mostly plunge to the northwest. These fold the S_{1a} foliation or gneissic layering and are associated with an axial planar foliation of variable intensity. An intersection lineation (S_{1a}/S_{2a}) that plunges parallel to the F_{2a} fold axes is extensively developed. The vergence of metre-scale folds in the northwestern corner of MAROONAH can be used to define a megascopic, northwesterly plunging synform.

The age of D_{2a} is constrained by a SHRIMP U–Pb zircon date on a monzogranite dyke (GSWA 169086) that intruded parallel to the axial surface of an F_{2a} fold, and truncates S_{1a}. The dyke has an igneous foliation parallel to S_{2a}, and it was probably intruded during or after D_{2a}; therefore, the date of 1784 ± 5 Ma for this dyke (Geological Survey of Western Australia, 2005) provides an estimate for the age of D_{2a}. In the Ashburton Fold Belt to the north, a date of 1786 ± 5 Ma for the Boolaloo Granodiorite (Krapez and McNaughton, 1999), provides a maximum age for S_{2a}, which cuts the pluton (Thorne and Seymour, 1991). In the southern Capricorn Orogen, a D_{2n} fabric in the Yarlarweelor Gneiss Complex and Errabiddy Shear Zone is dated at 1797 ± 4 Ma (Occhipinti et al., 1998; Sheppard and Occhipinti, 2000; Sheppard et al., 2003).

The S_{2a} fabric on MAROONAH is primarily defined by the widespread development in the granitic rocks of chlorite (after biotite) and sericite. All rock compositions are marked by replacement of plagioclase formed during M_{1a} by albite–oligoclase, sericite, and clinozoisite. In mafic rocks, magnetite and ilmenite have been pseudomorphed by epidote and titanite, respectively, in association with plagioclase recrystallization. Pelitic rocks show extensive replacement of garnet by chlorite and pseudomorphs of very fine grained sericite after andalusite. Biotite and muscovite formed during M_{1a} are largely recrystallized to chlorite and sericite. Collectively, these assemblages suggest greenschist facies conditions during M_{2a}.

Limejuice Zone

Deformation and metamorphism

Screens and rafts of quartz–mica schist and metamorphosed sandstone (*EmsqmGAL*) within granites of the Moorarie Supersuite contain a vertical or subvertical foliation that strikes east-southeast. It is unclear as to whether or not this foliation correlates with D_{1a} or D_{2a}. The foliation is truncated by the host granites, which are dated at 1795–1783 Ma (see **Palaeoproterozoic Moorarie Supersuite**).

Late Palaeoproterozoic Gascoyne Complex

Mangaroon Zone

Late Palaeoproterozoic Pooranoo Metamorphics (EPP-m)

The Pooranoo Metamorphics is a newly defined unit named after Pooranoo Well (MGA 382249E 7363317N) in the southeastern part of MANGAROON. The unit comprises pelitic gneiss and metamorphosed feldspathic sandstone, with minor amounts of metamorphosed conglomerate, quartz sandstone, amphibolite, and calc-silicate rock. These metasedimentary and meta-igneous rocks were previously included within the 'Morrissey Metamorphic Suite' (Williams et al., 1983; Williams, 1986).

The term 'Morrissey Metamorphic Suite' referred to a suite of metamorphosed and deformed sedimentary and minor igneous rocks which were thought to form a single supracrustal sequence throughout the Gascoyne Complex. However, many components of the suite are separated by major faults or shear zones, and by large areas of granite. The geochronological framework established during remapping of the southern Gascoyne Complex has shown that the metasedimentary rocks in the complex have a range of depositional ages, and comprise several discrete sedimentary packages (Occhipinti and Myers, 1999; Sheppard and Occhipinti, 2000; Occhipinti and Sheppard, 2001).

In the northern Gascoyne Complex, rocks of the 'Morrissey Metamorphic Suite' were thought to pass with decreasing metamorphic grade into metasedimentary rocks of the upper Wyloo Group (Danniels, 1970; Williams, 1986). Sampling for SHRIMP U–Pb geochronology was undertaken on metasedimentary rocks from EDMUND. Samples were taken from the two main rock units in the Pooranoo Metamorphics: metamorphosed feldspathic sandstone and interbedded pelitic gneiss. Two samples of metamorphosed feldspathic sandstone in the Mangaroon Zone — GSWA 169056 and GSWA 169091 (Geological Survey of Western Australia, 2005) — provide a maximum depositional age of c. 1800 Ma for the protoliths. The youngest population of detrital zircons from a sample of

unmelted pelitic gneiss gives a maximum depositional age of c. 1680 Ma. As the pelitic rocks are interbedded with the metamorphosed feldspathic sandstone, a maximum depositional age of c. 1680 Ma is inferred for protoliths to the Pooranoo Metamorphics. In contrast, recent work on the Ashburton Formation and Capricorn Group to the north indicates that protoliths to these units were deposited at about 1840–1795 Ma (Evans et al., 2003; Sircombe, 2003). Therefore, the protoliths to the Pooranoo Metamorphic rocks are not the more deformed and higher grade equivalents of the upper Wyloo Group.

Sedimentary protoliths in the Pooranoo Metamorphics are much younger than those in the Camel Hills Metamorphics, which were deposited between c. 2025–1970 Ma (Occhipinti et al., 2001) and Moogie Metamorphics (>2005 Ma; Occhipinti and Sheppard, 2001) in the southern part of the Gascoyne Complex. Therefore, the metasedimentary rock packages throughout the Gascoyne Complex are not correlatives.

The Pooranoo Metamorphics outcrop between the Minga Bar Fault in the southwest corner of MANGAROON, and the proposed Collins Fault on the southern part of MAROONAH to the north (Fig. 2). The belt is about 70 km wide and is covered to the west and east by Phanerozoic and Mesoproterozoic sedimentary rocks, respectively. Unmelted pelitic gneiss is best exposed on top of a knoll about 200 m north of the main shaft at the Star of Mangaroon mine (MGA 372290E 7360030N). The gneiss is interlayered with migmatitic gneiss, which is very well exposed at the foot of the south side of the same knoll (MGA 372340E 7359950N). Metamorphosed feldspathic sandstone is best exposed as pavements beside a creek about 750 m west-northwest of Doorawarrah Well (MGA 355550E 7376850N).

Amphibolite (EP-mwa)

Amphibolite is a very minor component of the Pooranoo Metamorphics, and is virtually confined to two exposures in the area around James Bore. Immediately west-northwest of James Bore, a folded layer of amphibolite up to 30 m thick outcrops. The amphibolite ranges from coarse grained with relict porphyritic texture, to medium grained and even-textured. About 3 km southeast of James Bore (centred at MGA 374255E 7374540N) metamorphosed layered mafic and minor ultramafic rocks outcrop over an area of about 0.15 km^2. Thin layers of felsic (?anorthositic) rock are present in places.

The mafic rocks consist primarily of medium-grained actinolite enclosed by fine-grained, granoblastic plagioclase, actinolite, epidote, and titanite. Actinolite crystals may contain cores of clinopyroxene. The ultramafic rocks consist of cummingtonite, some crystals with cores of orthopyroxene, in a matrix of fine-grained serpentinite and green spinel. The rock was probably originally an olivine orthopyroxenite. The metamorphosed mafic rocks contain evidence for only the second metamorphic event during the Mangaroon Orogeny (see **Late Palaeoproterozoic Mangaroon Orogeny: Metamorphism and deformation (D_{2m}/M_{2m})**), unlike the surrounding pelitic gneisses. This observation is consistent with an intrusive origin for the mafic and ultramafic rocks.

Calc-silicate gneiss (EP-mkq)

Calc-silicate gneiss and schist (*EP-mkq*) is a very minor rock type, being restricted to small discontinuous lenses approximately 3 km south-southeast of Kanes Gossan (MGA 424198E 7359754N). Pearson (1996) described the calc-silicate rocks as wollastonite–diopside–grossular garnet–carbonate rocks which are variably brecciated and veined by carbonate, and actinolite–epidote–carbonate–titanite rocks. A pegmatitic diopside-rich calc-silicate rock outcrops at the core of a wollastonite–diopside–grossular–carbonate gneiss just south of Kanes Gossan (Pearson, 1996).

Pelitic gneiss and granofels (EP-mln, EP-mli)

Pelitic gneiss and granofels (*EP-mln*) outcrops over a wide area north of the Mangaroon Syncline, and with a more restricted distribution to the south of the syncline. The majority of the gneiss and granofels is unmelted, but locally metatexite migmatite is present. Migmatitic pelitic gneiss (metatexite migmatite and minor diatexite migmatite; *EP-mli*) dominates in the area around the Star of Mangaroon mine on southern MANGAROON, but even in this area there are layers of unmelted pelitic gneiss. Both units contain layers of metamorphosed feldspathic sandstone in places.

A sample of pelitic gneiss (GSWA 169094) southeast of Maroonah Homestead on MAROONAH has populations of zircons at 1680 ± 14 Ma (5 grains), 1741 ± 23 Ma (3 grains) and 1785 ± 7 Ma (18 grains), in addition to older ungrouped zircons (Geological Survey of Western Australia, 2005). The sample has been contact metamorphosed at high grade by a large pluton of monzogranite, and contains sparse leucosomes. The youngest zircons are small euhedral grains or fragments with no pitting or rounding, in contrast to older zircons. In cathodiluminescence (CL) images the youngest zircons contain complex growth zoning typical of granitic rocks (Corfu et al., 2003), and resemble those of the older populations (Geological Survey of Western Australia, 2005). In addition, the youngest zircons do not have the low Th/U ratios common in many metamorphic zircons (Rubatto and Gebauer, 2000), suggesting that the population at 1680 ± 14 Ma is detrital, and that this population defines the maximum depositional age of the sediment precursor to the gneiss. The existing geochronology indicates rapid erosion of the source terrain, deposition, and high-grade metamorphism and deformation before granite intrusion.

The pelitic gneiss and granofels preserve few or no original sedimentary textures and structures. Some slightly coarser grained semi-pelitic beds still contain a small proportion of coarse sand and granule sized quartz grains.

Metamorphosed conglomerate and quartz sandstone (EP-mtq)

Metamorphosed conglomerate and quartz sandstone (*EP-mtq*) mainly outcrops in the northwestern part of MANGAROON. The unit forms lenses up to about 3 km long within arkosic and pelitic gneiss (*EP-mtf*, *EP-mln*).

Metamorphosed quartz sandstone also forms several thin (<10 m) laterally persistent units north of James Bore. Metamorphosed conglomerate and quartz sandstone typically forms strike ridges with a relief of nearly 50 m above the surrounding units.

The most common rock types are metamorphosed cobble and pebble conglomerate, coarse quartz sandstone, and pebbly quartz sandstone. Graded bedding is well preserved. In the area north of James Bore, metamorphosed quartz sandstone commonly contains abundant biotite and magnetite. In places, the mafic minerals form clots or nodules (along with quartz and plagioclase) up to several centimeters long that lie within the bedding but overprint the S_{1m} fabric. Metamorphosed conglomerate and quartz sandstone is intruded by medium-grained, even-textured muscovite–tourmaline monzogranite (*EU-gmvt*) and pegmatite (*EU-gpt*) north of Chubba Well. On Maroonah, metamorphosed conglomerate and quartz sandstone is intruded by porphyritic biotite(–muscovite) monzogranite (*EU-gmp*) north-northeast of Hogan's Well. In the area between Maroonah Homestead and Red Rock Well, metamorphosed quartz sandstone is interbedded with calc-silicate gneiss (*EP-mkq*).

Metamorphosed conglomerate on Mangaroon is confined to a large exposure along the northern edge of the sheet area. This rock type outcrops more extensively on Maroonah to the north, and Winning Pool to the northwest (Hocking et al., 1985). On Mangaroon, metamorphosed conglomerate contains clasts of milky vein quartz and subordinate dark grey to black, very fine to fine-grained quartz–magnetite(–muscovite) rock. The matrix of the conglomerate is composed of granules of quartz and minor muscovite. Metamorphosed conglomerate beds are 2–5 m thick, and are interbedded with metamorphosed sandstone beds 0.15–0.4 m thick. The conglomerate typically has a prominent lineation defined by strongly stretched clasts, a feature also noted by Hocking et al. (1985).

Metamorphosed quartz sandstone is typically pale grey, blocky, and medium to coarse grained, although in places it is fine grained and micaceous. Most of the rocks are composed almost entirely of quartz. Where the metamorphosed quartz sandstone is more strongly recrystallized, it is a metaquartzite. Metamorphosed quartz sandstone beds range from 0.05 to 3 m thick. North of Chubba Well, white, thickly bedded, metamorphosed quartz sandstone with thin heavy mineral bands is exposed.

Metamorphosed felspathic sandstone and minor interbedded pelitic rock and pebbly sandstone (EP-mtf)

Metamorphosed feldspathic sandstone is interbedded with minor metamorphosed pelitic rock and pebbly sandstone. The unit outcrops over a wide area in the northwestern corner of Mangaroon (and in the adjacent southwestern corner of Maroonah), and between the Mangaroon Syncline and the Minga Bar Fault. To the southeast on Edmund (1:100 000 sheet), metamorphosed feldspathic sandstone forms numerous rafts and screens in granites of the Durlacher Supersuite. The rocks range from massive metasandstones with well-preserved sedimentary structures to pegmatite-banded gneissic rocks. Metamorphosed feldspathic sandstone forms a gently undulating land surface with low rises covered in small boulders.

In low-strain zones, grey, metamorphosed feldspathic sandstone beds are typically 20–30 cm thick, with graded bedding preserved in places. The rocks are fine-grained, but contain up to about 10% coarse sand and granule-sized clasts of quartz. Some beds contain scattered granules and pebbles of milky quartz. Lenses of metamorphosed pebble conglomerate are locally present; for example, in the area about 4 km northwest of Chubba Well (MGA 356600E 7399110N). The metamorphosed conglomerate lenses have sharp bases, and are typically less than 2 m thick.

An inclusion (about 10 m^2) of metamorphosed feldspathic sandstone in Pimbyana Granite on Edmund (1:100 000 sheet) was sampled for SHRIMP U–Pb geochronology on detrital zircons. Twenty four of 25 analysed zircons are Palaeoproterozoic in age, with the youngest population of 1808 ± 11 Ma providing a maximum age for deposition of the protolith (Geological Survey of Western Australia, 2005; GSWA 169056). A strongly hornfelsed, metamorphosed felspathic sandstone on the southern part of Maroonah contains only Palaeoproterozoic detrital zircons. The youngest population in this sample (Geological Survey of Western Australia, 2005; GSWA 169091) of 1800 ± 4 Ma provides a maximum depositional age of the precursor sediment that is within error of that provided by the sample on Edmund (1:100 000 sheet). Metamorphosed feldspathic sandstone is interbedded with pelitic gneiss (*EP-mln*, *EP-mli*), which has a maximum depositional age of c. 1680 Ma. Therefore, the precursor sediment to the metamorphosed feldspathic sandstone must also have a depositional age of less than c. 1680 Ma.

Metamorphosed feldspathic sandstone is composed of coarse sand and granules of strained quartz in a matrix of fine-grained, granoblastic quartz, plagioclase (oligoclase), biotite, sericite, and epidote. Porphyroblasts of muscovite 0.5–1.5 mm in diameter are common, but not abundant. Quartz is the most abundant mineral, typically forming 50–60% of the rock. Microcline is a minor component of some samples. Accessory minerals include zircon, apatite, and, in some samples, tourmaline.

On Edmund (1:100 000 sheet), tourmaline-bearing psammitic gneiss is also present. This rock type consists of muscovite, quartz, biotite, tourmaline (schorl), and opaques, and rare, small (50–100 μm diameter) crystals of very pale pink to colorless, euhedral to subhedral garnet (possibly spessartine).

Late Palaeoproterozoic Durlacher Supersuite

The Durlacher Supersuite is a newly defined igneous unit, which comprises granitic and minor gabbroic intrusions emplaced at 1680–1620 Ma, during the Mangaroon Orogeny. The bulk of the granites intruded the Mangaroon Zone at 1680–1660 Ma, but large plutons also intruded the adjacent Boora Boora and Limejuice Zones (this work and Culver, 2001), as well as the Glenburgh Terrane in

the southern Gascoyne Complex (Geological Survey of Western Australia, 2005; GSWA 168948), and the adjacent Yarlarweelor Gneiss Complex (Sheppard and Swager, 1999) until as late as c. 1620 Ma.

Porphyritic biotite granodiorite (PU-ggp)

Grey, massive, medium-grained porphyritic biotite granodiorite (*PU-ggp*) is exposed in the northwestern corner of MANGAROON, and in the southwestern corner of MAROONAH to the north. In addition, several small exposures, some of which are too small to show on the map, are present in the northwestern corner of MAROONAH. The granodiorite outcrops as whalebacks and tors amongst sheetwash and calcrete. It forms numerous plugs, which may be part of a large pluton or plutons below the current level of exposure. Typically the granodiorite contains up to 30% tabular phenocrysts of K-feldspar 1–2 cm long. The phenocrysts locally define a weak flow fabric.

The granodiorite intrudes the various Palaeoproterozoic metasedimentary rock units of the Pooranoo Metamorphics east of Maroonah Homestead, and foliated and gneissic granodiorite and tonalite (*PmggGAB*) in the north. Near the edges of the pluton east of the homestead, the granodiorite contains numerous inclusions of metamorphosed feldspathic sandstone and biotite-rich pelitic gneiss. About 2 km northeast of Maroonah Homestead (MGA 352919E 7404146N), the granodiorite contains round to elliptical inclusions, up to 5 m in diameter, of muscovite–biotite granite (*PU-gmv*). Some of the inclusions contain segregations of tourmaline pegmatite, veins of which intrude the porphyritic granodiorite. Collectively, these features imply that the granodiorite intruded the muscovite–biotite granite before the latter had entirely solidified; that is, the two plutons are the same age.

A granodiorite sample (GSWA 178030) from about 3 km southeast of Robinson Well contains a single population of zircons dated by SHRIMP U–Pb at 1678 ± 6 Ma, which defines the igneous crystallization age (Geological Survey of Western Australia, 2005). Given the field relationships outlined above, this date also is the age of the igneous crystallization of the muscovite–biotite granite described below.

Porphyritic biotite(–muscovite) monzogranite (PU-gmp)

Massive, medium-grained porphyritic biotite(–muscovite) monzogranite (*PU-gmp*) on MAROONAH is confined to the area south and southwest of Collins Well. This rock type is pale grey to cream, and its porphyritic texture and a greater abundance of biotite distinguishes it from the muscovite–biotite granite (*PU-gmv*). The porphyritic biotite(–muscovite) monzogranite forms low hills covered with tors and boulders, or pavements amongst sheetwash and colluvium. The monzogranite is exposed over an area of about 15 km^2, and it probably forms a pluton that extends farther west onto TOWERA. The monzogranite and associated dykes intrude pelitic gneiss (*PP-mln*) and metamorphosed feldspathic sandstone (*PP-mtf*) of the Pooranoo Metamorphics. A pluton of the same rock type also outcrops on the southern edge of MANGAROON around Nelsons Bore, and there is a folded, sheet-like intrusion of the same unit north of the Star of Mangaroon mine.

The monzogranite was sampled (GSWA 169090) for SHRIMP U–Pb zircon geochronology about 4.5 km north-northeast of Hogan Well (MGA 349780E 7412530N). The sample consists of a porphyritic monzogranite with phenocrysts of microperthite/microcline in an anhedral granular groundmass with a grainsize of 1.5–3.0 mm. The phenocrysts have abundant subhedral plagioclase inclusions, as well as some quartz and biotite inclusions. The rock contains about 7–10% biotite and less than 1% muscovite. Accessory apatite, allanite, and zircon are predominantly enclosed within, or adjacent to, biotite. Rare magnetite is present, although most has been replaced by epidote in conjunction with the sericitization of plagioclase. Biotite crystals commonly contain lamellae of prehnite or, less commonly, epidote. The monzogranite has an igneous crystallization age of 1696 ± 20 Ma, derived from the youngest population of five zircons (Geological Survey of Western Australia, 2005).

The monzogranite mainly intrudes metamorphosed feldspathic sandstone (*PP-mtf*). Adjacent to the pluton of monzogranite, the metamorphosed feldspathic sandstone is hornfelsed. About 5.6 km west-northwest of North Mullara Bore, porphyritic biotite–muscovite monzogranite intrudes massive metagabbro (*PU-og*). In places, the monzogranite also has lenticular inclusions of biotite-rich metapelitic rocks (*PP-mln*). The monzogranite is typically homogeneous, but about 5 km north-northeast of Hogan Well, the unit consists of alternating sheets of sparsely and strongly porphyritic monzogranite. The sheets are 0.3–1.0 m thick and dip steeply to the south-southeast.

Yangibana Granite (PUyn-gmv, PUyn-gmi)

The Yangibana Granite (*PUyn-gmv*) (Pearson, 1996; Martin et al., 2002) is a massive, leucocratic, medium-grained biotite–muscovite syenogranite to monzogranite, which ranges from being equigranular to slightly porphyritic. Locally the granite contains clots of tourmaline. On EDMUND (1:100 000 sheet) the Yangibana Granite forms two distinct plutons, one approximately 1.5 km south of the Lions Ear rare earth element (REE) prospect and another about 1.5 km south of the Fraser Creek Prospect. Thin (up to 2 cm wide) schlieren of biotite, which trend parallel to the edge of the pluton, form part of the Yangibana Granite adjacent to, and a few hundred metres south into the pluton.

Dykes and veins of the Yangibana Granite intrude metasedimentary rocks in the area, and in some areas the abundance of sedimentary material within the granite warrants a separate mappable unit (*PUyn-gmi*). Dykes and veins of the granite consistently intrude the Pimbyana Granite; however, its relationship to the extensive Dingo Creek Granite was not observed during mapping. Some thin tourmaline-bearing pegmatite dykes (*PU-gpt*) intrude the Yangibana Granite. Most of these are too small to show on the map but some are large enough to show; for example a pegmatite dyke 3.5 km west of Henderson Bore that intrudes the Pimbyana Granite.

The granite has been dated at two localities on EDMUND (1:100 000 sheet): 4 km southeast of Fraser Bore (Geological Survey of Western Australia, 2005; GSWA 169055) and 4 km southeast of Yangibana Bore (Geological Survey of Western Australia, 2005; GSWA 169059). Nineteen zircons from sample 169055 were selected for SHRIMP U–Pb dating; of these, the youngest population of 15 zircons defines an age of 1659 ± 10 Ma, which is interpreted as the age of igneous crystallization (Geological Survey of Western Australia, 2005). Sixteen concordant to slightly discordant analyses of 16 zircons in sample 169059 selected for analysis gave an age of 1660 ± 9 Ma, which is interpreted as the crystallisation age.

Muscovite–biotite granite (PU-gmv, PU-gmvt)

Muscovite–biotite granite (*PU-gmv*, *PU-gmvt*) is a voluminous unit on MAROONAH, and outcrops as plutons, plugs and dykes over a wide area on MANGAROON. The unit consists of equigranular or weakly porphyritic, medium-grained, muscovite–biotite granodiorite and monzogranite (*PU-gmv*) and medium-grained, muscovite–tourmaline(–biotite) monzogranite (*PU-gmvt*). These two rock types may grade into each other; for example, in the pluton about 8.5 km west-northwest of Mundong Well. In this pluton the monzogranite is locally garnet bearing. The rocks are uniformly massive, except where cut by narrow faults or shear zones. The unit outcrops as whalebacks and pavements, which are readily visible on aerial photographs, and low rugged hills covered with tors and boulders.

Muscovite–biotite granite forms a large pluton (>240 km^2) centred west of the Joy Helen prospect. This pluton comprises muscovite–biotite granodiorite and monzogranite, and, at its northwestern and southern ends, muscovite–tourmaline(–biotite) monzogranite. Exposures of weakly porphyritic muscovite–biotite granodiorite and monzogranite west of Middle Bore, and east and south of Red Rock Bore, represent either continuations of the same pluton or separate intrusive bodies. Several plugs or plutons of muscovite–tourmaline(–biotite) monzogranite are also present along the western edge of the sheet area. Dykes of muscovite–biotite granite extensively intrude all rocks of the Gascoyne Complex, including all other granites of the Durlacher Supersuite. The muscovite–biotite granite contains the same rock types as the Yangibana Granite on EDMUND (1:100 000 sheet), but the latter name has been retained only for intrusions on EDMUND (1:100 000 sheet) because geochronology studies indicate that at least some of the intrusions on MANGAROON and MAROONAH are probably significantly younger.

Medium-grained, weakly porphyritic muscovite–biotite granodiorite (*PU-gmv*) was sampled for SHRIMP U–Pb zircon geochronology about 1 km east-northeast of Red Rock Bore (MGA 361420E 7409000N). The rock at this locality contains scattered clots <1 cm in diameter of fine-grained tourmaline and feldspar. The sample (GSWA 169092) is a partly recrystallized muscovite–biotite–tourmaline(–garnet) granodiorite and contains a range of zircon ages, with most of the zircons belonging to two groups at 1681 ± 10 Ma (12 analyses) and 1810 ± 21 Ma (8 analyses; Geological Survey of Western Australia, 2005). The youngest analysis in the sample — 1619 ± 15 Ma — was derived from a structureless rim. The analysis is concordant, and it is interpreted as approximating the crystallization age of the granodiorite. About 10 km to the southwest of this sample site, field relationships indicate that a small intrusion of muscovite–biotite granodiorite is coeval with a pluton of porphyritic biotite granodiorite (*PU-ggp*) dated at 1678 ± 6 Ma. These results suggest that intrusions grouped into the muscovite–biotite granite are diachronous.

Plutons, plugs and dykes of muscovite–biotite granite intrude all the metamorphosed sedimentary and igneous rocks in the Mangaroon and Boora Boora Zones. There is commonly little evidence of contact metamorphism associated with the muscovite–biotite granite, which may be, in part, related to the quartzo-feldspathic nature of many of the country rocks. However, even pelitic schists around and to the southeast of the Laura Prospect, show no evidence of hornfels texture. The large pluton centred west of the Joy Helen Prospect contains several screens of pelitic schist. Inclusions are not common in the muscovite–biotite granite, but 1.2 km southeast of Red Rock Bore inclusions of pegmatite-banded, metamorphosed feldspathic sandstone up to 1 m long are present.

The muscovite–biotite granite is intruded by numerous planar veins and dykes of tourmaline–muscovite pegmatite (*PU-gpt*). The large pluton of muscovite–biotite granite on MAROONAH is unconformably overlain to the east and south by sedimentary rocks of the Bangemall Supergroup.

Muscovite–biotite granodiorite and monzogranite (*PU-gmv*) typically contains less than 10% tabular microcline phenocrysts, 7–15 mm long in a groundmass with a 2–3 mm average grainsize. The phenocrysts locally define a weak flow fabric and contain inclusions of quartz and plagioclase; the latter are commonly aligned with the microcline crystal faces. Rare oval-shaped phenocrysts up to 4 cm long are present in places. Muscovite is generally more abundant than biotite, although in the eastern part of the large pluton west of the Joy Helen Prospect, the reverse is common. Muscovite–biotite granodiorite and monzogranite locally has clots or splays of fine- to medium-grained tourmaline crystals. Plagioclase is extensively sericitized, and biotite is recrystallized and partly replaced by chlorite.

Muscovite–tourmaline(–biotite) monzogranite (*PU-gmvt*) is medium to fine grained, and even textured or sparsely porphyritic. The rocks are typically leucocratic, and comprise plagioclase, quartz, microcline, muscovite, biotite, and tourmaline. Tourmaline forms prismatic or skeletal crystals up to 4 mm long intergrown with quartz and plagioclase. In the pluton west-northwest of Mundong Well, fine-grained biotite locally forms small (2–3 mm) hexagonal clots after garnet. In a sheet to the north of this pluton fresh garnet is present. Plagioclase is variably replaced by albite (An_{05}) and sericite, and biotite is partly recrystallized and chloritized. Muscovite–tourmaline(–biotite) monzogranite locally contains pegmatitic pods and segregations.

Tourmaline–muscovite pegmatite and leucocratic granite (PU-gpt)

Tourmaline–muscovite pegmatite and fine-grained, leucocratic granite (*PU-gpt*) form dykes that intrude all rocks of the Boora Boora and Mangaroon Zones, and to a lesser extent, granites of the Limejuice Zone. The dykes are particularly abundant in the area southeast of Bookathanna Well on central MANGAROON, and in the northwestern corner of MAROONAH, where they are up to 1 km long and 3 m wide. On MAROONAH many of the dykes strike north to north-northeast, but others, where they intrude metamorphosed sedimentary and granitic rocks, are subparallel to the existing foliation or gneissic layering. Several sheet-like composite bodies of tourmaline–muscovite pegmatite and leucocratic granite are present around the Laura Prospect. Northwest of James Bore on MANGAROON composite dykes of pegmatite and leucocratic granite are well developed.

Dykes and sheets mainly comprise pegmatite or leucocratic granite, but the two rock types locally grade into each other, and some dykes contain pegmatite margins and leucocratic granite cores. The leucocratic tourmaline–muscovite granite has a similar mineralogy to the tourmaline-bearing phase of the muscovite–biotite granite (*PU-gmvt*). The two rock types have the same field relationships, and pegmatitic segregations are present within the muscovite–biotite granite. For these reasons, the pegmatite and leucocratic granite are considered to be the same age as the muscovite–biotite granite.

Pimbyana Granite (PUpi-gmg, PUpi-gt, PUpi-gmi)

The Pimbyana Granite (*PUpi-gmg*, *PUpi-gt, PUpi-gmi*) (Pearson et al., 1996; Martin et al., 2002) is the largest granite unit on MANGAROON and EDMUND (1:100 000 sheet). It is mainly restricted to north of the Mangaroon Syncline and its extension to the southeast. The granite is very well exposed, and forms extensive low rugged hills covered in boulders, tors, and whalebacks; the latter commonly have a reddish appearance on aerial photographs and in the field. The most abundant rock type is a coarse-grained porphyritic to megacrystic biotite(–muscovite) monzogranite to syenogranite (*PUpi-gmg*). Fine- to medium grained biotite tonalite and granodiorite (*PUpi-gt*) is only abundant in the area east and southeast of the Star of Mangaroon mine, and around the Frasers–Yangibana Prospect on EDMUND (1:100 000 sheet). Where the Pimbyana Granite contains abundant inclusions of metasedimentary and mafic meta-igneous rocks it is mapped as a separate unit (*PUpi-gmi*).

The two main phases of the Pimbyana Granite (*PUpi-gmg*, *PUpi-gt*) have been dated using SHRIMP U–Pb in zircon. A porphyritic biotite–muscovite syenogranite (*PUpi-gmg*) from 5 km southeast of Yangibana Bore (GSWA sample 169060) on EDMUND (1:100 000 sheet) has an igneous crystallization age of 1673 ± 15 Ma (Geological Survey of Western Australia, 2005). A porphyritic to megacrystic biotite(–muscovite) monzogranite from the same phase 4 km southeast of Coorabia Tank on MANGAROON (GSWA 178029) has an igneous crystallization age of 1675 ± 11 Ma (Geological Survey of Western Australia, 2005). A sample of fine- to medium-grained, even-textured biotite tonalite (*PUpi-gt*) from about 500 m northwest of the Frasers–Yangibana Prospect (GSWA sample 169054) has an igneous crystallization age of 1674 ± 8 Ma (Geological Survey of Western Australia, 2005), which is indistinguishable from the age of the monzogranite to syenogranite phase. The two samples from EDMUND (1:100 000 sheet) also have a xenocrystic zircon population at 1788 ± 17 Ma, which is within error of the crystallization age of the Gooche Gneiss.

The geochronology suggests that there is little or no age difference between the porphyritic to megacrystic phase of the Pimbyana Granite (*PUpi-gmg*) and the fine- to medium-grained tonalite and granodiorite (*PUpi-gt*). This conclusion is in accord with observed field relationships. About 200 m northwest of Frasers–Yangibana Prospect on south-central EDMUND (1:100 000 sheet), fine- to medium-grained and equigranular to sparsely porphyritic tonalite locally grades into a medium-grained granite with scattered 2–6 cm long tabular K-feldspar megacrysts. The megacrystic phase locally forms veins in the tonalite, but the irregular nature of the veins and dykes, and the cuspate and lobate nature of the contacts, suggests that the tonalite was not fully crystallized when intruded by the megacrystic granite.

The Pimbyana Granite intrudes metasedimentary rocks of the Pooranoo Metamorphics, and near the margins of intrusions, inclusions and screens of metasedimentary rock may be abundant. Elsewhere the granite typically contains scattered small (<5 cm diameter), dark-grey inclusions of biotite-rich metapelitic rock. Inclusions of vein quartz are locally abundant. The megacrystic monzogranite to syenogranite phase is intruded by both the Dingo Creek Granite and the Yangibana Granite, and by extensive veins and dykes of muscovite–biotite granite (*PU-gmv*) and tourmaline-bearing granite and pegmatite (*PU-gmvt*, *PU-gpt*).

The phenocrysts and megacrysts (i.e. phenocrysts larger than 5 cm) that characterize the Pimbyana Granite typically comprise 20–40% of the rock, and are tabular. The phenocrysts are commonly aligned to define an igneous foliation, which typically trends subparallel to the regional tectonic foliation in the area. Tabular phenocrysts and megacrysts typically have a microperthitic texture, and commonly contain inclusions of quartz, plagioclase and biotite. However, in places the granite contains abundant rounded megacrysts up to 8 cm in diameter, some with graphic textures. For example, northeast of Bald Hill North, and between Bald Hill North and Henderson Bore, the Pimbyana Granite locally contains rounded megacrysts of K-feldspar that are up to 7 cm long and 6 cm wide. Some of the megacrysts are concentrated in narrow zones or channels where they may comprise up to 90% of the rock. Groundmass muscovite and biotite are commonly partly recrystallized, with some biotite replaced by chlorite. Sericitization of plagioclase is accompanied by titanite pseudomorphs after ilmenite or titanomagnetite.

Dingo Creek Granite (PUdi-grpv)

The Dingo Creek Granite (*PUdi-grpv*) (Martin et al., 2002) is a fine- to medium-grained porphyritic biotite–muscovite

monzogranite to syenogranite. The unit forms several southeast-trending intrusions over an area about 35 km long and 5 km wide on the central part of MANGAROON. Another intrusion on the eastern edge of the sheet area is probably part of another southeast-striking belt of intrusions of similar dimensions on EDMUND (1:100 000 sheet). This unit also forms a pluton around Doorawarrah Spring on the western edge of MANGAROON, and numerous veins and dykes in the area north of James Bore. The Dingo Creek Granite was previously referred to as the Dingo Granite by Pearson (1996), but was renamed because of potential confusion with the Dingo intrusion in the Pilbara. The Dingo Creek Granite forms low, rugged hills, and outcrops as boulders, tors, and, locally, whalebacks.

The Dingo Creek Granite was first dated by Pearson (1996) using SHRIMP U–Pb in zircon. The sample was taken from MOUNT PHILLIPS, about 3 km south of the EDMUND sheet boundary, and has an igneous crystallization age of 1674 ± 6 Ma. Two further samples were collected for SHRIMP geochronology during the course of this remapping on EDMUND (1:100 000 sheet), and from nearly 50 km to the west-northwest on MANGAROON. The two samples (GSWA 169062 and GSWA 178028) have identical igneous crystallization ages of 1674 ± 8 Ma (Geological Survey of Western Australia, 2005).

The Dingo Creek Granite is mainly surrounded by large areas of the Pimbyana Granite. At the margins of separate intrusions about 4.5 km southeast of Coorabie Tank (MGA 385760E 7367230N) and 2 km east of Chararoo Outcamp (MGA 370940E 7386770N), and on EDMUND (1:100 000 sheet), fine- to medium-grained porphyritic granite of the Dingo Creek Granite intrudes megacrystic monzogranite of the Pimbyana Granite. In the area about 2 km northeast of Chararoo Outcamp there are numerous inclusions and rafts of megacrystic Pimbyana Granite in Dingo Creek Granite. Around Doorawarrah Spring on MANGAROON, the Dingo Creek Granite intrudes rocks of the Pooranoo Metamorphics. The Dingo Creek Granite is extensively intruded by veins and dykes of muscovite–biotite(–tourmaline) granite and pegmatite (*EU-gmv*, *EU-gmvt*, *EU-gpt*). On EDMUND (1:100 000 sheet), rafts of leucocratic tourmaline-bearing granite (*EU-gmvt*) are locally present within the Dingo Creek Granite.

Intrusions of Dingo Creek Granite are composed of numerous southeast-striking sheets from a few metres up to a few hundred metres wide. Thin tabular K-feldspar phenocrysts mostly less than 1 cm long comprise 30% or more of the rock; locally they make up to 60% of the rock (Pearson, 1996). Phenocrysts commonly have a strong preferred orientation defining a magmatic foliation. This foliation typically strikes southeast parallel to a tectonic foliation (S_{2m}: see **Late Palaeoproterozoic Mangaroon Orogeny**) in rocks of the surrounding Pooranoo Metamorphics, and dips steeply to the northeast or southwest. The Dingo Creek Granite is composed of porphyritic, fine- to medium-grained biotite–muscovite monzogranite and syenogranite. Phenocrysts of microperthite commonly contain inclusions of plagioclase and blebby quartz. Chocolate-brown biotite and muscovite are partly recrystallized to finer grained aggregates.

Medium-grained biotite granite (EU-gmb)

On MANGAROON, medium-grained biotite granite (*EU-gmb*) is confined to a pluton nearly 4 km long and about 1.5 km wide west of Alma Outcamp. The granite is fine to medium grained and mostly even-textured, although it is locally weakly to moderately megacrystic. Veins and dykes of the granite intrude strongly megacrystic, coarse-grained biotite monzogranite of the Pimbyana Granite.

Mesocratic biotite granodiorite (EU-ggb)

Mesocratic biotite granodiorite (*EU-ggb*) forms several small plutons (<4 km^2) in the area between White Bore and Old Alma Well in the eastern part of MANGAROON. One of the plutons has a sharp contact with the Dingo Creek Granite, but the relative ages of the two units cannot be determined. Mesocratic biotite granodiorite intrudes megacrystic biotite monzogranite of the Pimbyana Granite about 2.8 km southeast of White Bore (MGA 385570E 7374080N). Elsewhere, in the pluton centred southwest of North Well, the granodiorite contains abundant xenocrysts of partly rounded tabular K-feldspar crystals, and has diffuse contacts with megacrystic monzogranite of the Pimbyana Granite. These observations are consistent with local mingling of the two granite units. Mesocratic biotite granodiorite is intruded by veins and dykes of muscovite–tourmaline pegmatite (*EU-gpt*).

The mesocratic biotite granodiorite is much darker than most other granites of the Durlacher Supersuite, and it has a pitted texture on weathered surfaces. Rocks of this unit characteristically contain crystals of hydrated allanite about 1 mm long. The granodiorite is moderately recrystallized to an anhedral granular rock composed of sutured quartz, sodic plagioclase, microcline, green-brown biotite, and sericite.

Schlieric, inclusion-rich granodiorite (EU-ggvs)

On MANGAROON schlieric, inclusion-rich muscovite–biotite granodiorite (*EU-ggvs*) extensively intrudes the Pooranoo Metamorphics, and Gooche Gneiss, between the Minga Bar Fault and the Mangaroon Syncline. Here the granodiorite forms irregular plutons composed of numerous steeply dipping to vertical sheet-like bodies with numerous screens of country rock. The granodiorite also intrudes the Pooranoo Metamorphics north of the Mangaroon Syncline, but forms only veins and thin sheets that are too small to display separately. Areas underlain by the granodiorite consist of undulating countryside similar to that of the Pooranoo Metamorphics, but with outcrops consisting mainly of boulders with some tors and pavements.

The schlieric, inclusion-rich granodiorite was sampled about 3 km south of Russell Well (MGA 363140E 7357610N) for SHRIMP U–Pb zircon geochronology. Out of 26 zircons analyzed from the sample (GSWA 178027), the youngest 12 grains define a single population at 1677 ± 5 Ma (Geological Survey of Western Australia, 2005). This is interpreted as the igneous crystallization age of the granodiorite.

The granodiorite normally contains up to 50% inclusions and screens, chiefly of metasedimentary rock,

but also of foliated and gneissic granite of the Gooche Gneiss. Contacts between the granodiorite and Pooranoo Metamorphics, both at outcrop scale and smaller scales, are commonly gradational. The gneissic layering in inclusions is truncated at a high angle by enclosing granodiorite, indicating that the schlieric, inclusion-rich granodiorite post-dates the first deformation and associated high-grade metamorphism in the Mangaroon Domain (see **Late Palaeoproterozoic Mangaroon Orogeny: Deformation and metamorphism (D_{1m}/M_{1m})**).

The granodiorite is intruded by most of the other major granite units of the Durlacher Supersuite; for example, the Pimbyana Granite (*EUpi-gmg*, *EUpi-gt*), Dingo Creek Granite (*EUdi-grpv*), muscovite–biotite granite (*EU-gmv*, *EU-gmvt*) and tourmaline–muscovite pegmatite and leucocratic granite (*EU-gpt*). The schlieric, inclusion-rich granodiorite commonly contains a southeast-striking, steeply dipping tectonic foliation parallel to S_{2m} in rocks of the enclosing Pooranoo Metamorphics, but which is absent or less-well developed in the granites that intrude the granodiorite (see **Late Palaeoproterozoic Mangaroon Orogeny: Deformation and metamorphism (D_{2m}/M_{2m})**). The granodiorite typically displays a weak to prominent igneous layering parallel to the S_{2m} foliation, and veins and dykes intrude along the S_{2m} fabric in the country rocks. Larger intrusions of granodiorite are composed of steeply dipping, southeast-striking sheets. Collectively, these features indicate that the granodiorite was emplaced broadly coeval with D_{2m}.

The most abundant rock type is a layered, medium-grained, sparsely porphyritic muscovite–biotite granodiorite with abundant inclusions of metasedimentary rock (pelitic gneiss and metamorphosed feldspathic sandstone), with lesser amounts of vein quartz (with or without tourmaline), pegmatite and augen gneiss (Gooche Gneiss). Inclusions can usually be related directly to the local country rocks. In the area between Minga Bar Well and Coolinbah Well near the western edge of Mangaroon, a biotite–muscovite phase is commonly interlayered with the granodiorite. The granodiorite is heterogeneous on an outcrop and regional scale. Layering in the granodiorite is defined by composition (locally monzogranitic or tonalitic), grainsize, and phenocryst abundance. Some layers are rich in rounded megacrysts of K-feldspar up to about 5 cm in diameter and in inclusions of pegmatite up to 10 cm in diameter. Along the southern edge of Mangaroon (for example, at MGA 384470E 7345340N) the megacrysts can be traced along to partly disaggregated dykes of pegmatite, which appear to have intruded the granite before it had solidified.

Biotite–muscovite–cordierite tonalite (EU-gtr)

A bioite–muscovite–cordierite tonalite (*EU-gtr*) with abundant inclusions (up to 30%) of pelitic and calc-silicate schist outcrops as an irregularly shaped plug approximately 0.5 km^2 about 2 km southwest of Fraser Bore on Edmund (1:100 000 sheet). The rock is massive, medium grained and equigranular. Cordierite is very fresh, and is readily identifiable in hand-specimen as a grey rounded mineral. The tonalite contains accessory tourmaline, titanite and opaques.

The presence of abundant muscovite and cordierite, and the large concentration of metasedimentary inclusions, suggests that the granite represents an anatectic melt derived from sedimentary material. SHRIMP U–Pb analysis of zircons from a sample of this unit shows a range of populations identified between 2400 and 1635 Ma, supporting an S-type origin. Most zircons contained Th/U ratios greater than 0.1, suggestive of igneous crystallization. However, two groups of concordant to near concordant analyses at 1677 ± 7 Ma, and 1635 ± 15 Ma mostly contained Th/U rations less than 0.1, suggestive of crystallization under metamorphic or anatectic conditions (Maas et al., 1992; Tyler et al., 1999; Hoskin and Black, 2000). The youngest population was derived from structureless rims or a structureless clear crystal fragment, consistent with metamorphic/anatectic growth. Thus, it is probable that the c. 1635 Ma population is the age of the anatectic melting that produced the tonalite; however, the melting did not take place at or near the current level of exposure, because older granites in the region show no high-grade metamorphic overprint.

Thin (<1 m-wide) dykes of equigranular, medium-grained granite (*EU-gmb*) cut the tonalite, but are too small to show on the map.

Massive metagabbro (EU-og)

On Mangaroon, massive metagabbro (*EU-og*) outcrops over an area of only approximately 0.2 km^2 roughly 3 km north-northeast of James Bore, in another outcrop less than 50 m^2 in extent about 2 km to the north-northwest (MGA 372160E 7380270N), and east-northeast of High Range–Daniels prospect. On Maroonah, metagabbro forms two exposures, each about 0.2–0.3 km^2, 6 km west-northwest of North Mullara Bore and 3 km west-southwest of Red Rock Bore. Both exposures consist of rocky knolls that rise about 30–35 m above surrounding sheetwash and scattered outcrop. At the outcrop west-northwest of North Mullara Bore, the metagabbro is intruded by a sheet of porphyritic biotite(–muscovite) monzogranite (*EU-gmp*) at the base of the knoll. At both localities on Maroonah, metagabbro is intruded by planar veins and thin dykes of tourmaline–muscovite pegmatite (*EU-gpt*) that have selvedges of epidote and chlorite alteration in the mafic rock.

The metagabbro ranges from equigranular to moderately porphyritic. Net-vein structures are present along the contacts of the metagabbro and a pale grey, fine-grained granite at both localities, implying that the mafic and felsic magmas have mingled. The K-feldspar phenocrysts in the metagabbro are commonly partly rounded, and have the same shape and size as those in the pale-grey granite: therefore, the K-feldspar crystals are probably xenocrysts. The pale-grey granite, and to a lesser extent the metagabbro, is intruded by veins of fine- to medium-grained, strongly porphyritic monzogranite of the Dingo Creek Granite.

The massive metagabbro north-northeast of James Bore is a fine-grained anhedral granular rock composed of very pale green actinolite and sodic plagioclase and minor quartz, with xenocrysts of microcline. Biotite has exsolved ?rutile needles, and recrystallization of plagioclase to more sodic composition was associated with pseudomorphs

of titanite and epidote after ilmenite and magnetite, respectively. Apatite and zircon are abundant accessory minerals. Metamorphosed gabbro uncontaminated with granitic melt is composed of decussate actinolite (α = straw yellow, β = blue-green, γ = deep green), andesine (An_{35}), epidote, and altered ?titanite. Quartz and microcline are accessory minerals. Actinolite is commonly intergrown with, or rimmed by, tremolite.

Ultramafic sills and dykes (PaGA)

Ultramafic sills and dykes (*PaGA*) include the 'Lyons River ultrabasic sills', and the 'Spider Hill sills' and 'Bald Hill weathered intrusions' of Pearson (1996), Pearson and Taylor (1996) and Pearson et al. (1996), who have studied the intrusions in detail. The ultramafic sills and dykes are concentrated in an east-southeasterly trending zone, about 12 km long and 2 km wide, just north of the Lyons River on EDMUND (1:100 000 sheet). These bodies appear to be mostly less than 10 m wide, although in one place a larger sill, up to 750 m thick, is present. The ultramafic rocks outcrop predominantly as rubbly zones within the granite, although in some instances they form ferruginized outcrops. It is likely that the apparently separate thin elongate outcrops of the ultramafic bodies are actually sills which have been deformed around east-southeasterly trending upright, shallow-plunging folds in the granitic body that they intrude. One such fold was mapped 2 km southwest of the Fraser Creek Prospect (MGA 420812E 7347726N).

The Lyons River ultrabasic sills mostly consist of secondary arfvedsonite, riebeckite, and aegerine with some clots of phlogopite. Pearson (1996) interpreted the primary mineralogy to consist of olivine macrocrysts in a groundmass of mica, perovskite, titanian magnetite and carbonate. These intrusions are associated with an extensive zone of alkali metasomatism. Pearson (1996) and Pearson and Taylor (1996) divided the Lyons River sills into two main types — primary-textured ultrabasic sills and deformed lenses. The primary-textured ultrabasic sills were further subdivided into four types. They found that some sills were commonly porphyritic and contained 1–2 mm phenocrysts of either olivine, titanian magnetite, perovskite, phlogopite, or clinopyroxene in a fine-grained matrix. The matrix may consist of a variety of minerals including carbonate, phlogopite, sodic pyroxene, apatite, barite, and Fe-oxides (Pearson and Taylor, 1996). The sills around the Spider Hill Prospect are composed of aegerine, phlogopite, apatite, magnetite and pyrochlore. Pearson (1996) interpreted these as either metasomatized intrusions or metasomatized country rock.

Age constraints on the Lyons River ultrabasic sills and Spider Hill sills are poor. Pearson (1996) obtained a SHRIMP U–Pb zircon date of 1679 ± 6 Ma for a sample of fenitized Pimbyana Granite adjacent to an ultrabasic sill. This sample has very high Zr (approximately 2,000 ppm) and the date was interpreted by Pearson (1996) as the age of metasomatism; two older analyses at 1791 ± 10 Ma were thought to represent xenocrysts from the Pimbyana Granite. However, new SHRIMP U–Pb zircon dates accompanying this remapping show that the igneous crystallization age of the Pimbyana Granite is indistinguishable from the date from the fenite. Either all the zircons dated in the fenite are xenocrysts, or the ultrabasic sills are of similar age to the Pimbyana Granite. The first explanation leaves the high Zr content of the rock unexplained, but the latter explanation is possible, since alkali pyroxenes and amphiboles may contain up to several thousand ppm ZrO_2 (e.g. Deer et al., 1997; Preston et al., 2000). Pearson (1996) suggested that one of the 'deformed lenses' intruded sedimentary rocks of the Bangemall Supergroup 6 km southeast of Yangibana Yard. This relationship was not observed during the current study, and the ultramafic sills in this area appear to have intruded and mingled with altered basement granite just beneath the unconformity with the overlying Edmund Group rocks. However, ferruginous veins (*zi*) do intrude sandstones of the Kiangi Creek Formation on the Lyons River crossing (MGA 411120E 7350230N) and may be part of a younger magmatic event. At this locality the veins cross-cut strata and also intrude along bedding planes. No metamorphism of the host rock was observed along contacts with the veins.

A sample from an ultramafic sill that intruded the Pimbyana Granite about 2.5 km north of Fraser Bore was dated by the K–Ar method at 752 ± 11 Ma (Geological Survey of Western Australia, 2005). This date was interpreted as the minimum crystallization age of the rock. Contacts between the sill and Pimbyana Granite are commonly lobate and cuspate suggesting that the sill intruded the granite before the latter had entirely crystallized. The contacts contain mixed rocks of granite and ultramafic rock; these can be recognized by large (up to 2 cm long) tabular K-feldspar phenocrysts, ordinarily present in the Pimbyana Granite, surrounded by mats of riebeckite and arfvedsonite, normally present in the ultramafic rocks. The date obtained by Geological Survey of Western Australia (2005) is likely to reflect the time at which the rock was cooled through the blocking temperature for K–Ar in phlogopite (<400°C; McDougall and Harrison, 1999).

The 'Bald Hill weathered intrusions', 'Spider Hill sills', and the 'Yangibana ferrocarbonatites and ironstones' were considered by Pearson (1996), Pearson and Taylor (1996) and Pearson et al. (1996) as younger than the Lyons River ultrabasic sills. This is mainly based on a single SHRIMP U–Pb analysis of 1250 ± 73 Ma of a bipyramidal zircon from a weathered intrusion at Bald Hill.

Late Palaeoproterozoic Mangaroon Orogeny

The 1680–1620 Ma Mangaroon Orogeny is a newly identified tectonothermal event in the Gascoyne Complex (Sheppard et al., in press). On EDMUND (1:100 000 sheet), Pearson (1996) dated a granite pluton ('Dingo Granite' renamed here as the Dingo Creek Granite) at 1674 ± 6 Ma. However, it was not until the Gascoyne Complex rocks on the remainder of the EDMUND 1:250 000 sheet area were mapped and then dated, that the regional-scale nature of the deformation, metamorphism, and granitic magmatism was established.

Mapping carried out as part of this study shows that the orogeny encompasses complex and progressive

deformation and metamorphism. This has been divided into two deformation and regional metamorphic 'events' (D_{1m}/M_{1m}, D_{2m}/M_{2m}), which probably are broadly associated with intrusion of voluminous granite plutons of the Durlacher Supersuite. These deformation and metamorphic events are younger than 1680 ± 13 Ma, the age of the youngest detrital zircon population in the precursor sediments to the Pooranoo Metamorphics, and continue until c. 1620 Ma, the age of the youngest syntectonic granites. The Mangaroon Orogeny is therefore much younger than tectonic fabrics and metamorphic mineral assemblages related to the 1830–1780 Ma Capricorn Orogeny. High-grade contact metamorphism, including hornfels migmatites, is also seen to overprint the regional metamorphic fabrics.

On MANGAROON, the effects of the Mangaroon Orogeny are largely confined to the Mangaroon Zone. None of the granitic rocks of the Moorarie Supersuite in the adjacent Limejuice Zone contain a high-grade metamorphic fabric that could be attributed to D_{1m}/M_{1m}. Many of the granites show minor to moderate static recrystallization at greenschist-facies conditions (?during D_{2m}/M_{2m}), but none contain a penetrative fabric other than adjacent to the Minga Bar Fault near the western edge of the sheet area.

Deformation and metamorphism (D_{1m}/M_{1m})

The oldest fabric in the Mangaroon Zone is a regionally extensive gneissic layering or foliation (S_{1m}) developed in metamorphic rocks of the Pooranoo Metamorphics, as well as in the Gooche Gneiss. In the area around the Star of Mangaroon mine this fabric includes stromatic leucosomes in metatexite migmatite and diatexite melts. The age of D_{1m}/M_{1m} is constrained by the youngest detrital zircon population of c. 1680 Ma in the sediment precursor to the pelitic gneiss and granofels, and by granites of the Durlacher Supersuite (< c. 1680 Ma) that intrude S_{1m}.

The S_{1m} gneissic layering is cut by an upright foliation associated with F_{2m} folds. Folds associated with D_{1m} are difficult to identify, but about 5 km northwest of James Bore (MGA 368020E 7380090N) a steeply inclined, metre-scale isoclinal F_{1m} fold in pelitic gneiss in the hinge of a large F_{2m} fold is exposed. Other evidence for F_{1m} folds comes from small-scale F_{1m}/F_{2m} fold interference structures in psammite near the Star of Mangaroon mine (MGA 372200E 7360090N). However, there are also larger scale fold interference structures in Gooche Gneiss about 4 km northeast of Six Mile Well and 6 km east of Burridges Well. In addition, F_{1m} inclined folds are inferred from downward facing metamorphosed feldspathic sandstone beds in the hinge of an F_{2m} fold west of Doorawarrah Well (MGA 355550E 7376850N).

Mineral assemblages developed during M_{1m} are commonly well preserved in the fold hinges of macroscopic F_{2m} folds. Pelitic gneiss and granofels contain assemblages including biotite, muscovite, quartz, plagioclase and sillimanite; quartz, biotite, cordierite, plagioclase, muscovite and minor sillimanite; and, plagioclase, biotite, quartz, sillimanite, muscovite and cordierite. All assemblages include accessory tourmaline and iron oxides. Sillimanite consists of seams and patches of fibrolite that typically nucleate on biotite crystals or large muscovite plates. In some rocks sillimanite also forms small prismatic crystals intergrown with plagioclase and quartz.

Garnet is restricted to two small areas on MANGAROON: in the area around Mount Thompson near the southern edge of the sheet area, and about 4 km northwest of Bookatharra Well in the northwestern part of the sheet area. Southeast of Mount Thompson (MGA 379090E 7345630N) pelitic gneiss consists of sillimanite, biotite, quartz, muscovite, garnet and minor cordierite, in association with diatexite migmatite. Northwest of Bookatharra Well non-migmatitic pelitic gneiss consists of cordierite, biotite, muscovite and sillimanite with minor layers of garnet, quartz, cordierite, biotite and sillimanite.

Non-migmatitic pelitic gneiss and granofels in the area north and northwest of James Bore commonly have layers rich in porphyroblasts up to 1 cm in diameter. The porphyroblasts overprint S_{1m} and give rise to prominent pits on weathered surfaces. The porphyroblasts consist of fine-grained polygonal plagioclase, biotite, prismatic sillimanite and minor muscovite.

The assemblages outlined above are typical of high-Al and low-Al pelites regionally metamorphosed at low pressures (Spear, 1993, p. 374–382). The absence of garnet (other than locally where it may have been stabilized by high whole-rock MnO) and staurolite, or kyanite, combined with the abundance of cordierite, suggests that the rocks were not metamorphosed at intermediate to high pressures. The cordierite and sillimanite bearing assemblages noted above are stable at about 600–630°C at 200 MPa or 650–700°C at 500 MPa (Spear, 1993, p. 375–382). The appearance of sillimanite in non-migmatitic pelitic gneiss is consistent with a metamorphic grade equivalent to amphibolite facies.

The migmatites around the Star of Mangaroon mine are associated with pelitic gneisses consisting of cordierite, biotite, quartz, microcline, sillimanite, and minor muscovite, or quartz, cordierite, biotite, microcline, sillimanite and minor plagioclase. The major difference with non-migmatitic pelitic gneisses north of the Mangaroon Syncline is the paucity or absence of plagioclase or muscovite, and the appearance of microcline in gneisses associated with the migmatites. The co-existence of sillimanite and K-feldspar is consistent with onset of the equivalent of upper amphibolite facies conditions (Bucher and Frey, 2002, p. 110). These changes suggest that melt formed due to either of the following reactions:

muscovite + plagioclase + quartz = sillimanite + K-feldspar + melt (1)

muscovite + plagioclase + quartz = sillimanite + K-feldspar + biotite + melt (2)

The temperatures at which these reactions take place are strongly dependent on pressure, but a minimum temperature of approximately 650°C is required (Spear,

1993, p. 368). These reactions do not produce more than about 5% partial melting (Clemens and Vielzeuf, 1987), and are unlikely to be the reaction responsible for the diatexite migmatites, which correspond to large degrees of melt. The diatexite melts are a medium-grained, muscovite- and biotite-bearing granodiorite to tonalite that also contain cordierite, with or without minor garnet and sillimanite. Palaeosomes consist of biotite, cordierite, sillimanite, muscovite and plagioclase, or cordierite, plagioclase, quartz, sillimanite and muscovite. The diatexites may have been derived from farther below at higher temperatures by biotite dehydration, which, on both theoretical and experimental grounds, can produce large amounts of melting (Clemens and Vielzeuf, 1987).

Metamorphosed feldspathic sandstone is a widespread rock type, but is a poor indicator of metamorphic grade. Some layers of metamorphosed sandstone west and northwest of James Bore contain rosettes of fine-grained magnetite and biotite, commonly with leucocratic haloes. The rosettes overprint the S_{1m} fabric, but are commonly flattened within the compositional layering and are cut by the S_{2m} foliation. Rosettes range from nearly spherical and 2 cm in diameter, to oblate and more than 10 cm long. Leucocratic haloes are mostly a few millimetres wide but may exceed 10 mm. The origin of these rosettes is unclear. Garnet is also locally present in metamorphosed feldspathic sandstone on EDMUND (1:100 000 sheet).

The dominant foliation or gneissic layering in granodioritic to monzogranitic rocks of the Gooche Gneiss is also interpreted to have formed during D_{1m}. Augen of microcline and quartz are wrapped by fine-grained quartz, plagioclase, biotite and muscovite. The micas have a strong preferred orientation and define the foliation.

Deformation and metamorphism (D_{2m}/M_{2m})

The dominant fabric in rocks of the Pooranoo Metamorphics in the Mangaroon Zone is a pervasive, east-southeast striking foliation. This foliation cuts the gneissic layering, and is parallel to the axial surfaces of metre- to kilometre-scale folds. A widespread lineation defined either by the intersection of S_{1m} and S_{2m} or, less commonly, as a crenulation of S_{1m} by S_{2m} plunges parallel to F_{2m} folds. The F_{2m} folds are upright, and range from close to tight, and plunge moderately to steeply to the west-northwest or east-southeast. There are locally large variations in plunge direction over short distances, but there is no crosscutting fabric to suggest a later phase of folding or shearing, and there are no large swings in the strike of the F_{2m} axial surfaces.

The S_{2m} fabric is present in some of the granites of the Durlacher Supersuite, particularly in the schlieric inclusion-rich granodiorite (*PU-ggvs*). In addition, some of the granite units, most commonly the Pimbyana Granite and the Dingo Creek Granite, contain a magmatic foliation defined by tabular K-feldspar phenocrysts parallel to S_{2m}. Both granites are composed of a series of sheets parallel to S_{2m} suggesting that they were emplaced during D_{2m}. However, other granite plutons cut across S_{2m}, and contact metamorphism associated with the granites has recrystallized M_{2m} mineral assemblages. These observations suggest that D_{2m}/M_{2m} is the same age as the granites of the Durlacher Supersuite: that is, c. 1674 Ma.

In the hinges of F_{2m} folds, M_{1m} mineral assemblages are commonly preserved, but on the limbs, these assemblages are overprinted partly or wholly by M_{2m} metamorphism. This has resulted in replacement of sillimanite by sericite, and recrystallization of cordierite to sericite and chlorite. Microcline is replaced by sericite, and biotite is commonly recrystallized to a greenish variety and it shows exsolution of fine ?rutile needles. Plagioclase is partly sericitized. The result is typically a sericite–chlorite–quartz–plagioclase–biotite schist. This assemblage, along with the absence of andalusite, chloritoid or staurolite, is consistent with greenschist facies metamorphism of a low-Al bulk composition (Spear, 1993).

Metamorphosed mafic rocks are rare in the Pooranoo Metamorphics, and where present they do not seem to contain high-grade M_{1m} assemblages. Assemblages of actinolite, plagioclase, epidote and titanite suggest upper greenschist-facies metamorphism during M_{2m}. Some actinolite crystals have cores of clinopyroxene. Metamorphosed ultramafic rock contains cummingtonite and serpentine with minor green spinel. Lenticular patches of coarser grained cummingtonite contain cores of orthopyroxene with a relict subophitic texture. This observation suggests that the pyroxene is not related to M_{1m}, but is igneous in origin. It also implies that the rocks post-date M_{1m}, and therefore, are intrusive.

In the granitic rocks of the Durlacher Supersuite, the effects of M_{2m} are most pronounced in the schlieric granodiorite (*PU-ggvs*), which field relationships suggest is the oldest of the granites in the supersuite. Mineralogical changes during M_{2m} consist of epidote and titanite replacement of magnetite and ilmenite in conjunction with plagioclase recrystallization, as well as recrystallization of biotite to a green variety with exsolved rutile needles. Plagioclase is recrystallized to albite–oligoclase, sericite and epidote.

Along the western edge of MANGAROON adjacent to the Minga Bar Fault, medium-grained porphyritic biotite monzogranite (*PM-gmp*) is moderately to strongly foliated. The foliation strikes southeast and dips steeply to the southwest, and becomes more intense toward the northeast. About 1.7 km west and 3.6 km south of Minga Bar Well (MGA 347930E 7373710N and 350070E 7370420N) a phyllonite derived from porphyritic biotite monzogranite is juxtaposed against medium- to coarse-grained and pebbly sandstone of the Edmund Group. The Edmund Group rocks are folded about open to close upright folds, but are otherwise weakly strained. At the latter locality, a folded unconformity is preserved between the Edmund Group rocks and the phyllonite. The majority of the deformation in the shear zone must have pre-dated deposition of the Edmund Group, and may relate to the Mangaroon Orogeny. The general absence of a stretching lineation suggests that the rocks underwent non-rotational strain. Locally, a steeply dipping stretching lineation defined by biotite or chlorite is developed, and is associated with asymmetric K-feldspar porphyroclast tails implying southwest side up on steep normal or reverse faults.

Narrow shear zones (<2 m wide) in granites on the southwestern side of the Minga Bar Fault locally contain S–C fabrics suggesting dextral strike-slip movement. Deformed porphyritic biotite monzogranite consists of microcline and quartz porphyroclasts wrapped by fine-grained quartz, muscovite, chlorite, untwinned ?albite, titanite and minor green-brown biotite. This assemblage is consistent with recrystallization under lower greenschist facies conditions. However, the age of this deformation and recrystallization is unknown. It may relate to D_{2m}/M_{2m} or, alternatively, it may relate to the Neoproterozoic Edmundian Orogeny (see **Neoproterozoic Edmundian Orogeny**).

In the areas between the Yannarie River on northwestern MANGAROON and outcrop of the Edmund Group to the northeast, and along the western side of the fault that runs near Old Deep Well and Middle Well, granites of the Durlacher Supersuite are cut by narrow zones of shearing. This tectonic fabric strikes southeast and mostly dips steeply to the southwest. It is commonly parallel to an igneous foliation in the granites defined by the alignment of tabular K-feldspar phenocrysts. At one locality (MGA 382980E 7373950N), weakly to moderately foliated porphyritic biotite granodiorite (*PU-ggb*) is intruded by northeast-striking dykes of muscovite–biotite granite and pegmatite (*PU-gmv*). The latter contain a foliation, but are not offset, suggesting that they have undergone non-rotational strain. Therefore, granites of the Durlacher Supersuite both intrude the shear zones and are overprinted by them, indicating that supersuite emplacement, at least in part, accompanied the deformation. Most sense-of-shear criteria indicate reverse movement (that is, southwest side up), although normal movement is indicated in places.

Contact metamorphism

Narrow contact aureoles are developed in the Pooranoo Metamorphics adjacent to granites of the Durlacher Supersuite. The main exception consists of plutons of muscovite–biotite granite (*PU-gmv*, *PU-gmvt*), which commonly have no discernable contact metamorphic aureole. Migmatitic hornfels is located within about 20 m of the margins of granites. Most of the migmatites have a nebulitic structure. Pelitic granofels over a wide area north of James Bore, has a hornfelsed 'knobbly' appearance, and is intensively veined by the Dingo Creek Granite. The granofels is resistant to weathering and caps many of the hills and ridges. Much of this region may be underlain by the Dingo Creek Granite and some biotite gabbro, of which the latter is exposed about 3 km north-northeast of James Bore.

Late Palaeoproterozoic to Mesoproterozoic Edmund and Collier Basins

The Edmund and Collier Basins are the youngest tectonic units within the Capricorn Orogen and correspond to the present day outcrop of the Edmund and Collier Groups that together make up the Bangemall Supergroup. These rocks unconformably overlie the Palaeoproterozoic Ashburton and Blair Basins to the northeast and rocks of the Palaeoproterozoic Gascoyne Complex to the southwest (Fig. 2 and Plate 1). The Edmund Basin was initiated during intracratonic extensional reactivation of structures formed during earlier stages of the Capricorn Orogen. These structures were intermittently active throughout the evolution of the basin, but do not appear to have had a signifcant influence on the Collier Basin. Subsidence of the Edmund and Collier basins was most likely driven by plate boundary forces generated in the Pinjarra, Albany–Fraser, and Paterson Orogens.

Bangemall Supergroup

The Bangemall Supergroup was first recognized as a stratigraphic entity by Woodward (1891), and named the Bangemall Series or Bangemall beds by Maitland (1909). The name Bangemall Group was introduced by Halligan and Daniels (1964) during the first edition 1:250 000-scale geological mapping. However, the recognition of a significant regional unconformity between the Edmund and Collier Subgroups (Cooper et al., 1998a,b) and their correlatives and the consequent elevation of these units to group status, has required elevation of the Bangemall Group to supergroup status (Martin et al., 1999; Martin and Thorne, 2002).

The Bangemall Supergroup forms a broad regional syncline between the Yilgarn and Pilbara Cratons (Martin and Thorne, 2002, 2004). On EDMUND, it is exposed within the Wanna Syncline, unconformably overlying the Gascoyne Complex on the southwestern limb of the syncline, and the Wyloo and Capricorn Groups on the northeastern limb. In this area, the syncline can be further subdivided into a relatively stable shelf (Pingandy Shelf), separated by the Talga Fault from a horst-and-graben terrain floored by Gascoyne Complex rocks to the southwest (Fig. 2). This structural framework follows earlier proposals by Brakel and Muhling (1976), Muhling and Brakel (1985) and Chuck (1984). Outliers of Bangemall Supergroup rocks are also preserved in tight isolated synclines, such as the Mangaroon Syncline on MANGAROON, within the Gascoyne Complex.

The main rock types within the Bangemall Supergroup are fine-grained siliciclastic and carbonate sedimentary rocks, with lesser coarse-grained clastic rocks. The most common lithologies are siltstone, dololutite, dolarenite, stromatolitic dolostone, and fine- to coarse-grained sandstone.

The maximum age of the Bangemall Supergroup can be broadly constrained by SHRIMP U–Pb zircon ages of units truncated by the basal unconformity, and by the ages of detrital zircons in sandstones. The underlying Capricorn Group on CAPRICORN has been dated at 1804 ± 7 Ma (Hall et al., 2001). Granodiorite from the Coobarra Dome on COLLIER has been dated at 1797 ± 8 Ma (Geological Survey of Western Australia, 2005), and the Boolaloo Granodiorite on WYLOO at 1786 ± 5 Ma (Krapez and McNaughton, 1999). The Dingo Granite (1674 ± 6 Ma) and Lyons River ultrabasic sills

(1679 ± 6 Ma) on EDMUND, also predate the Bangemall Supergroup (Pearson, 1996). More recent dating in this area and in the southern Gascoyne Complex has identified a number of granite bodies with ages ranging from about 1680 to 1620 Ma (Durlacher Supersuite) that appear to predate the Bangemall Supergroup (Pearson et al., 1996; Sheppard and Swager, 1999, 2002; Geological Survey of Western Australia, 2005). The youngest detrital zircons in sandstones at the base of the Bangemall Supergroup are about 1805 Ma (Geological Survey of Western Australia, 2005); however, a rhyolite in the Coobarra Formation near the base of the succession on COLLIER has an interpreted maximum age of 1638 ± 14 Ma, based on two zircons (Geological Survey of Western Australia, 2005). These ages suggest that the maximum age of the Bangemall Supergroup is about 1620 Ma.

SHRIMP U–Pb dating of zircon and baddeleyite has identified two discreet suites of dolerite that place constraints on the minimum age of the Bangemall Supergroup. The oldest suite, which is intruded exclusively into the Edmund Group, has been dated at c. 1465 Ma and constrains the minimum depositional age of the Edmund Group. The youngest suite, which intrudes both the Edmund and Collier Groups is c. 1070 Ma (Wingate, 2004; Geological Survey of Western Australia, 2005). The c. 1070 Ma sills constrain a minimum depositional age for the Collier Group and Bangemall Supergroup.

Edmund Group (PME-s)

The Edmund Group unconformably overlies older tectonic units of the Capricorn Orogen, and consists, from bottom to top, of the Yilgatherra, Irregully, Gooragoora, Blue Billy, Cheyne Springs, Kiangi Creek, Muntharra, Discovery, Devil Creek, Ullawarra, and Coodardoo Formations. It is unconformably overlain by the Collier Group (Martin and Thorne, 2002), which is correlated with the Mucalana Subgroup of Muhling and Brakel (1985). The Edmund Group is best developed and exposed along Irregully Creek on ULLAWARRA, CAPRICORN and ELLIOTT CREEK, and in the Barley Range on MAROONAH. Although the thickness is variable, it exceeds 4 km (Muhling and Brakel, 1985).

The main lithologies include siltstone, sandstone, conglomerate, dolostone, stromatolitic dolostone, carbonaceous siltstone, and chert that are commonly intruded by thick dolerite sills. The Edmund Group is younger than 1680–1620 Ma granites in the underlying Gascoyne Complex, and older than c. 1465 Ma dolerite sills that intrude it over large areas of EDMUND (Martin and Thorne, 2004).

Yilgatherra Formation (PMEy-s, PMEy-sl)

The Yilgatherra Formation (Martin and Thorne, 2002) is the oldest lithostratigraphic unit in the Edmund Group. It consists of a basal sandstone and conglomerate unit (*PMEy-s*), overlain by siltstone (*PMEy-sl*).

North of the Talga Fault (Fig. 2), the Yilgatherra Formation forms a discontinuous unit at the base of the Bangemall Supergroup along the unconformity with the Wyloo and Capricorn Groups, but is more continuous south of the fault. The formation is well exposed on northeast EDMUND, particularly southeast of Irregully Gorge, and on northwest MAROONAH west of the Joy Helen prospect. On northern EDMUND the formation is generally less than 30 m thick, but increases to about 350 m in the vicinity of the Mangaroon Syncline (Martin and Thorne, 2000).

The Yilgatherra Formation unconformably overlies the Palaeoproterozoic Ashburton Formation and Capricorn Group, and igneous and metamorphic rocks of the Gascoyne Complex. The formation is conformably overlain by the Irregully Formation, but is locally absent where the latter onlaps basement highs, particularly north of the Talga Fault.

The basal Yilgatherra Formation consists of an upward-fining succession, from localized pebble to cobble conglomerate (up to 20 m), through very coarse grained sandstone, to fine-grained sandstone and siltstone. North of the Talga Fault, this succession fills topographic lows, and is locally interbedded with stromatolitic dolostone and planar-laminated siltstone, particularly on ELLIOTT CREEK and CAPRICORN. Conglomerate clasts are mostly tabular to equant, subrounded to well rounded, and comprise quartz sandstone, ferruginous quartz sandstone, vein quartz, jaspillite, and silicified siltstone in a coarse-grained sandstone matrix. The conglomerates are tabular bedded with poorly to moderately developed parallel stratification in the lower levels that is transitional into parallel-stratified interbedded conglomerate and sandstone. The sandstones that overlie and are interbedded with the conglomerates are trough cross-stratified, and commonly contain disseminated pebbles.

South of the Talga Fault, where conglomerates are generally thinner, the Yilgatherra Formation consists of an upward-fining succession from coarse- to very coarse grained sandstone to planar-laminated siltstone. Sandstones are mainly small- to medium-scale trough cross-stratified, but also display planar and undulatory lamination and commonly contain tabular mudstone-pebble moulds. Symmetrical straight-crested ripples, current ripples, planar- to wavy-laminated siltstone partings, and weak normal grading are also present. The gradation into planar-laminated siltstone is marked by a decrease in sandstone bed-thickness and grainsize. The uppermost siltstone unit of the Yilgatherra Formation is generally poorly exposed, and consists mainly of fissile, parallel-planar laminated siltstone. This unit is thickest south of the Talga Fault, especially in the Mangaroon Syncline. The sandstone and siltstone facies of the Yilgatherra Formation are frequently overlain by silcrete, especially north of Talga Fault where Irregully Formation dolostones tend to directly overlie sandstone or basement. Palaeocurrent directions from trough cross-stratified sandstone are highly variable with palaeoflow to the northwest, west, southwest, and southeast. Current directions may be either unimodal, polymodal, or bipolar.

Although the youngest population of detrital zircons in a sample from near Boora Boora Bore has been dated at 1805 ± 9 Ma (Geological Survey of Western Australia, 2005; GSWA 152956), the maximum age of the Yilgatherra Formation is constrained by its unconformable

relationship to the c. 1674 Ma Dingo Granite (Pearson et al., 1996), and the c. 1673 Ma Pimbyana Granite and c. 1660 Ma Yangibana Granite (Geological Survey of Western Australia, 2005; GSWA 169060 and 160059). A granophyric plug that intrudes the Yilgatherra Formation about 2 km north of Horse Well on MAROONAH contains a c. 1778 Ma population of zircons (Geological Survey of Western Australia, 2005; GSWA 169089) that are interpreted as xenocrysts. This plug provides a slightly younger maximum age. The Discretion Granite on MARQUIS is the youngest granite in the Gascoyne Complex and has been dated at 1619 ± 15 Ma (Geological Survey of Western Australia, 2005; GSWA 142855; Sheppard and Swager, 1999). Since no granites are known to intrude the Bangemall Supergroup, these data suggest a probable maximum age for the Yilgatherra Formation of about 1620 Ma (Martin and Thorne, 2004). The minimum age is constrained by c. 1465 Ma dolerite sills intruded into overlying units of the Edmund Group (Wingate, 2002; Geological Survey of Western Australia, 2005).

The sandstones of the Yilgatherra Formation are fine to very coarse grained, and consist mainly of angular to well-rounded monocrystalline to polycrystalline quartz (70–90%), plagioclase and K-feldspar (10–20%), lithic quartz–sericite clasts (≤10%), and trace amounts of heavy minerals (zircon, epidote, sphene, muscovite, and tourmaline). The matrix generally consists of microcrystalline quartz and sericite, with quartz forming syntaxial overgrowths. Sandstone composition ranges from quartz arenite to lithic arenite and arkose. Conglomerate clast compositions are similar to those of the sandstones. However, the matrix comprises recrystallized quartz and feldspar sand, with some quartz cement overgrowths.

Numerous costeans have been excavated in uranium-bearing calcrete that overlies the Yilgatherra Formation in the Telfer River region of MAROONAH. This mineralization is most likely related to the basal Yilgatherra Formation unconformity.

Deposition of the upward-fining Yilgatherra Formation occurred during a marine transgression in environments ranging from fluvial to shallow marine, and was controlled by active basement highs south of the Talga Fault on western EDMUND (Martin and Thorne, 2000), as indicated by palaeocurrent directions and thickness variations. Depositional environments north of the Talga Fault appear to be dominated by fluvial to intertidal mixed siliciclastic-carbonate settings, whereas fluvial to subtidal settings predominate south of the fault.

Irregully Formation (PMEi-k, PMEi-st, PMEi-sl)

The Irregully Formation was established by Daniels (1966) as a result of revision of the 'Top Camp Dolomite', and originally included all units below the Kiangi Creek Formation. The current definition follows the revisions of Chuck (1984) and Copp (1998), and includes only the lower dolostone interval ('Wongida Dolomite Member') of the original Irregully Formation.

The Irregully Formation is present throughout the lower Bangemall Supergroup on EDMUND, but is absent on southeast EDMUND (1:100 000) and southwest ELLIOTT CREEK. The thickness increases from about 350 m in the type area on Irregully Creek to over 2000 m on MAROONAH and northeast MANGAROON. This thickness change is related to syndepositional movement along the Talga Fault. The thickness of the Irregully Formation decreases markedly towards the southeast corner of EDMUND due to erosion on a disconformity at the base of the Kiangi Creek Formation.

The Irregully Formation conformably overlies the Yilgatherra Formation in most areas, but where the latter is absent it unconformably overlies the Palaeoproterozoic Wyloo Group and Gascoyne Complex. It is conformably to unconformably overlain by either the Gooragoora Formation, the Blue Billy Formation, or the Kiangi Creek Formation.

The principal lithologies are laminated and stromatolitic dolostone and dolorudite (*PMEi-k*), minor sandstone and dolomitic sandstone with rare conglomerate (*PMEi-st*), and laminated siltstone (*PMEi-sl*). Stromatolite types include *Conophyton garganicum australe* Walter 1972, *Paniscollenia* Koroljuk 1960, *Colonella* Komar 1964, and *Baicalia capricornia* Walter 1972. A major facies change, from predominantly peritidal stromatolitic dolostone north of the Talga Fault, to mainly slope breccias and planar-laminated dolostones south of the fault, has also been documented (Martin and Thorne, 2004). A significant thickness of sandstone and siltstone is interbedded with the dolostone on MAROONAH and northeast MANGAROON (Martin and Thorne, 2000). Palaeocurrent directions in sandy dolostones on southeast MANGAROON were generally to the south, with a wide spread between southwest and east-southeast (Daniels, 1966).

There are no direct age constraints for the Irregully Formation which is inferred on the basis of regional stratigraphic relationships to be of similar age to the Yilgatherra Formation (i.e. 1620–1465 Ma).

The most common lithology in the Irregully Formation is massive to laminated dololutite, which in thin section consists of fine-grained dolomicrite that is locally recrystallized to patches and veins of dolospar. Lamination within this facies is planar to undulatory and commonly indistinct and clotted in thin section. Stromatolitic dololutites are defined by irregular and laminoid fenestrae infilled with microcrystalline quartz or dolospar. Pink weathering dololutite can be attributed to the presence of finely disseminated iron oxides along dolomite grain boundaries. Dolarenites and pebbly dolarenites are generally coarse to very coarse grained (0.5–5 mm) with clasts composed mainly of dolomicrite in a micritic to sparry dolomite cement (approximately 15–20%). Irregular sparry fenestrae are common. Clasts within the dolorudite facies are mainly angular dolomicrite, although some are very well rounded, and enclosed in a recrystallized sparry dolomite matrix. Textures within the dolomicrite clasts suggest that they are intraclastic. Stylolites along clast margins are defined by iron oxides. Some cavities have a geopetal infill of dololutite. Many of the carbonate lithofacies of the Irregully Formation contain lamina-parallel detrital muscovite flakes as well as locally abundant (up to 10%) detrital quartz, feldspar, and accessory minerals (tourmaline, zircon,

and rounded opaque minerals). Most of the sandstones in the Irregully Formation consist of medium- to coarse-grained, subrounded to well-rounded, poorly sorted quartz and dololutite grains in a matrix of recrystallized sparry dolomite and fine-grained quartz. The cement consists of syntaxial quartz, opaques, and poikilotopic dolomite. Accessory minerals include well-rounded tourmaline, zircon, detrital muscovite, granular hematite, K-feldspar, and plagioclase. Cross-lamination is locally defined by variations in the carbonate content of the matrix.

The Irregully Formation hosts localized Pb and Zn mineralization on the Pingandy Shelf, in the vicinity of Irregully Creek (around MGA 448376E 7415626N) and at the Joy Helen Prospect. Contact metamorphic aureoles around dolerite sills locally contain chrysotile asbestos, talc, and marble.

The depositional environment of the Irregully Formation ranges from a peritidal platform north of the Talga Fault, in an area known as the Pingandy Shelf, to mainly slope and deep-marine deposits with localized fluvial and shallow-marine facies south of the fault. Fluvial and shallow marine facies south of the Talga Fault were deposited around the margins of palaeotopographic highs on Maroonah, Mangaroon, and Edmund (1:100 000). The middle and upper parts of the Irregully Formation on the Pingandy Shelf consist of slope lithofacies and stromatolitic bioherms that record shallowing of the carbonate platform to wave base. This shallowing is also recorded south of the Talga Fault. In the Mangaroon Syncline the Irregully Formation is dominated by slope facies carbonates, suggesting localized steep palaeoslopes, possibly due to movement along the major bounding faults.

Gooragoora Formation (PMEg-s, PMEg-st)

The Gooragoora Formation was originally defined as a member of the Irregully Formation by Daniels (1970) and Muhling and Brakel (1985), but is now recognized as a persistent mappable unit that is best developed north of the Talga Fault on northwestern Edmund (Martin and Thorne, 2002).

The formation has a maximum thickness of about 150–250 m (Martin and Thorne, 2002). The thickest sections are on central Ullawarra and thin towards the southeast, pinching out beneath the overlying Blue Billy Formation on northeastern Elliott Creek. South of the Talga Fault, the Gooragoora Formation is present on Maroonah and Mangaroon, but pinches out on northwestern Edmund (1:100 000). Excellent exposures of the formation are present in the Barley Range Nature Reserve on a tributary of Wongida Creek (MGA 396800E 7441600N), 10 km west of Murgundarra Pool on Maroonah. In contrast to the underlying Irregully Formation, the Gooragoora Formation does not show any marked thickness variation between the Talga Fault and Mangaroon Syncline.

The Gooragoora Formation sharply overlies the Irregully Formation and is in turn overlain by the Blue Billy Formation, although the basal contact is often not well exposed, especially on Maroonah. A slight local angular discordance with the Irregully Formation noted by Chuck (1984) suggests the lower contact of the Gooragoora Formation may be unconformable. The upper contact with the Blue Billy Formation is marked by an abrupt change to pyritic, carbonaceous siltstone. On southeastern Edmund, the Gooragoora Formation is truncated beneath a disconformity at the base of the Kiangi Creek Formation.

The Gooragoora Formation (*PMEg-s*) consists mainly of medium- to thick-bedded, trough cross-stratified, fine- to very coarse grained sandstone, with lesser amounts of conglomerate and planar-laminated siltstone, that fine towards the north and southeast (Martin and Thorne, 2002, 2004). In some areas, sandstone-dominated intervals form mappable units (*PMEg-st*). Coarse- and medium-grained sandstones contain abundant intraclast moulds and small- to medium-scale trough cross-strata in stacked sets. Pebbly sandstones are also common in some areas. Fine- and medium-grained sandstones are very thinly bedded and parallel-planar laminated. Sandstones are also locally highly silicified, or contain irregular brown clots of carbonate or weathered sulfide. On Maroonah, the formation is more heterogeneous, consisting of cross-stratified sandstone, planar-laminated siltstone and locally significant amounts of carbonate. Carbonate units in this area are planar to irregular in shape, and consist of dolorudite, dolarenite, and dololutite, and are interbedded with siltstone and trough cross-stratified medium- to coarse-grained quartz arenite. Trough cross-stratification is locally distorted, possibly by dewatering. Palaeocurrent directions in sandstone units of the Gooragoora Formation on Edmund are locally highly variable, but predominantly towards the southeast.

The age of the Gooragoora Formation is similar to that of underlying formations and is constrained between about 1620 and 1465 Ma.

Sandstones in the Gooragoora Formation are mainly feldspathic lithic quartz arenites and quartz arenites. The mineralogy is typically 70–80% monocrystalline and polycrystalline quartz, 10–15% lithic fragments (chert, possible felsic volcanic fragments, graphic granite, sericite, chlorite, and opaque mineral aggregates), 5% feldspar (dusty and partially sericitized K-feldspar and microcline), and less than 1% accessory detrital minerals (opaques, apatite, epidote, and zircon). The sandstone framework is moderately to well sorted, subrounded to rounded, and compacted with sutured grain contacts. The matrix consists of syntaxial quartz cement with a veneer of clay minerals around some grains. Some sandstones contain up to 10% carbonate cement that is partially weathered and replaced by iron oxides. Planar-laminated siltstones consist of coarse silt with disseminated very fine quartz-sand grains and very fine acicular white mica. They are also commonly silicified. Dolostone interbeds are commonly ferruginous and contain disseminated angular to subangular quartz grains ranging from silt to very fine sand. Hematite and goethite are present as disseminated mottles or concentrations along spaced fracture cleavage planes.

The Gooragoora Formation is interpreted to have been deposited by the progradation of coarse-grained

deltaic sandstones during a period of high or rising sea level (Martin and Thorne, 2004). Deltaic sedimentation was restricted to the northwestern parts of EDMUND where uplift to the northwest exceeded the rate of sea level rise. Finer grained facies interbedded with planar-laminated siltstone were probably deposited in a proximal shelf environment.

Blue Billy Formation (PMEb-sl, PMEb-st)

The Blue Billy Formation is a newly recognized unit (Martin and Thorne, 2002) that is partly equivalent to the Jillawarra Formation of Muhling and Brakel (1985), and is characterized by its distinctive lithology and relative stratigraphic position with respect to the Irregully and Gooragoora Formations below, and Cheyne Springs and Kiangi Creek Formations above.

The Blue Billy Formation is present throughout most of EDMUND, and ranges from 0 to 500 m thick (Martin and Thorne, 2002), but is generally less than 200 m thick. The formation is thickest in the vicinity of Irregully Gorge on CAPRICORN and ULLAWARRA, and thins to the south and east. On northwestern EDMUND it overlies the Gooragoora Formation, but on parts of ELLIOTT CREEK it overlies the Irregully Formation. The Blue Billy Formation is truncated by a disconformity beneath the Kiangi Creek Formation on western EDMUND (1:100 000; in the vicinity of MGA 406000E 7383000N) and is consequently not present southeast of here.

The contact with the Gooragoora Formation is apparently sharp and conformable on most of EDMUND, but forms an apparent non-depositional unconformity or disconformity with the Irregully Formation on northeastern ELLIOTT CREEK. The basal contact is taken as the top of the uppermost sandstone of the Gooragoora Formation. On most parts of EDMUND the Blue Billy Formation is gradationally overlain by the Cheyne Springs Formation, this occurring over a few metres and involving intercalation of fine-grained siliciclastic and carbonate lithologies. However, on MAROONAH, MANGAROON, and EDMUND (1:100 000), the Blue Billy Formation is locally disconformably overlain by the Kiangi Creek Formation. The formation is intruded by dolerite sills in most areas, except in the northern Barley Range on MAROONAH.

The formation consists primarily of a distinctive parallel-planar laminated, black, pyritic, carbonaceous, fissile to flaggy siltstone (*PMEb-sl*), that weathers to a blue-grey colour. Weathered surfaces are also commonly coated with a white efflorescence of gypsum, particularly in creek-bed exposures. Parallel-bedded gypsum layers, with crystals oriented normal to bedding, and carbonate are present in Irregully Gorge on ULLAWARRA. Pyrite is largely weathered to goethite and hematite, and is concentrated in thin beds or laminae, or disseminated throughout the rock. The characteristic blue-grey to black colour is due to finely disseminated opaques, a high total organic carbon content (1.60–3.87%), and localized silicification. Goethite and hematite nodules and concretions are also present locally. On a regional scale, siltstones become more dolomitic towards the top of the Blue Billy Formation, and the contact with the Cheyne Springs Formation. The Blue Billy Formation also contains tabular to lenticular bodies of thick-bedded, massive, medium- to coarse-grained quartz sandstone, dolomitic sandstone, and pebbly sandstone interbedded with planar-laminated siltstone and minor dolostone (*PMEb-st*). These sandstones are present at the top of the formation on ULLAWARRA, MAROONAH, and MANGAROON. Common sedimentary features include normal coarse tail grading, weak dish structures, mudstone rip-up clasts, ripple marks, and sole marks. Groove casts at the base of a sandstone bed on MAROONAH trend northwest–southeast, whereas ripple marks on ELLIOTT CREEK give a palaeocurrent direction to the southwest. Bed thickness in the sandstones increases upwards, and ranges from 1 to 4 m. Individual beds are commonly separated by siltstone beds less than 0.5 m thick.

The minimum age is constrained by the intrusion of a regionally discordant dolerite sill dated at 1072 ± 8 Ma (Geological Survey of Western Australia, 2005; GSWA 169011). Reinterpretation of the same data by Wingate (2002) provides a similar age of 1071 ± 8 Ma for this sill. However, since these sills also intrude the overlying Collier Group, age constraints are the same as for older units in the Edmund Group, ranging between about 1620 and 1465 Ma.

Siltstones of the Blue Billy Formation typically consist of finely laminated coarse silt to very fine sand set in a matrix of very fine to medium silt and felted sericite with disseminated opaques. Recognizable detrital grains consist of angular quartz, muscovite, fresh plagioclase and K-feldspar, and indeterminate heavy minerals. Quartz grains are subrounded to rounded. A strong wavy to lenticular fabric is commonly defined by very fine grained opaques. Opaque phases consist of iron oxides (mainly after euhedral pyrite) and carbonaceous material, and in some cases constitute up to 80% of the rock. Dolomitic siltstones are characterized by euhedral dolomite grains weathered to goethite, or dolomite concretions with similar internal lamination to the surrounding siltstone. Silicified siltstone consists almost entirely of clastic-textured microquartz with disseminated fine-grained opaque minerals. Most of the sandstones in the Blue Billy Formation are medium-grained lithic quartz arenites. They comprise about 80% polycrystalline and monocrystalline quartz, 13% lithic fragments (chert, quartz–feldspar aggregates, sericitized siltstone, detrital muscovite), 8% plagioclase and K-feldspar, and less than 1% accessory detrital minerals (epidote, tourmaline, zircon, and apatite). Sand grains are mainly subangular to well rounded, and the matrix consists of silicified fine quartz sand. Brown anhedral fine-grained iron oxides form a widespread scattered replacement of both clasts and matrix. The hematite–goethite nodules are composed of anhedral to subhedral, bladed to tabular iron oxide pseudomorphs cemented by iron oxide and carbonate spar.

The Blue Billy Formation has been an important exploration target for sediment-hosted base-metal deposits (Cu, Pb, Zn), especially in the type area around Irregully Gorge on ULLAWARRA and CAPRICORN, and in the Mangaroon Syncline (Chuck, 1984; Cooper et al., 1998b; Pye et al., 1998). The formation is anomalously thick in the type area, and enriched in zinc (Cooper et al., 1998b).

The Blue Billy Formation is interpreted as a transgressive deposit of deep-marine anoxic mudstone that records transgression and expansion of the Edmund Basin beyond the preserved limits of the Pingandy Shelf. Sandstones in the upper part of the Blue Billy Formation, which were deposited north and south of the Talga Fault on Ullawarra, Maroonah, Mangaroon, and Edmund (1:100 000), are interpreted as turbidite and mass-flow deposits (Martin and Thorne, 2004). The upward increase in grain size, sandstone bed thickness, and dolomite content suggests that the Blue Billy Formation is an upward-shallowing distal shelf succession.

Cheyne Springs Formation (PMEp-k, PMEp-ss)

The boundaries and regional correlations of the Cheyne Springs Formation as originally defined by Chuck (1984) have been modified slightly as a result of abandonment of the 'Jillawarra Formation' and redefinition of the Kiangi Creek Formation (Martin and Thorne, 2002). In particular, the basal 700 m of argillaceous rocks in the Cheyne Springs Formation type section are now assigned to the Blue Billy Formation.

The Cheyne Springs Formation is widely distributed throughout the western Bangemall Supergroup, but is not present on parts of Maroonah, northeast Mangaroon and southeast Edmund (1:100 000), or south of the Talga Fault on Elliott Creek. The formation ranges from 50 to 300 m thick on Edmund, but seldom exceeds 200 m. It is thickest immediately adjacent to the Talga Fault, and thins rapidly to the south. The Cheyne Springs Formation is truncated beneath a disconformity at the base of the Kiangi Creek Formation on northeastern Mangaroon (MGA 388400E 7396400N).

In general, the Cheyne Springs Formation gradationally overlies siltstones of the Blue Billy Formation, and is in turn disconformably overlain by the Kiangi Creek Formation. However, the contact with sandstone in the upper Blue Billy Formation on northwestern Edmund is sharp. These contacts are defined by the first and last appearance respectively of dolostone or dolomitic siltstone at this stratigraphic level. The formation is intruded by a discordant dolerite sill on Maroonah and Mangaroon.

The Cheyne Springs Formation is characterized by a striped airphoto pattern due to the presence of interbedded dololutite, dolomitic siltstone, and siltstone (*PMEp-k*), which is thin to medium bedded, mostly parallel-planar to gently undulatory laminated, with local scour surfaces and ripple cross-lamination. The dolostone contains quartz silt and sand and is interbedded with minor thin siltstone beds. In the lower part of the Cheyne Springs Formation, the proportion of dolostone interbeds increases up-section, and is accompanied by an increase in bed thickness from less than one centimetre to tens of centimetres. Goethite pseudomorphs after pyrite are common in the planar laminated siltstones, and are typically concentrated in thin layers. Thin beds of fine- to medium-grained dolomitic sandstone and quartz sandstone are also common, and locally form mappable units (*PMEp-ss*) on Maroonah. The fine- to medium-grained quartz arenite beds are typically less than 5 cm thick, and planar to ripple cross-laminated, with goethite pseudomorphs after pyrite concentrated at the base and in ripple troughs. Basal bedding surfaces are locally marked by load structures and weak palaeocurrent lineation defined by flute and groove casts. Sandstone beds increase in abundance up-section, and are locally hummocky cross-stratified. Mappable units of sandstone are medium to coarse grained, and medium to thick bedded. East of Blue Billy Bore on Ullawarra (around MGA 446050E 7410900N), the Cheyne Springs Formation contains a 20 m-wide lenticular channel-fill consisting of conglomerate overlain by ripple-laminated sandstone. The channel trends towards 240°, and the fill is graded with a laminated top. The base is eroded into dolostone, and sandstone beds are present below the conglomerate towards the middle of the channel. The conglomerate is clast supported, and consists of tabular pebble- to cobble-sized tan dolostone clasts. The matrix is ferruginous medium- to coarse-grained quartz sandstone. Fine- to medium-grained ferruginous quartz sandstone overlies the conglomerate sharply with local ripple development. Adjacent to dolerite sills, the Cheyne Springs Formation is commonly silicified and consists of finely parallel-planar laminated chert or silicified siltstone. Thicker white chert laminae alternate with thin to medium beds of finely laminated pink-weathering chert. Palaeocurrent directions determined mainly from ripple cross-lamination and current lineation on the soles of sandstone beds range from south to northwest.

Age constraints for the Cheyne Springs Formation are the same as those for older units in the Edmund Group, ranging from about 1620 to 1465 Ma.

Dolomitic siltstone consists of planar-laminated, normally graded, very fine grained, subrounded to rounded sandstone to siltstone with abundant detrital muscovite flakes and trace amounts of plagioclase. The matrix consists of euhedral carbonate, probably dolomite, weathered to goethite. The thin sandstone beds consist mainly of subrounded to rounded quartz grains, with minor lithic clasts, K-feldspar and plagioclase, detrital muscovite, and trace tourmaline. Secondary euhedral dolomite is partially weathered to goethite, and euhedral cubic hematite possibly after pyrite is also present. Quartz grains are rimmed with syntaxial quartz cement. Matrix-supported dolomitic quartz wackes contain large floating tabular clasts of dolomitic siltstone and fine sandstone.

The Cheyne Springs Formation has been interpreted as an association of shelf and pelagic dolostones (Chuck, 1984) that marks a slight shallowing of the Edmund Basin (Martin and Thorne, 2004). The presence of localized hummocky cross-stratification suggests shallowing to storm wave-base, and sandstones of possible turbidite origin indicate a broadly southwest-sloping shelf.

Kiangi Creek Formation (PMEk-s, PMEk-st, PMEk-sl, PMEk-kd)

The Kiangi Creek Formation is defined as the succession of interbedded siltstone, sandstone, and local dolostone that disconformably overlies the Cheyne Springs Formation and lower units in the Edmund Group, and is overlain by either the Muntharra or Discovery Formations (Martin and Thorne, 2002). Use of the term 'Terrys Camp Member' for a sandstone dominated unit at the base of

the Kiangi Creek Formation (Martin et al., 1999; Martin and Thorne, 2002) has been abandoned because it is not regionally distinctive.

The formation is present throughout EDMUND, and typically ranges from 200 to 550 m thick, with the thickest sections found southwest of the Talga Fault.

The basal contact of the Kiangi Creek Formation is a very low-angle disconformity on EDMUND. In complete sections, the basal contact overlies the uppermost carbonate in the Cheyne Springs Formation; however, it succeeds the Blue Billy Formation on parts of MAROONAH, MANGAROON, and EDMUND (1:100 000) and directly overlies the Irregully Formation in the vicinity of Pimbyana Hill on southeast EDMUND (1:100 000). The formation is overlain by the Muntharra Formation on ELLIOTT CREEK and ULLAWARRA, and by the Discovery Formation elsewhere on EDMUND. It is intruded by a discordant dolerite sill throughout much of EDMUND.

The Kiangi Creek Formation consists mainly of varying proportions of interbedded planar-laminated siltstone and thin- to thick-bedded sandstone, with minor conglomerate and dolostone (*PMEk-s*). The siltstones are commonly carbonaceous with goethite and hematite pseudomorphs (up to 5 mm) after pyrite, and are locally silicified. Sandstone beds are mainly massive to planar and ripple laminated, commonly with well-preserved sole marks. Dewatering dishes and pillars are also common. Conglomerate beds are very localized, generally less than 0.5 m-thick, and consist mainly of tabular mudstone or fine-grained sandstone intraclasts that are usually preserved as moulds. Conglomerates comprising well-rounded to tabular chert and quartz pebbles are rare. The base of the formation is locally marked by a thin pebble-conglomerate on ELLIOTT CREEK. Distinctive mappable units are present in some areas, and include thin- to very thick bedded, fine- to very coarse grained sandstone and interbedded siltstone (*PMEk-st*), thick units of planar-laminated siltstone and carbonaceous siltstone with pseudomorphs after pyrite, gypsum, and dolomite (*PMEk-sl*), and dolostone and dolomitic sandstone (*PMEk-kd*). Sandstone beds in *PMEk-st* are thick bedded and commonly amalgamated, with localized basal intraclast conglomerates, normal grading, and thin siltstone interbeds. Dolomitic sandstones are interbedded with cross-stratified dolarenite, laminated dololutite, dolomitic siltstone, and pyritic black chert. Highly lenticular units of dolomitic sandstone are present directly below the contact with the Discovery Formation west of Mount Palgrave on MAROONAH and on southeastern EDMUND (1:100 000). The thickness and proportion of sandstone in the Kiangi Creek Formation increases significantly southwest of the Talga Fault, a trend that is not observed across the other major structures. Acid volcanic rocks have been reported from west of Mount Palgrave (Daniels, 1969; Brakel and Muhling, 1976) but were not found during the present study. Palaeocurrent directions determined from sole marks on sandstone beds are principally towards the southwest.

SHRIMP U–Pb detrital zircon ages from two sandstone samples in the Kiangi Creek Formation suggest a maximum depositional age between 1798 ± 12 Ma (Geological Survey of Western Australia, 2005; GSWA 169061) and 1782 ± 13 Ma (Cawood, P., and Nemchin, A., 2002, written comm.; GSWA 156734). However, regional stratigraphic and intrusive relationships indicate that the Kiangi Creek Formation is similar in age to older units in the Edmund Group, ranging from about 1620 to 1465 Ma.

Sandstones in the Kiangi Creek Formation are predominantly medium- to coarse-grained, moderately sorted, lithic quartz arenite and sublitharenite. Monocrystalline and polycrystalline quartz grains constitute 80–90% of the rock, and are generally angular to rounded with sutured contacts and syntaxial cement. Lithic fragments, consisting mostly of microcrystalline quartz aggregates, comprise approximately 10–15% of the rock. Additional components include K-feldspar and plagioclase (2–5%) and trace amounts of detrital tourmaline, zircon, sphene, chlorite, muscovite, and opaques. The matrix is compacted, and consists of either quartz cement or silt-sized microcrystalline quartz with clay minerals and opaque iron oxides. Secondary hematite fills primary porosity in some cases. Siltstones are generally fine- to coarse-grained, planar to wavy-crinkly laminated, and composed of equigranular quartz and micas (sericite and/or chlorite) with disseminated fine-grained anhedral opaques (iron oxides and possible carbonaceous material). Coarser grained end-members commonly contain up to 40% disseminated fine- to coarse-grained, angular to well-rounded, sand consisting of quartz, chert, plagioclase, K-feldspar, or heavy minerals (mainly tourmaline). Silicified siltstones are characterized by a matrix of microcrystalline quartz. Silicification is particularly common along the margins of dolerite sills where hornfels occurs in the immediate contact zone. Hornfelsed siltstone consists of a groundmass of anhedral microcrystalline quartz and minor feldspar, with a matrix characterized by random needles and blades of a colourless, low birefringent mineral (possibly chiastolite) and minor fresh biotite locally.

Carbonaceous siltstones in the Kiangi Creek Formation are locally stained with copper oxides, particularly on MAROONAH in the area west of Mount Palgrave, and at the Blue Rocks Prospect. Veinlets and disseminations of copper oxides along bedding planes in siltstone have been mined for agricultural purposes at the Blue Rocks Prospect on northeast MAROONAH. The Kiangi Creek Formation also contains minor zinc.

With the exception of hummocky and trough cross-stratified units, the Kiangi Creek Formation on EDMUND was deposited mainly below storm wave-base. The planar-laminated carbonaceous and pyritic siltstones are interpreted to be deep-water anoxic deposits. The bulk of the sandstones display characteristics that are typical of turbidites and can be interpreted in terms of the classical Bouma sequence. The broadly lenticular geometry of sandstone packages, and the marked lateral and vertical variations in siltstone to sandstone ratio, were interpreted by Chuck (1984) as reflecting turbidite fan-lobes. The localized presence of hummocky stratification, trough cross-stratification, and dolostone and dolomitic sandstone indicates that parts of the Kiangi Creek Formation were deposited above storm wave-base. However, there is no evidence for intertidal or subaerial deposition.

Muntharra Formation (PMEm-k)

The Muntharra Formation is a newly recognized unit (Martin et al., 1999; Martin and Thorne, 2002).

The Muntharra Formation is restricted mainly to the area southeast of Doolgarrie Creek on Ullawarra, and northwest of Thorpe Bore on Elliott Creek. The formation is generally 30–50 m thick and appears to be restricted to an area immediately adjacent to the Talga Fault. However, isolated units of dolomitic sandstone, which have been mapped as part of the upper Kiangi Creek Formation on Maroonah and Edmund (1:100 000), may be correlatives of the Muntharra Formation.

The Muntharra Formation conformably overlies the Kiangi Creek Formation, and is overlain by the Discovery Formation. Both the lower and upper contacts are generally sharp. The limited areal distribution suggests that it may be truncated beneath an unconformity at the base of the Discovery Formation.

The Muntharra Formation consists mainly of thinly bedded, planar-laminated siltstone, dolomitic siltstone, and dolostone, with interbedded dolomitic sandstone and quartz sandstone (*PMEm-k*) on Elliott Creek and Ullawarra. Most dolostones comprise either massive to laminated dololutite, or weakly laminated dolarenite that contains disseminated pebble- to cobble-sized chert clasts and large (up to 2 cm) pseudomorphs of goethite after pyrite. Dolomitic sandstones are medium-grained, planar laminated, and contain scattered coarse quartz grains in a dolomitic matrix. Black chert nodules, which are around 15 cm long and 3 cm wide, are present locally. In addition, dolomitic sandstones are locally conglomeratic, and contain angular clasts of dolarenite and large prismatic pyrites up to 10 mm across along stylolite horizons. Medium-grained, planar-laminated dolomitic sandstone is interbedded with siltstone, dolomitic siltstone, and layers of black chert and chert nodules. The beds are planar, around 5–6 cm thick, and there is evidence of solution collapse structures along the chert horizons. Dolomitic sandstone beds are locally up to 10 m thick. Quartz sandstones are fine- to coarse-grained, planar laminated, contain clay-pellet casts, and appear to be stylolitic in places. They are generally interbedded with dolarenite or laminated siltstone, and locally contain angular chert, quartz and siltstone clasts. All lithologies are silicified to varying degrees, and siltstone and sandstone both contain goethite and hematite pseudomorphs after pyrite.

Age constraints for the Muntharra Formation are the same as those for older units in the Edmund Group, ranging from about 1620 to 1465 Ma.

Dololutite in the Muntharra Formation is generally recrystallized, and the irregular lamination is defined by layers of cryptocrystalline dark, iron- and organic-rich dolostone alternating with light-coloured, sparry dolostone layers and areas that locally show a coloform texture. Lamination is also locally defined by recrystallized microcrystalline ferroan dolomite. Fenestral cavities are defined by concentrations of light-coloured sparry dolostone in places. Late-stage iron oxide crystals are disseminated throughout the rock or concentrated along laminae, and post-date any dolomite veining. Peloidal grainstone is composed of clast-supported, recrystallized, equant to elliptical rounded peloids (0.2–0.5 mm) that may be partially replaced by chert. These clasts are set in a matrix of anhedral dolomite microspar. There is extensive yellow iron-oxide replacement of some clasts. This material also occurs as a dissolution residue along stylolite surfaces. Medium- to coarse-grained lithic quartz sandstone consists of angular to well-rounded monocrystalline or polycrystalline quartz and chert or silicified siltstone. Syntaxial quartz cement predates compaction, and grain boundaries are defined by concentrations of clay minerals.

No mineralization is known from the Muntharra Formation, but silicified quartz sandstones in the type area around Doolgarrie Creek are commonly cut by quartz veins and ferruginous breccias with quartz stringers. The veins essentially follow bedding, but criss-cross the unit as stringers. The veining implies extension in a vertical direction and is possibly related to F_1.

Lithofacies and sedimentary structures of the Muntharra Formation suggest background deposition predominantly below storm wave-base, with localized high-energy deposition of carbonate grainstone, dolomitic sandstone and sandstone. The absence of stromatolites suggests deposition below the photic zone. This is supported by the presence of sulfide pseudomorphs that suggests deposition and diagenesis in an anoxic environment. The transition from the Kiangi Creek to the Muntharra Formation represents a shoaling of the basin.

Discovery Formation (PMEd-c, PMEd-sl)

The Discovery Chert was renamed Discovery Formation because the dominant primary lithology is silicified carbonaceous siltstone (Martin et al., 1999; Martin and Thorne, 2002) rather than chert, which is restricted to near-surface exposures.

The Discovery Formation is recognized throughout the study area and has been regarded as a major regional marker horizon (Muhling and Brakel, 1985). Its thickness generally ranges from 50 to 70 m on northern Edmund (Martin et al., 1999) to an estimated 280 m south of Wanna Bore on Elliott Creek (Muhling and Brakel, 1985). Isopachs presented by Daniels (1966) show thickening towards the southwest, with a maximum thickness for the siliceous component of 365 m (Daniels, 1975). A prominent non-silicified siltstone unit forms the middle part of the formation on Edmund, between the Talga and Lyons River Faults.

The basal boundary is sharp, and marked by the contact between predominantly carbonaceous siltstone and the top of the last dolostone or sandstone in the Muntharra Formation, or the last sandstone in the Kiangi Creek Formation where the former is absent. A number of features suggest that the basal contact is a regional disconformity. These include apparent very low angle truncation of underlying units, reflected in the localized distribution of the Muntharra Formation, and the presence of basal silicified conglomerate near Strama Bore on Elliott Creek (MGA 457900E 7397698ON). The upper contact between basal-laminated siltstone and silicified

planar-laminated dolorudite and dololutite of the Devil Creek Formation is sharp.

Throughout much of the region the Discovery Formation consists predominantly of planar-laminated, pyritic, silicified carbonaceous siltstone with cubic and rhombohedral mineral casts after pyrite or evaporites (*PMEd-c*), comprising a lower unit characterized by pinch-and-swell structures and an upper planar-laminated unit (Brakel and Muhling, 1976). The truncation of laminae in pinch-and-swell structures suggests that they may have behaved as concretionary structures with a planar basal surface and undulating upper surface. The pinch-and-swell structure characteristic of undeformed areas is superimposed by tight upright folding with a strongly undulose form surface in tightly deformed areas. Intrafolial folds and sheath folds with axial surfaces parallel to bedding are also common in these areas, particularly in the Mangaroon Syncline and north of the Lyons River Fault. A unit of planar-laminated siltstone (*PMEd-sl*) can commonly be distinguished at the base or in the middle of the formation. This unit includes white-weathering carbonaceous shale on MAROONAH, previously considered by Daniels (1969) to be part of the succession below the Discovery 'Chert' (Martin et al., 1999; Martin and Thorne, 2002). In outcrop, the rocks are thin to medium bedded and fine grained, and generally range in colour from white, through light grey, to black. Silicified beds of medium-grained sandstone, pebble conglomerate, and sedimentary breccia are present locally. Sandstones are very thick bedded and locally contain mudstone pebbles and sulfide clasts. Silicified chert-pebble conglomerate and sandstone are present at the base of the succession in the Strama Gap reference section (Martin and Thorne, 2002). Sedimentary breccias consist of banded chert clasts in a silicified sandstone matrix and commonly display weak reverse grading. Pseudomorphs of goethite and limonite after iron sulfides, generally less than 2–3 mm but up to 10 mm in diameter, are abundant in bedding parallel layers throughout the formation. Rhombohedral gypsum pseudomorphs have been recorded towards the upper and lower contacts (Marshall, 1968) and are a characteristic feature of the unit in many areas. Siltstones of the Discovery Formation have been converted to hornfels in the contact zones of dolerite sills that intrude the formation throughout most of EDMUND.

The Discovery Formation is intruded by a 1462 ± 3 Ma dolerite sill north of Coolinbah Well in the Mangaroon Syncline (Geological Survey of Western Australia, 2005; GSWA 156751). Reinterpretation of the same data by Wingate (2002) provides an age of 1465 ± 3 Ma for this sill. The age constraints are therefore the same as for older units of the Edmund Group, ranging between about 1620 and 1465 Ma.

Silicified siltstone of the Discovery Formation consists mainly of planar to wavy and lenticular-laminated coarse- to fine-grained silt and very fine grained sand (mostly <0.1 mm) and microquartz (<0.05 mm) with disseminated very fine grained (<0.001 mm) anhedral to subhedral and rounded hematite and coarser opaques. The matrix consists of microcrystalline quartz and sericite. Silt grains are well rounded, whereas microquartz grains are predominantly polygonal or anhedral, and locally recrystallized to form irregular patches and veins of macroquartz. Concretions of macroquartz contain abundant intergranular opaques and sericite, and are wrapped by laminae defined by opaques. Opaque minerals are predominantly euhedral pyrite, or iron oxide pseudomorphs after pyrite, and carbonaceous material. Minor jarosite or limonite occurs as translucent orange anhedral grains which are either scattered throughout the rock or occur in cross-cutting veins. Quartz pressure shadows are commonly preserved around the margins of pyrite pseudomorphs. Microquartz locally totally replaces siltstone and cross-cuts lamination, but pre-dates the formation of penetrative S_{1e} cleavage. Relict diagenetic subhedral rhombs 0.25 – 0.5 mm across, or 1 mm-sized anhedral aggregates, composed of carbonate, clay minerals, and granular iron-oxide are commonly preserved. The diagenetic mineral post dates the detrital lamination, but predates the cleavage. Close to the contact with dolerite sills, the siltstones are recrystallized and consist of subequal amounts of anhedral microcrystalline quartz 10's – 100's μm in diameter and felted tremolite 30–75 μm in length. Oval aggregates of anhedral mosaic quartz ranging from 1 to 4 mm, and anhedral aggregates of microcrystalline carbonate are also commonly present. Sandstones in the Discovery Formation are highly silicified, and typically moderately sorted, fine-grained quartz arenites with polygonal grain boundaries.

Outcrops of the Discovery Formation are locally stained with copper oxides. The formation is a major target for sediment-hosted base-metal deposits and hosts stratabound copper and zinc mineralization at Mount Palgrave and in the area south of Illirie Bore. The most common copper minerals are malachite and azurite, which are mainly present in thin bedding-parallel seams and along late-stage fractures. The late-stage fractures appear to feed stratiform zones in siltstone and fine- to very fine grained planar-laminated sandstone. Copper mineralization is also associated with thin beds rich in hematite and goethite pseudomorphs after pyrite.

The origin and depositional environment of the Discovery Formation is controversial and previous authors have argued for both a primary and secondary origin for the chert. Suggested origins include a primary chemical precipitate (Daniels, 1966), silicification of algal mats and local primary deposition (Marshall, 1968), and deposition as a silica gel (Muhling and Brakel, 1985). The sedimentary and petrographic features of the Discovery Formation outlined above suggest that it is a silicified carbonaceous siltstone rather than a primary chert. Deposition appears to have taken place mainly in a starved anoxic environment below storm wave-base. Higher energy deposits are locally abundant, especially at the base of the formation. Silicification was an early diagenetic feature. The Discovery Formation marks a major marine transgression that crossed the region from southwest to northeast. Silicified sandstone and conglomerate at the base of the formation along the southwestern margin of the Pingandy Shelf are possible remnants of a ravinement surface developed during the initial marine transgression.

Devil Creek Formation (PMEv-k)

The Devil Creek Formation is a prominent carbonate unit, with a distinctive striped airphoto pattern, that occurs

above the Discovery Formation and below the Ullawarra Formation (Martin and Thorne, 2002).

The succession is present throughout EDMUND, is generally 85–200 m thick, and thickens from northeast to southwest across the Talga Fault. The thickest sections are on EDMUND (1:100 000) where up to 450 m of dolomitic siltstone and dolostone are preserved.

This unit conformably overlies the Discovery Formation, and is gradationally overlain by the Ullawarra Formation, although this upper contact is often poorly exposed. In most cases the upper contact is taken at the top of the youngest major dolostone bed or where the proportion of dolostone falls below 10% in thinly bedded sections (Muhling and Brakel, 1985). An exception to this is found near Strama Bore, where both the basal and upper contacts are sharp, the latter being taken at the top of a 1.5 m-thick chert-pebble conglomerate.

The Devil Creek Formation (*PMEv-k*) comprises thin- to thick-bedded dolostone, dolomitic siltstone, siltstone, dolostone breccia, dolomitic sandstone, stromatolitic dolostone, and minor chert. The distribution of these lithologies is strongly controlled by the Talga Fault. North of the Talga Fault, the formation consists of interbedded planar to gently undulatory and hummocky laminated dololutite (40–95%) and massive to imbricated dolostone breccia (5–60%). Medium-grained, planar-laminated dolomitic sandstone is also present locally. Breccia beds are tabular to lenticular, between 0.2 and 0.8 m thick, contain large dololutite and shale clasts in a dololutite matrix, and pass laterally into laminated dololutite. Basal contacts are generally flat and mildly erosional, and the upper contacts with laminated dolostone are sharp. Both the breccia and laminated dolostone have locally abundant spheroidal diagenetic inclusions and pseudomorphs after former iron sulfide (?marcasite) that are 3–10 mm across. Dolostone breccias immediately adjacent to the Talga Fault are considerably thicker (1–10 m) and coarser grained (pebbles to cobbles) with a chaotic internal structure, and display an upward-thickening trend. Near Strama Bore on ELLIOTT CREEK, these breccias contain disaggregated columnar stromatolites (*Baicalia capricornia* Walter 1972, Grey, 1985) that are inclined at an angle of up to 35° parallel to the inferred southwesterly palaeoslope. Slightly further to the north of the fault, inclined columnar digitate stromatolites predominate, and are in situ with a packstone in-fill indicating formation in a relatively high-energy environment. The proportion of stromatolitic clasts in dolostone breccias increases up section in this area. South of the Talga Fault, the Devil Creek Formation consists mainly of thin- to medium-bedded dolomitic siltstone (75–90%), with varying proportions of thin-bedded dololutite, fine- to medium-grained dolarenite, and siltstone. Parallel-planar laminated to ripple cross-laminated dolarenite beds are generally 5–45 cm thick, but form local composite units 1.5–2 m thick. All lithologies in this area are characteristically ferruginous or manganiferous, and notably less dolomitic than those to the north of the Talga Fault. Large goethite and hematite concretions (up to 3 cm) after cubic pyrite are common, and are locally sheathed in chrysotile. Sedimentary structures are dominated by parallel-planar lamination, although low-angle ripple cross-lamination, climbing ripple lamination, wave ripples and hummocky lamination are also common. Palaeocurrent directions recorded by Daniels (1966) are mainly towards the northwest and west. Dolerite sills commonly intrude the upper contact of the formation on EDMUND.

The contact with the Discovery Formation is intruded by a 1462 ± 3 Ma dolerite sill in the area north of Coolinbah Well in the Mangaroon Syncline (Geological Survey of Western Australia, 2005; GSWA 156751). Reinterpretation of the data by Wingate (2002) provides a similar minimum age of 1465 ± 3 Ma. Age constraints are therefore between about 1620 and 1465 Ma, similar to older units in the Edmund Group.

Dolomitic siltstones consist of coarse silt to fine sand-sized fragments of quartz (approximately 10%), dolomite, muscovite, and rare tourmaline in a matrix of fine- to very fine grained quartz, dolomite, and white mica. Angular, tabular, fine siltstone clasts up to 0.6 mm long, and floating sparry dolomite clasts are present locally. Fine-grained red-brown iron oxides are disseminated throughout. Subhedral to euhedral dolomite rhombs (0.025 – 0.1 mm) commonly overprint the rock and pre-date the S_1 cleavage. Dolostones are commonly recrystallized, and locally contain irregular microbial lamination defined by fine-grained dolomite with darker brown finer grained carbonate material (possibly rich in organic carbon) alternating with light-coloured areas composed of anhedral microspar. Siltstones consist of about 50% quartz grains (0.02 – 0.1 mm) set in a matrix of very fine grained anhedral quartz silt, clay minerals, and chlorite. The matrix and clasts are locally replaced by anhedral aggregates of sparry carbonate up to 1–2 mm across. These are in turn overprinted by anhedral to euhedral iron oxide pseudomorphs, probably after pyrite. Silicification is locally pervasive and characterized by a microquartz overprint. Quartz pressure shadows around pyrite indicate dilation normal to lamination. Dolarenites are composed mainly of angular to rounded clasts (0.2 – 4 mm) of recrystallized dolomite microspar and minor siliciclastic material, especially quartz, plagioclase, and chert. Some dolomite clasts are probably flattened peloidal intraclasts that are rounded and equant to elliptical in shape. Iron oxide is concentrated by pressure solution along sutured grain contacts and also occurs as a scattered late-stage replacement in the form of aggregates of subhedral crystals. Secondary euhedral to anhedral partially oxidized sulfide occurs as a partial replacement of grains, along the pressure solution veins, or as post-compaction cubes. Recrystallization commonly converts dolarenite to anhedral microspar. Silicification is characterized by patchy to total replacement by microquartz.

The most common mineral occurrence in the Devil Creek Formation is manganese, which is a weathering product of dolostones and dolomitic siltstones, and occurs mainly south of the Talga Fault. Chrysotile asbestos is present in small seams where the formation has been intruded by dolerite sills.

Chuck (1984) identified four facies within the Devil Creek Formation: algal dolostones (subtidal), dolostone breccias (slope debris flows), turbidites, and parallel-laminated dolostones (deep-water suspension settling).

Overall, the distribution of lithofacies in the Devil Creek Formation reflects platform carbonates north of the Talga Fault, and basinal mudstones south of the fault. The fault itself is marked by slope-facies breccias, and may have been rimmed by a stromatolite reef. The alignment of *B. Capricornia* at Strama Gap is interpreted as reflecting a palaeoslope towards the southwest, perpendicular to the Talga Fault. Daniels (1966), however, documented a preferential orientation with tops toward 124°, which was interpreted as the product of a current from the south-southeast.

Ullawarra Formation (PMEl-s, PMEl-st, PMEl-sf)

The definition of the Ullawarra Formation has been revised to include the overlying former Curran Formation (Daniels, 1966; Chuck, 1984; Muhling and Brakel, 1985) as a member of the Ullawarra Formation (Martin et al., 1999; Martin and Thorne, 2002).

The Ullawarra Formation occurs throughout EDMUND where it mostly consists of fine-grained siliciclastic rocks intruded by numerous dolerite and gabbro sills. The sedimentary component varies in thickness from 100 m immediately north of the Talga Fault on ELLIOTT CREEK, to 650 m thick on southern EDMUND.

The Ullawarra Formation conformably overlies the Devil Creek Formation, and its upper unit, the Curran Member, is transitional with the overlying Coodardoo Formation. The basal contact is locally sharp and planar to slightly irregular at outcrop scale, but is generally poorly exposed and taken as the top of the youngest major dolostone bed in the Devil Creek Formation, or where the proportion of dolostone falls below 10% in thinly bedded sections (Muhling and Brakel, 1985). The contact between the lower part of the Ullawarra Formation and the Curran Member is marked by a gradational increase in the proportion of interbedded sandstone and cannot be placed with certainty. Dolerite sills intrude both the upper and lower contacts locally, further obscuring contact relationships with adjacent units.

The formation consists mainly of thin-bedded black and maroon siltstone and mudstone with lesser interbedded fine- to medium-grained sandstone, and minor chert and dolostone. A characteristic feature of the Ullawarra Formation is the large volume of dolerite sills intruded south of the Talga Fault. Siltstones (*PMEl-s*) are predominantly thin bedded and parallel-planar to undulatory laminated, and commonly ferruginous to locally calcareous. Fissile parting parallel to bedding is characteristic of Ullawarra Formation siltstones, except adjacent to dolerite sills where flaggy parting is generally present. Massive siltstone beds locally contain abundant thin mudstone rip-ups and euhedral moulds after evaporites and pyrite. Open-cast slump folds are also locally well preserved and consist of layer-parallel isoclinal folds around which differential compaction has occurred. Tabular to lenticular fine- to medium-grained sandstone beds (*PMEl-st*) that are interbedded with parallel-planar laminated siltstone are generally less than 0.5 m thick and mostly in the range 10–20 cm. Sandstone content ranges between 15 and 30% and generally increases up-section in conjunction with bed thickness. The internal structure is dominated by parallel-planar lamination, which locally passes upward into climbing ripple cross-lamination and undulatory lamination, forming Bouma T_{b-c} units. Sole marks consisting mainly of bounce, brush, prod, and flute marks are commonly well preserved at the base of these beds, and give palaeocurrent directions towards the west and northwest, consistent with palaeocurrent directions determined from ripple cross-lamination. These palaeocurrent directions are also consistent with the earlier observations of Daniels (1966). Sedimentary structures are also locally modified by soft sedimentary deformation. Dolomitic units consist mainly of dolomitic siltstone and less commonly dololutite. All units are locally silicified, particularly adjacent to dolerite sills where hornfels spotting is commonly developed in siltstones. Weathered siltstone and sandstone surfaces are typically coated with iron and manganese oxides or calcrete, depending on the composition of the parent unit, and liesegang banding is well developed locally.

A dolerite sill dated at 1074 ± 17 Ma is intruded at the base of the Curran Member north of Curran Well (Geological Survey of Western Australia, 2005; GSWA 156750). Reinterpretation of the same data by Wingate (2002) provides an age of 1068 ± 22 Ma. North of Coodardo Well, approximately 65 km along strike to the southeast, a dolerite sill at the same stratigraphic level has been dated at 1067 ± 14 Ma (Wingate, 2002). Integration of geochronologic and palaeomagnetic data indicates that c. 1070 Ma dolerite sills are not restricted to this level in the Ullawarra Formation, and were also intruded as far down as the Irregully Formation and into the overlying Collier Group (Wingate, 2002). The minimum age of the Ullawarra Formation is constrained by a second dolerite sill dated at Coodardo Well which has a minimum age of 1449 ± 5 Ma, and may be as old as c. 1470 Ma (Wingate, 2002).

Siltstones consist of recrystallized quartz silt to very fine grained sand in a matrix of sericite, chlorite, granular epidote, and opaques. Minor recrystallization has produced a granular mosaic of anhedral to subhedral quartz crystals 0.05 – 0.25 mm across enclosing smaller dusty crystals of quartz and possible feldspar 0.02 – 0.08 mm across. Some siltstones contain up to 20% feldspar (mostly plagioclase and minor K-feldspar). The lamination is commonly cross-cut by subhedral, bladed or tabular to equant, anhedral moulds (mostly 0.25 – 5 mm long) filled with microquartz and clay minerals, or with iron oxides and microquartz. These moulds represent former dolomite or evaporite minerals. Anhedral opaque-mineral grains less than 0.1 mm are scattered throughout. Micro-enterolithic lamination comprising irregular cryptocrystalline and microcrystalline quartz-rich laminae is also present locally. In silicified siltstones, discontinuous irregular layers of microcrystalline anhedral quartz alternate with darker layers of cryptocrystalline opaque minerals occurring as scattered grains or as aggregates. These opaques could be either kerogen or iron sulfide. Epidote is primarily a secondary replacement mineral and probably related to contact metamorphism adjacent to dolerite sills. Close to these sills, the siltstones are characterized by fine-grained microquartz with disseminated irregular clots of carbonate, acicular talc, subhedral bladed to tabular andalusite, and opaques.

Most of the sandstones in the Ullawarra Formation are moderately well-sorted, angular to well-rounded, fine- to medium-grained lithic quartz wackes. They comprise mainly monocrystalline and polycrystalline quartz (60–70%) with local syntaxial quartz-cement rims. Some quartz grains have faintly preserved lamellae. Lithic fragments (20–35%) are mainly composed of microcrystalline quartz aggregates, quartz–feldspar–chlorite intergrowths, silicified siltstone, and fine-grained quartz sandstone. Sandstones may contain up to 5–10% plagioclase and K-feldspar that commonly are partly to completely replaced by sericite. Rounded to anhedral accessory minerals, including zircon, tourmaline, apatite, and muscovite, usually comprise less than 1% of the rock. The matrix generally consists of microcrystalline quartz, sericite, chlorite group minerals, carbonate, and iron oxides. Diagenetic aggregates of anhedral iron oxides commonly replace both grains and matrix. Moderately sorted, subangular, very fine grained quartz wackes are less common, and consist of 70–80% quartz sand in a microcrystalline quartz–sericite matrix (10–20%), with trace amounts of detrital muscovite, tourmaline, and zircon, and rare tabular mudstone clasts. Dolomitic sandstones are relatively common, and characterized by extensive replacement by anhedral to subhedral carbonate microspar (up to 25%) and granular iron-oxide.

There are no known mineral deposits hosted within the Ullawarra Formation, although locally significant occurrences of manganese have been produced by secondary concentration during weathering.

The general lack of shallow-water facies characterized by sedimentary structures formed above wave-base in the Ullawarra Formation suggests that it was deposited in a deep-marine shelf environment. Background sedimentation is dominated by suspension settling to form parallel-planar laminated mudstone, and was interrupted by the deposition of sandstone beds from dilute turbidity currents. Palaeocurrent data further indicate that deposition took place in response to uplift to the southeast of the study area. This uplift represents a major change in palaeogeography compared to underlying units that were primarily derived from the northeast and northwest.

Curran Member (*PMElc-sf*)

The Curran Formation of previous authors (e.g. Muhling and Brakel, 1985) is not always easily recognized as a mappable stratigraphic unit on Edmund, and consequently was lowered to member status and included in the Ullawarra Formation by Martin and Thorne (2002).

The Curran Member is present on Elliott Creek, Ullawarra, and northeast Edmund (1:100 000) where it is characterized by a break in slope between the low hills and flats of the Ullawarra Formation and the steep cliffs of the Coodardoo Formation. The thickness is estimated to be 100 m in the type section along the eastern fork of Wannery Creek at Curran Well on Ullawarra, increasing to 250 m towards the southeast (Daniels, 1966; Muhling and Brakel, 1985).

On Edmund, the Curran Member has gradational contacts with the remainder of the Ullawarra Formation below and the Coodardoo Formation above. A dolerite sill has intruded along the contact with the underlying Ullawarra Formation on Ullawarra, most of Edmund (1:100 000) and southern Elliott Creek.

The Curran Member is lithologically similar to the remainder of the Ullawarra Formation, consisting of parallel-planar laminated siltstone interbedded with thin- to medium-bedded, fine- to coarse-grained sandstone and minor chert (*PMElc-sf*). The principal difference is the greater proportion of sandstone. Sandstone beds commonly show normal grading and both bed thickness and maximum grain size increase towards the top of the member. In areas where the proportion of sandstone is low, the Curran Member is often lithologically indistinguishable from the Ullawarra Formation. Palaeocurrent indicators are rare but generally indicate flow to the northwest (Daniels, 1966).

A dolerite sill dated at 1074 ± 17 Ma is intruded along the contact with the underlying part of the Ullawarra Formation north of Curran Well on Ullawarra (Wingate, 2002; Geological Survey of Western Australia, 2005; GSWA 156750). The same sill has been dated at 1071 ± 8 Ma north of Coodardo Well (Wingate, 2002), providing a minimum age of c. 1070 Ma. The maximum age is constrained by the age of the youngest granite in the Gascoyne Complex, which is c. 1620 Ma (Sheppard and Swager, 1999; Geological Survey of Western Australia, 2005).

Deposition of the Curran Member marks a period of significantly increased siliciclastic-sediment supply which culminated in deposition of the Coodardoo Formation.

Coodardoo Formation (PMEc-s)

The Coodardoo Sandstone (Daniels, 1966) was renamed Coodardoo Formation by Muhling and Brakel (1985), and is named after a prominent break in the Godfrey Range, 1.5 km northeast of Coodardo Well on Elliott Creek. The stratigraphic name appears to have originated through a misspelling of Coodardo Gap.

The Coodardoo Formation outcrops throughout Edmund where it forms a series of prominent sandstone-dominated ridges that define the Wanna Syncline. The formation ranges in maximum thickness from 150 to 370 m (Daniels, 1975) and thins to the southeast. The type section on the southern limb of the Wanna Syncline in Coodardo Gap is 238 m thick.

The Coodardoo Formation is the youngest stratigraphic unit in the Edmund Group. The gradational contact with the Curran Member of the Ullawarra Formation is marked by an upward increase in the proportion of sandstone to siltstone. The lower contact is placed at the base of the first thick-bedded sandstone, which usually forms a readily identifiable break in slope. The Coodardoo Formation is unconformably overlain by laminated dolostone or siltstone of the Backdoor Formation (Collier Group).

The Coodardoo Formation is dominated by thick- to very thick bedded, fine- to very coarse grained lithic quartz sandstone and pebbly sandstone, interbedded with siltstone (*PMEc-s*). The transition from the Curran Member to the

Coodardoo Formation is marked by an increase in both the thickness and number of sandstone beds, and takes place over an interval of approximately 15 m. The Coodardoo Formation can be divided into at least three thick-bedded sandstone-dominated units that form distinctive outcrop ridges, separated by units of poorly exposed planar-laminated siltstone and minor fine-grained sandstone.

Sandstone beds are generally tabular, massive to normally graded, and either amalgamated or capped by very thin parallel-planar laminated mudstone. Amalgamated beds are commonly massive, 0.3–2 m thick, with gently undulating contacts and localized scour-and-fill structures. Graded beds locally contain very coarse grained sandstone to granule pebble conglomerate at the base, and diffuse horizontal lamination is highlighted by selective silicification. The parallel-planar laminated mudstone that caps graded sandstone beds comprises less than 40% of sandstone-dominated units. Well-preserved dewatering structures are a characteristic feature of the Coodardoo Formation, and include streaks, dishes, dykes, and disrupted lamination. Load casts are locally well preserved where sandstone beds overlie mudstone. Hummocky stratification and low-angle cross-stratification are locally preserved in coarse to very coarse sandstone. Some sandstone beds contain disseminated goethite cubes and moulds after pyrite, up to a maximum of 1 cm. Bed thickness displays both upward thickening and thinning trends, although the latter is more typical of the upper Coodardoo Formation. Sole markings are abundant but are mostly lineation tool marks with no polarity. In cases where polarity can be determined, such as with prod marks and flute casts, palaeocurrent directions are towards the southeast and northwest. However, it is not possible to determine which of these transport directions predominates, or whether they are axial or transverse to the basin margins. Ripple lamination is rare at the tops of graded sandstone beds, but gives palaeocurrent directions towards the southeast.

The age of the Coodardoo Formation is poorly constrained. A c. 1070 Ma dolerite sill intruded along the contact with the overlying Backdoor Formation on Elliott Creek (Wingate, 2002) constrains the minimum age. The Coodardoo Formation contains a c. 1713 Ma population of detrital zircons from the upper part of the formation in the type section at Coodardo Gap (Cawood, P., and Nemchin, A., 2003, written comm.; GSWA 152962), although the formation must also be younger than c. 1620 Ma granites in the Gascoyne Complex (Sheppard and Swager, 1999; Geological Survey of Western Australia, 2005).

Sandstones in the Coodardoo Formation are mainly lithic quartz arenites and quartz arenites, consisting of 60–80% monocrystalline and polycrystalline angular to rounded quartz, 20–30% lithic fragments (mainly chert or silicified siltstone, siltstone, and possible felsic volcanic rock), and less than 5% feldspar (mostly fresh K-feldspar and plagioclase). Accessory minerals include tourmaline, zircon, detrital muscovite, apatite, sphene, iron oxides, and opaque minerals. The grain size is typically 0.25 – 0.5 mm, with a maximum of about 1 mm, and grains are poorly sorted. The matrix is largely indeterminate due to compaction; however, the presence of syntaxial quartz overgrowths suggests it was originally quartz cement. Compaction has also resulted in the formation of sutured grain contacts. Minor anhedral opaque minerals (possibly iron oxides) occur as diagenetic aggregates. Minor lithic quartz wackes in the Coodardoo Formation have a similar grain composition to the lithic quartz arenites, with a matrix of microcrystalline quartz silt rich in chlorite and sericite. Minor anhedral carbonate is present locally as a diagenetic replacement.

The graded, amalgamated sandstones and interbedded planar-laminated siltstones of the Coodardoo Formation are interpreted as turbidite fan deposits. However, the ambiguity surrounding the palaeocurrent data makes it difficult to interpret the significance of these turbidites to basin evolution. Daniels (1966) had earlier suggested that during deposition of the Coodardoo Formation, uplift to the north had changed palaeocurrent directions from easterly to southerly. The limited palaeocurrent data available points to an increasing contribution from an upland area to the northwest, compared to the underlying Ullawarra Formation.

Collier Group (PMC-s)

The Collier Subgroup was elevated to Collier Group by Martin et al. (1999) during revision of the former Bangemall Group. As a result of these changes the Mucalana Subgroup was abandoned and its various formation names discarded in favour of their Collier Group equivalents. On Edmund, the Collier Group is subdivided, in ascending order, into the Backdoor, Calyie, and Ilgarari Formations (Martin and Thorne, 2002).

The Collier Group is present in the core of the Wanna Syncline on Edmund (1:100 000) and Elliott Creek, where it has an estimated thickness of about 2–2.5 km.

The Collier Group unconformably overlies Archaean to early Palaeoproterozoic rocks of the Pilbara Craton (including the Fortescue and Hamersley Groups) to the north, whereas to the south it is unconformable on Archaean rocks of the Marymia Inlier and the Palaeoproterozoic Bryah and Earaheedy Groups. Available evidence suggests a low-angle disconformable contact with the underlying Edmund Group on Edmund. Its upper contact is not exposed in this area.

The Collier Group is dominated by siltstone, fine- to very coarse grained sandstone, pebbly sandstone, dolostone, and minor chert and conglomerate. The succession is intruded by thick dolerite sills on Edmund, which are absent further to the east.

Detrital zircons from the Backdoor Formation, near the base of the Collier Group, constrain a maximum age of about 1400 Ma for the group (Cawood, P., and Nemchin, A., 2002, written comm.). The minimum age of the Collier Group is constrained by a suite of dolerite sills with a consistent thermoremanent magnetization that is interpreted to date from the time of dolerite intrusion, and has been used as an aid to correlation of other undated sills. These sills were intruded into both the Edmund and Collier Groups, and have been dated at c. 1070 Ma in the Edmund Group (Wingate, 2002). Current geochronological

constraints imply a hiatus between the Edmund and Collier Groups of at least 65 m.y (Martin and Thorne, 2004), and possibly as much as 395 m.y.

Backdoor Formation (PMCb-s, PMCb-st, PMCb-kd)

The Backdoor Formation was originally defined in the eastern Bangemall Supergroup on COLLIER as a succession of siltstone and shale overlying either the Wonyulgunna Sandstone (the base of the Collier Group but not present in the western Bangemall Supergroup) or basement rocks, and underlying the Calyie Sandstone (Brakel and Muhling, 1976). This definition has now been extended to replace the Fords Creek Shale of the former Mucalana Subgroup in the western Bangemall Supergroup (Martin and Thorne, 2002).

The Backdoor Formation crops out in the Wanna Syncline on central and southeastern EDMUND. The formation is approximately 1500 m thick on southern ELLIOTT CREEK.

The formation has a sharp regionally disconformable contact with the underlying Coodardoo Formation (Cooper et al., 1998a). The gradational upper contact with the overlying Calyie Formation is characterized by a rapid increase in the sandstone to siltstone ratio.

The Backdoor Formation consists of planar-laminated green, maroon, and cream-coloured siltstone and mudstone (*PMCb-s*), interbedded with subordinate fine- to very coarse-grained lithic sandstone (*PMCb-st*), dolostone (*PMCb-kd*), and minor thin chert beds. The formation is also intruded by locally discordant dolerite sills.

A distinctive unit of interbedded siltstone and dolostone (*PMCb-kd*) marks the base of the Backdoor Formation on EDMUND. On the northern limb of the Wanna Syncline, the unit consists of interbedded reverse-graded oolitic grainstone and planar-laminated siltstone. Planar-bedded grainstone cycles are approximately 25 cm thick, and maximum ooid size is 8 mm. Cycles grade-up from dololutite and are locally ripple cross-laminated. Ooid textures are best preserved in the silicified tops of cycles. In this area, the unit is sharply overlain by interbedded chloritic sandstone and olive-green shale. On the southern limb of the Wanna Syncline, the unit consists of interbedded dololutite and massive to thinly parallel-planar laminated olive-green siltstone that conformably overlies medium- to coarse-grained sandstone at the top of the Coodardoo Formation. Dololutite beds are generally tabular to locally lenticular. This unit pinches out west of Coodardo Gap, but is persistent along the northern limb of the Wanna Syncline.

The basal dolostone and siltstone unit is sharply overlain by fissile siltstone (*PMCb-s*) and interbedded fine- to medium-grained sandstone (*PMCb-st*) that characterize the lower Backdoor Formation. This contact is marked by a loss of dololutite and possible change in composition of siltstone, which is more fissile in the overlying unit. The bulk of the Backdoor Formation consists of planar-laminated flaggy to fissile siltstone (*PMCb-s*), which ranges in colour from olive-green to maroon to grey.

Thin sandstone beds (*PMCb-st*) constitute less than 10% of the formation, and generally cap low rounded hills or are undercut to form steep scree slopes. Sandstone beds in the lower Backdoor Formation are generally fine to medium grained, less than 5 cm thick, and either massive or parallel laminated at the base and capped by ripple cross-lamination. Lenticular to flaser-bedded fine-grained chloritic sandstone is also present. Massive to graded and trough cross-stratified, medium- to coarse-grained sandstones up to 1.2 m thick are present locally, and mark the tops of upward thickening and coarsening intervals that are also characterized by increasing compositional maturity. These sandstones are commonly amalgamated into units up to 10 m thick, and are generally characterized by hummocky cross-stratification. Large-scale trough cross-stratification, graded bedding, imbricated tabular intraclast pebble lags, and localized pebble conglomerate are also typical of the upper portions of these intervals. Sandstone beds contain abundant goethite pseudomorphs and moulds after pyrite, forming beds up to 2–3 cm thick. Fossils of possible metaphytes (Grey and Williams, 1990; Grey et al., 2002) and impressions of microbial mats (Martin, 2004a) are also locally preserved on the soles of fine-grained sandstone beds.

A distinctive 3–4 m-thick unit of planar-laminated olive-green silicified mudstone overlain by medium- to coarse-grained feldspathic sandstone (*PMCb-st*) marks the middle of the Backdoor Formation on EDMUND. The upper 0.5 m of this mudstone is brecciated, with a poorly sorted coarse- to very coarse quartz wacke infill. The overlying sandstone is massive to planar laminated, and well sorted with local primary current lineation. The sandstone is in turn overlain by hundreds of metres of fissile maroon siltstone (*PMCb-s*). Above this siltstone unit, massive to planar-laminated and hummocky cross-stratified sandstone beds in the upper Backdoor Formation are predominantly medium- to very coarse grained with ferruginous mottles and mudstone intraclast moulds. Graded bedding is common, and sole marks include brush, bounce, and rare flute marks. Interference ripples and current ripples as well as flat-topped ripples and rare starved ripples are common in medium-grained sandstones in the upper Backdoor Formation. Palaeocurrent directions determined from sole marks and cross-stratification are consistently towards the southwest in the lower Backdoor Formation sandstones. Palaeocurrents in the upper Backdoor Formation are locally directed towards the east-southeast, particularly in the transition to the Calyie Formation.

The maximum age of the Backdoor Formation is constrained by a c. 1400 Ma detrital zircon in a sandstone in the lower part of the formation (Cawood, P., and Nemchin, A., 2002, written comm.; GSWA 152964). The minimum age is constrained by dolerite sills which are inferred from geochronologic and palaeomagnetic data to be c. 1070 Ma (Wingate, 2002) and were probably intruded prior to complete lithification of the Backdoor Formation based on the presence of peperitic sill margins (Martin, 2004b).

In thin section, the siltstones of the Backdoor Formation are characterized by fine laminae that are normally graded from very fine sand to fine silt. The sandstones are well sorted, and contain trace amounts

of detrital muscovite, zircon, feldspar, and tourmaline. Siltstones comprise microquartz and sericite with disseminated quartz silt to very fine sand. Fine- to medium-grained sandstones in the lower Backdoor Formation are moderately sorted quartz arenites and lithic quartz arenites that consist of subangular to well-rounded quartz with syntaxial quartz cement. Grain compositions are dominated by monocrystalline quartz with minor chert and microquartz, and trace amounts of detrital white mica, well-rounded tourmaline, and zircon. Opaque minerals, mainly very fine grained hematite, are concentrated in specific laminae or disseminated throughout. Medium- to very coarse grained sandstones in the upper Backdoor Formation also comprise moderately sorted quartz arenites and lithic quartz arenites. Rounded to well-rounded grains of monocrystalline quartz (90–95%) with well-developed syntaxial quartz cement overgrowths predominate over lithic fragments (<10%) dominated by microcrystalline quartz aggregates and trace amounts of tourmaline, zircon, plagioclase, and K-feldspar. Opaque oxides, mainly hematite, locally coat detrital grains and replace euhedral diagenetic pyrite. Aggregates of anhedral replacement carbonate are disseminated throughout some samples. Chert beds consist of fine-grained microquartz with 60–70% opaques. Two types of opaques can be identified. The first consists of disseminated hematite spheres and cubes (0.005 – 0.01 mm). The second consists of very fine grained brown to black spherules, that are probably carbonaceous microfossils. Their morphology is similar to that of smooth-walled spherical acritarchs. Very fine grained opaques also define a distinctive wavy-crinkly lamination in thin section. Localized large patches of microquartz and chalcedony are also common, and probably represent replacement or cavity-fill textures.

The parallel-planar laminated siltstones that form the bulk of the Backdoor Formation were most likely deposited below storm wave-base on a distal siliciclastic shelf. Interbedded fine- to medium-grained, thin-bedded sandstones in the lower Backdoor Formation are the product of storm-generated bottom currents that transported sediment offshore. Southwesterly directed palaeocurrent data suggests a source area to the northeast of Edmund and is consistent with the sediment slumping to the south noted by Daniels (1966). Medium- to very coarse grained, thick-bedded sandstones at the tops of upward-thickening packages in the lower Backdoor Formation, and throughout the upper Backdoor Formation, were probably deposited close to or above storm wave-base, as indicated by the presence of hummocky cross-stratification. The Backdoor Formation therefore records a progradation from distal shelf to proximal shelf and distal delta-front depositional environments.

Calyie Formation (PMCc-s)

The abandonment of the Mucalana Subgroup by Cooper et al. (1998b) necessitated the replacement of the Mount Vernon Sandstone (Muhling and Brakel, 1985) with the Calyie Sandstone (Martin and Thorne, 2002). The Calyie Sandstone was later renamed the Calyie Formation by Martin et al. (1999) to take into account its lithological variation.

The Calyie Formation is a cliff-forming, sandstone-dominated unit in the middle Collier Group that is present throughout Edmund. The formation is well exposed on Elliott Creek where it is about 190 m thick.

The basal contact with the Backdoor Formation on Edmund is gradational, and characterized by an increasing proportion of sandstone in a succession of interbedded siltstone and sandstone. The upper contact with the siltstone-dominated Ilgarari Formation is sharp and is placed at the top of the last major sandstone bed in the Calyie Formation.

The base of the Calyie Formation is marked by a unit of thick-bedded, trough cross-stratified, coarse- to very coarse grained sandstone, interbedded with thick-laminated siltstone, that overlies hummocky and ripple-laminated, fine- to medium-grained sandstone interbedded with siltstone in the upper Backdoor Formation. The overlying Calyie Formation consists mainly of medium- to very thick bedded, medium- to coarse-grained quartz sandstone that is typically massive to trough cross-stratified, and is interbedded with minor planar-laminated siltstone. Sets of trough cross-strata are typically 20 – 50 cm thick, and probably the result of the migration of dune bedforms. Bedding in the Calyie Formation is generally lenticular at outcrop scale. Calyie Formation sandstones typically contain disseminated mudstone rip-ups, fine-grained sandstone intraclast pebble lags, cubic moulds after pyrite (up to 0.5 cm), and dewatering structures marked by concentrations of iron and manganese oxides. Localized mud cracks and possible gypsum casts and pseudomorphs provided evidence for subaerial exposure. Two thick siltstone dominated units, with minor interbedded fine- to medium-grained planar-laminated sandstone, are present in the middle and upper parts of the formation, and locally contain hummocky cross-stratification. Palaeocurrent directions in the Calyie Formation are variable, with two major opposing components towards the southeast and northwest on Elliott Creek. Daniels (1966) recorded palaeocurrents which were generally to the north and south.

The maximum age of the Calyie Formation is constrained by an approximately 1400 Ma detrital zircon in the underlying Backdoor Formations (Cawood, P., and Nemchin, A., 2002, written comm.; GSWA 152968), and the minimum age by approximately 1070 Ma dolerite sills intruded into the Backdoor and Ilgarari Formations (Wingate, 2002).

Most of the sandstones in the Calyie Formation are poorly to well-sorted, well-rounded, medium- to coarse-grained quartz arenites. Grain compositions are dominated by monocrystalline quartz, minor polycrystalline quartz and chert/microquartz, with trace amounts of iron oxide and mica after labile grains, and well-rounded zircon and tourmaline. Feldspar is generally absent, in contrast to sandstones of the underlying Backdoor Formation. The matrix consists of syntaxial quartz cement and dusty hematite. Large cubic voids after weathered pyrite are locally abundant.

The rapid facies changes that characterize the Calyie–Backdoor Formation transition are interpreted to reflect

a change from a delta-front to delta-top depositional environment (Martin and Thorne, 2004). The bulk of the Calyie Formation was probably deposited in a shallow-marine to fluvial depositional environment, as suggested by the abundant evidence for intraformational reworking and subaerial exposure. Opposing palaeocurrent directions recorded by trough cross-strata are possibly due to ebb and flood flow in tidal channels.

Ilgarari Formation (PMCi-s)

The Ilgarari Formation replaces the former Kurabuka Formation of the Mucalana Subgroup which was abandoned by Cooper et al. (1998b).

The Ilgarari Formation is the uppermost unit of the Collier Group and is preserved in the core of the Wanna Syncline on Elliott Creek. There are no overlying units within the Bangemall Supergroup.

The sharp basal contact is taken as the top of the uppermost, thick, cross-stratified sandstone in the Calyie Formation. The formation is about 680 m thick on Elliott Creek, excluding dolerite sills (Martin et al., 1999).

The Ilgarari Formation consists almost entirely of greenish-grey to black, parallel-planar laminated, pyritic and carbonaceous siltstone (*PMCi-s*) that is locally silicified. Thin interbeds of massive to planar-laminated fine-grained sandstone are present in the upper parts of the formation. Muhling and Brakel (1985) note that the succession also includes chert (silicified lutite), minor limestone and calcareous siltstone. The formation is extensively intruded by dolerite sills on Elliott Creek.

The formation is younger than approximately 1400 Ma, the age of the youngest detrital zircon in the Backdoor Formation (Cawood, P., and Nemchin, A., 2002, written comm.), but is older than the dolerite sills which intrude it. On the basis of geochronological and palaeomagnetic data these sills are inferred to be approximately 1070 Ma (Wingate, 2002).

Muhling and Brakel (1985) interpreted the Ilgarari Formation as the lagoonal facies of a regressive marine shoreline. However, there is no evidence for lagoonal deposition on Edmund, and the formation is now regarded as a transgressive, deep-marine shelf deposit (Martin and Thorne, 2004).

Dolerite sills (*Pod$_{1,2}$*, *Pod$_2$*)

Two chemically and geochronologically distinct suites of dolerite sills have been intruded into the Bangemall Supergroup (Wingate, 2002; Geological Survey of Western Australia, 2005; Morris and Pirajno, 2005), but are indistinguishable in outcrop. Consequently, the dolerite sills are divided into two units based on the age of their host rocks. Dolerite sills in the Edmund Group (*Pod$_{1,2}$*) belong to both suites, whereas sills in the Collier Group (*Pod$_2$*) belong exclusively to the younger suite. This younger suite is the more widespread, and can be correlated with mafic intrusions of a similar age that have been identified well beyond the limits of the Bangemall Supergroup, and constitute the 1078–1070 Ma Warakurna Large Igneous Province (Wingate et al., 2004).

Dolerite sills have been intruded into all units of the Bangemall Supergroup on Edmund except the Cheyne Springs, Muntharra, Coodardoo, and Calyie Formations, although the contacts of these formations with adjacent units are commonly intruded by sills. By far the largest volume of sills is present within the Ullawarra Formation, south of the Talga Fault. There are no sills in the Ullawarra Formation north of the Talga Fault, and similarly sills are less abundant in other units in this area. Sill thickness ranges from thin screens on the order of metres thick to single intrusions up to hundreds of metres thick.

While most sills are locally conformable with the host sedimentary rocks, they are regionally discordant along strike and characterized by a step-and-stair geometry (Francis, 1982). This geometry is particularly evident in *Pod$_{1,2}$* sills intruded north of the Talga Fault, and in a *Pod$_2$* sill intruded into the Backdoor Formation on Elliott Creek. Evidence from the latter sill, on opposite limbs of the Wanna Syncline, suggests that the sills are also discordant in a down-dip direction. Contact relationships with the host sedimentary rocks are generally characterized by undisturbed chilled margins, although disharmonic folding of the host rocks has been documented locally and may be related to sill intrusion. On southern Maroonah, the contact between a *Pod$_{1,2}$* sill and the Irregully Formation has been structurally modified by south over north thrusting, most likely related to folding during the Edmundian Orogeny.

Dolerite sills in the Bangemall Supergroup are generally moderately to poorly exposed, and tend to be highly weathered. The best exposed dolerites are characterized by poorly exposed chilled margins of fine-grained dolerite that are commonly covered with scree derived from the host rocks. However, good exposures of these contact zones indicate that in some cases they are marked by folding or brecciation of the host rocks, plastically deformed xenoliths, amygdales, vesicles, varioles, and rare peperitic textures. These features suggest that some of the sills were emplaced at relatively shallow depths into unconsolidated or partially lithified sediments. The central portions of the sills consist of medium- to coarse-grained dolerite and gabbro that locally contain granophyric patches. The upper third of the sills is typically marked by prominent tors. Dolerite sills in low-lying areas are commonly indicated by the presence of gilgai (*C1c$_b$*). Contact metamorphic aureoles around the sills are in the order of decimeters to metres thick, depending on sill thickness and host-rock composition, and are mainly characterized by silicification and recrystallization to form hornfels. Quartz veins and rare calcite veins are also associated with the contact zones, and are typically found within the dolerite.

The older suite of sills (*Pod$_{1,2}$*) has been dated at c. 1465 Ma, and the younger suite (*Pod$_2$*) at c. 1070 Ma (Wingate, 2002; Geological Survey of Western Australia, 2005) using SHRIMP U–Pb geochronology of zircon and baddeleyite extracted from granophyric zones within coarse-grained dolerite and gabbro. Furthermore, regional correlation of each suite is facilitated by their

distinctive geochemistry (Morris and Pirajno, 2005) and palaeomagnetic remanence (Wingate, 2002). On the basis of available data all 1465 Ma sills are intruded into the Edmund Group, and the bulk of the 1070 Ma sills are intruded into the Collier Group.

It is generally not possible to distinguish between the two suites of sills in thin section on the basis of mineralogy or texture, although Morris and Pirajno (2005) report some subtle differences in the degree of alteration and amount of late-stage quartz and feldspar. On the whole, dolerite sills intruded into the Bangemall Supergroup consist of a granular intergrowth of approximately equal proportions of subhedral bladed to tabular pyroxene and plagioclase, with minor amounts of opaque oxide. The intergranular material comprises microcrystalline and cryptocrystalline quartz, feldspar, carbonate, chlorite, zoisite, leucoxene, and darker anhedral opaque minerals. Plagioclase is mainly labradoritic (Morris and Pirajno, 2005) with local granophyric margins, and is commonly replaced by albite, carbonate, or sericite, and possibly quartz. The pyroxene is mainly subhedral to anhedral augite and less commonly orthopyroxene or pigeonite. Pyroxene is partly or completely replaced by chlorite or biotite. Quartz occurs as a late-stage cavity fill, and epidote as granular anhedral aggregates. Accessory minerals include millimeter-sized subhedral magnetite and minor anhedral zircon. Subhedral to anhedral bladed to equant phenocrysts are replaced by carbonate and epidote together with some radiating crystals of possible zeolite. Granophyre is locally developed, particularly in coarse-grained dolerite and gabbro, and consists of 0.1 – 0.5 mm subhedral to anhedral crystals of K-feldspar, zoned plagioclase, and graphic intergrowths of quartz and K-feldspar, together with about 20% subhedral to anhedral, equant to bladed, chlorite–epidote pseudomorphs after a ferromagnesium mineral precursor. Chilled margins are locally characterized by amygdaloidal dolerite consisting of amygdales filled with aggregates of zoned K- feldspar and coarsely crystalline quartz, chlorite, epidote, and carbonate.

The two suites of dolerite sills are compositionally distinct in terms of their major and trace element geochemistry (Morris and Pirajno, 2005). Both suites are broadly tholeiitic in composition, and show enrichment in low field strength elements (LFSE) relative to high field strength elements (HFSE) that is indicative of melting of a subduction-modified mantle source (Morris and Pirajno, 2005). Differences between the two suites are reflected in variations of absolute concentrations of Zr, Th, U, Cr, Ni, Mn, Cu, Ga, Sn, and Rb at a given magnesium number (Mg#). Combination of the available geochemical and geochronological data indicates that most of the sills intruded into the Edmund Group have compositions consistent with the c. 1465 Ma suite, and those intruded into the Collier Group with the c. 1070 Ma suite (Morris and Pirajno, 2005). The exceptions in the case of the Edmund Group are a sill in the Blue Billy Formation, and a sill at the top of the Ullawarra Formation.

Most of the mineralization associated with dolerite sills is located on MANGAROON and MAROONAH, and is generally restricted to hydrothermal enrichment and contact metamorphism along sill margins. In most cases the mineralization is located in the adjacent host rocks in the form of subeconomic concentrations of base metals (Cu, Pb, Zn) or industrial minerals (talc, asbestos, marble). An exception is at Latham prospect where Cu–Pb(–Ag) mineralization is hosted by hydrothermal veins within dolerite.

Regional and outrop-scale observations suggest that dolerite sills were intruded into the Bangemall Supergroup shortly after sedimentation and prior to regional deformation during the Edmundian Orogeny. The anorogenic setting of these sills has led Wingate et al. (2004) and Morris and Pirajno (2005) to propose that the younger of the two suites (Pod_2) was emplaced as part of the Warakurna Large Igneous Province, which is interpreted as the product of a mantle plume. The regional distribution and hence origin of the older suite ($Pod_{1,2}$) is less well known, but is clearly also related to large-scale anorogenic magmatism within the Mesoproterozoic West Australian Craton. Palaeomagnetic evidence suggests that these sills were probably intruded during the early stages of assembly of the Rodinia supercontinent (Morris and Pirajno, 2005).

Neoproterozoic Edmundian Orogeny

The Edmundian Orogeny (Halligan and Daniels, 1964) is an intracratonic event that resulted in the locally pervasive deformation of the Bangemall Supergroup, and the formation or reactivation of structures in the underlying basement. The orogeny largely resulted in north–south shortening that formed easterly to southeasterly trending, open to tight, upright folds and normal, reverse, and strike-slip faults. The area affected by this regional deformation is here referred to as the Edmund Fold Belt. It is more extensive than the structural unit of the same name originally defined by Muhling and Brakel (1985), and includes the area covered by their Edmund Fold Belt, Pingandy Shelf, and Bullen Platform.

Bangemall Supergroup rocks in the Edmund Fold Belt are divided into three structural zones referred to informally as the northeastern, central, and southwestern zones. The northeastern zone occurs northeast of the Talga Fault and corresponds broadly to the Pingandy Shelf of Muhling and Brakel (1985). The central zone equates to the Wanna Syncline, an asymmetric southeasterly plunging synclinorium occurring between the Talga Fault and the main Gascoyne Complex outcrop to the southwest; whereas the southwestern zone is represented by the more highly deformed rocks of the Mangaroon and Cobra Synclines. The combined central and southwestern zones are approximately equivalent to the Edmund Fold Belt of Muhling and Brakel (1985).

Myers et al. (1996) suggested that the Edmundian Orogeny resulted from the collision of the North and West Australian Cratons between 1300 and 1100 Ma. However, dolerite sills dated at c. 1070 Ma (Wingate, 2002; Geological Survey of Western Australia, 2005) that intrude the Bangemall Supergroup are also deformed into easterly trending folds. The Bangemall Supergroup and the dolerite sills are refolded about a north to northeasterly

trend to form dome-and-basin structures. Undeformed dolerite dykes that cut both sets of folds have been dated at c. 755 Ma (Wingate and Giddings, 2000). This date, and the age of the deformed dolerite sills, constrains the Edmundian Orogeny to between 1070 and 755 Ma.

The Edmundian Orogeny may be associated with the c. 900 Ma thermal event identified from the Errabiddy Shear Zone in the southern Capricorn Orogeny (Occhipinti and Reddy, 2002, personal communication, quoted in Cawood and Tyler, 2004). Cawood and Tyler (2004) interpret the Edmundian Orogeny as a far-field reactivation of the Capricorn Orogen related to the break up of Rodinia and with events associated with Gondwana assembly (Fitzsimons, 2003).

The Edmundian Orogeny resulted in two main periods of deformation and low-grade metamorphism. The first of these (D_{1e}/M_{1e}) involved mostly north–south shortening whereas the second (D_{2e}/M_{2e}) reflected initial compression, then extension along an east-southeast to west-northwest line, followed by dextral strike-slip movement.

Deformation and metamorphism (D_{1e}/M_{1e})

Structures and mineral assemblages related to the first deformation (D_{1e}/M_{1e}) are widely developed in both the Bangemall Supergroup cover and the Gascoyne Complex basement. This first deformation event is responsible for much of the present-day pattern of anastomosing shear zones and faults.

Bangemall Supergroup Cover

Northeastern zone

The northeastern zone consists of a thin (mostly <1.5 km), relatively undeformed succession of Edmund and Collier Group rocks that unconformably overly Palaeoproterozoic rocks of the Ashburton and Blair Basins in the area northeast of the Talga Fault. Throughout much of the zone bedding dips gently towards the southwest at 5 to 25° although it is sometimes variable close to palaeotopographic highs along the northern margin of the outcrop.

Other exceptions to the general southwesterly tilt to bedding occur in the vicinity of Irregully Creek (around MGA 450000E 7419300N). Here large-scale, gentle to open, upright folds in the lower Edmund Group have curvilinear or gently sinuous axial traces that trend generally southeast–northwest. Only rarely do these folds develop a systematic axial-planar cleavage. They may have formed as the thin (<500 m) Edmund Group cover deformed in response to weak northeasterly directed compression and subsequent fault reactivation in the Palaeoproterozoic basement (Winsor, 1987).

Rocks of the northeastern zone are cut locally by small, steeply dipping, southeasterly or east-southeasterly trending faults. Along the northern outcrop margin, these fractures have either a south or north block down-sense of movement of a few tens of metres. East of Old Ullawarra Homestead (around MGA 421880E 7425760N) faulting along the hinge of a gently southeasterly plunging D_{1e} anticline has resulted in the development of a linear horst block whose relative uplift dies out toward the southeast. Steep northeast-trending fractures with generally small amounts of displacement record a general northwest–southeast extension and are associated with emplacement of the Mundine Well dyke swarm (Wingate and Giddings, 2000).

The metamorphic grade of M_{1e} was low throughout most of the northeastern zone, with generally good preservation of primary sedimentary and diagenetic textures. Buick et al. (1995) and Buick and Knoll (1999) recorded a southeast to northwest increase in kerogen colour index within the zone, corresponding to a slight increase in minimum metamorphic temperature from 100 to 125°C at Fords Creek (MGA 529000E 7370000N on adjacent Kenneth Range) to 150°C in the vicinity of Irregully Creek (around MGA 449800E 7419200N). The effects of contact metamorphism adjacent to thick dolerite sills ($Eod_{1,2}$) have been described by Buick et al. (1995) who record significant dolomite recrystallization and volatilization of kerogen in dolomitic rocks and growth of calcite–talc–tremolite(–K-feldspar) assemblages in siliceous dolostones. These effects may extend 100 m into the country rock (Buick and Knoll, 1999). The presence of olivine (?fosterite) in a recrystallized Irregully Formation dolostone from 7 km west of Irregully Gorge (WAROX SITEID IAC121, MGA 443680E 7420570N) is probably related to the presence of a dolerite sill at shallow depth.

Central zone

The central zone occupies the main area of Bangemall Supergroup outcrop between the Talga Fault in the northeast and the main Gascoyne Complex outcrop to the southwest. Structurally, the area is dominated by the Wanna Syncline, an asymmetric, southeasterly plunging synclinorium that developed over a reactivated system of late ?Mesoproterozoic to early Mesoproterozoic (Edmund Group) grabens and horst blocks (Muhling and Brakel, 1985). Evidence for the horst and graben system is based on thickness and sedimentary facies variations in the Edmund Group and their relationship to observed structural elements (Martin and Thorne, 2004) and interpretations of regional gravity and aeromagnetic data (Shevchenko, S., 2004, written comm.).

Martin and Thorne (2004) noted that the principal structural elements that controlled Edmund Group deposition are parallel to the trend of major structures in the underlying Ashburton Fold Belt and Gascoyne Complex. These structures include the Talga Fault, the partially faulted southern limb of the Wanna Syncline, the Lyons River Fault, and the northwest-trending fault system that bounds the Mangaroon Syncline. The sub-basin of lower Edmund Group rocks (Martin and Thorne, 2000) that outcrops east of Maroonah Homestead is believed to be the northwestern extension of a complex sinuous, linear graben. The northern margin of this sub-basin is defined by the faulted southern limb of the Wanna Syncline whereas the southern limit appears to be controlled partly by the

Lyons River Fault and partly by uplifted rocks of the Mangaroon Zone (Gascoyne Complex) on south-central EDMUND.

Shevchenko (2004, written comm.) carried out preliminary gravity modelling of the Edmund and Collier Basins using 11 × 11 km Bureau of Mineral Resources data (now Geoscience Australia; Fraser and Pettifer, 1980). His results point to the presence of a 40 km-wide southeast-trending graben, with a broad axial horst block, beneath the Wanna Syncline. The northern margin of the graben coincides with the Talga Fault. The southern margin is more complex and appears to extend from north of Maroonah Homestead (MGA 363000E 7415700N) to south of Wanna Homestead (MGA 454000E 7346000N) before being terminated by a possible east–west-trending transfer fault. Shevchenko (2004, written comm.) also records the likely presence of a narrow, north-trending graben beneath the northwestern part of the Wanna Syncline (between MGA 400000E 7353800N and MGA 390300E 7401500N).

The Talga Fault is a major northwest-trending normal fault that has undergone significant reverse movement during the Edmundian Orogeny. It separates the northeastern and central zones of the Edmund Fold Belt and is broadly equivalent to the northern margin fault of Chuck (1984). The throw of the Talga Fault decreases from the northwest, where it juxtaposes upper greenschist-facies rocks of the Ashburton Formation (Wyloo Group) against the Kiangi Creek Formation (middle Edmund Group) to the southeast where it cuts the upper Edmund Group. In the latter area, its surface trace is marked by an en echelon series of open to tight folds and short connecting fault segments. Hinges of both large- and small-scale folds close to the Talga Fault are aligned subparallel with the fault trace, suggesting relatively little strike-slip movement during Edmundian compression.

Although the Talga Fault is concealed beneath regolith units for much of its length, it can be seen in outcrop near Strama Bore on Irregully Creek (WAROX SITEID DMM1005, MGA 457800E 7398000N). At this locality there is evidence of significant reverse movement across the structure. The fault plane dips approximately 45° to the southwest and separates siliciclastic rocks of the Discovery Formation to the northeast from dolostones of the underlying Muntharra Formation to the south. Both footwall and hanging wall rocks are deformed into large-scale, upright open folds, with the southern limb of the footwall anticline being truncated by the fault plane. Shear sense indicators in the footwall succession give a top to the northeast sense of movement.

The fracture system on the southwestern limb of the Wanna Syncline is less clearly defined than on the northeastern limb. Faults are generally short (traces <10 km), northwesterly trending, and steeply dipping, and may show either a normal or reverse sense of movement. The principal fault-trace corridors cut the middle to upper Edmund Group between southeastern ELLIOTT CREEK and northwestern EDMUND (1:100 000 sheet) (MGA 479800E 7349100N to 418900E 7399600N)); and the lower to middle Edmund Group between south-central EDMUND (1:100 000 sheet) and southeastern MAROONAH (MGA 442600E 7363300N to 381700E 7423000N). The extensive system of northwest-trending quartz veins (*zq*) that cut the lower Edmund Group between northeastern MANGAROON and south-central MAROONAH (MGA 388700E 7379600N to 367000E 7401000N) may reflect the presence of another fault system at shallow depth.

Axial traces of large-scale folds formed during D_{1e} swing from southeast–northwest on ELLIOTT CREEK to south-southeast–north-northwest on MAROONAH. The major fold structure, the Wanna Syncline, is an asymmetric southeasterly plunging synclinorium whose gently dipping northeastern limb is cut by the Talga Fault. Its axial trace is kinked, and exhibits a marked change in trend, from south-southeasterly to southeasterly near Ferrier Bore (around MGA 436000E 7396000N). This change in orientation is interpreted as a cover response to dextral movement along a south-southeasterly trending basement splay of the Talga Fault during D_{1e}. The southwestern limb of the Wanna Syncline is more extensively deformed than the northeastern limb and comprises a series of large-scale anticlines and synclines. Most folds are upright open structures, although they may be tightened and inclined locally near exposed faults. Plunges are mostly gentle, toward either the southeast or northwest. Axial traces of the larger folds are often curvilinear, reflecting the influence of gentle refolding during D_{2e}. Many F_{1e} folds are associated with a weak to strong axial-planar cleavage defined by either a segregation of clay minerals, sericite, chlorite, microcrystalline quartz, or pressure solution residue material.

The greater intensity and more complex nature of folding on the southern limb of the Wanna Syncline probably results from a combination of factors. Firstly, this area probably overlies a relatively wide system of reactivated basement faults in which no single fracture was dominant. Secondly, the marked differences in competency between the mostly fine-grained sedimentary rocks of the Bangemall Supergroup and the thick dolerite and gabbro sills that intrude the stratigraphy southwest of the Talga Fault has probably contributed to the irregular fold geometry. Thirdly, the effects of refolding during D_{2e} are more evident in the southern part of the central zone.

Although most D_{1e} structures result from generally northeast–southwest compression, there is evidence for a localized, early episode of north-northwesterly directed compression in the area about 4 km west of Stinking Pool (MGA 373950E 7411650N) on south-central MAROONAH. Structures formed during this initial event occur in relatively incompetent siliciclastic and carbonate rocks of the Irregully Formation that outcrop below a prominent dolerite sill ($Pod_{1,2}$). They include a shallow to steeply dipping reverse fault and associated small- and large-scale folds in the footwall succession. Bedding in recrystallized dolostone below the reverse fault generally dips southeast, but is deformed locally into small-scale northwestward-verging asymmetric folds. These are cut by a shallow (about 35°) to steep (about 78°) southeasterly dipping pressure-solution cleavage. Three kilometres to the northeast, the dolerite sill overlies quartz sandstone and planar-laminated dolostone. Away from the contact these rocks are deformed into large-scale, open upright

folds with curvilinear axial traces that parallel the trend of the fault. From here bedding in the sedimentary succession steepens eastward towards the dolerite contact where it is deformed into steep, south-plunging small-scale folds. The plane of the contact between the sedimentary succession and the dolerite is marked by brecciated quartz veins. Both the reverse fault and the northeast-trending folds are refolded by the later northeast–southwest D_{1e} compression.

The metamorphic grade of M_{1e} in the central zone, while generally low, appears to be higher than in the northeastern zone. The typical assemblage for siltstones within the Edmund Group consists of clay minerals–sericite–chlorite–quartz–feldspar (K-feldspar and albite–oligoclase)–epidote, together with variable amounts of iron sulfide, iron oxide, and highly mature kerogen. Rock-Eval pyrolysis of a sample of carbonaceous siltstone from the lower Discovery Formation on MAROONAH (MGA 382578E 7425833N) indicates a maximum temperature during burial of 200–250°C (Ghori, A., 2004, written comm.). Country rock located close to thick dolerite sills shows the effects of contact metamorphism with andalusite and sillimanite present locally in metasiltstone.

Southwestern zone

Bangemall Supergroup rocks in the southwestern zone experienced generally higher levels of D_{1e} strain than either the northeastern or central zones. These rocks outcrop in faulted synclinal outliers that include the Mangaroon Syncline, the northwestern extension of the Cobra Syncline, and the unnamed syncline on southwestern MANGAROON (MGA 349300E 7374000N).

The Mangaroon Syncline is a southeast–northwest-trending, tight, upright, doubly plunging syncline of lower to middle Edmund Group rocks exposed on west-central MANGAROON (around MGA 359500E 7380500N). Rocks within the syncline show a marked contrast in competency, ranging from massive, thick dolerite sills (*Eod$_{1,2}$*) to thin-bedded siltstone and sandstone. The core of the syncline is cut by series of steep, northwest-trending faults that have undergone initial normal movement followed by transpression. Away from the faults, bedding dips are generally 20–50°, whereas closer to these fractures dips may be vertical or locally overturned. Traces of major and minor fold axes are generally subparallel to the major faults and the folds are characterized by a steeply dipping penetrative axial-planar cleavage. Bedding surfaces of tightly folded silicified siltstone may exhibit a strong movement striae (slickenside) lineation developed parallel to the direction of flexural slip. Locally this lineation may be folded about the hinges of steeply plunging small-scale intrafolial folds developed close to major faults.

On southwestern EDMUND (1:100 000 sheet; around MGA 413100E 7348200N) the northwestern extension of the Cobra Syncline is preserved between two major northwest-trending Edmundian faults. The most northerly of these, the Lyons River Fault (Lyons River Lineament of Pearson et al., 1996) preserves a south-block-down sense of movement and can be traced as an aeromagnetic lineament from southwestern EDMUND (1:100 000 sheet; around MGA 403100E 7358500N) to the eastern part of MOUNT AUGUSTUS. The unnamed bounding fault on the south side of the syncline extends from central-eastern MANGAROON (MGA 381600E 7379200N), where it juxtaposes Gascoyne Complex rocks to the south against lower Edmund Group on the north, to the southern limb of the Cobra Syncline on MOUNT AUGUSTUS where it is interpreted from aeromagnetic data. Both fault traces are aligned subparallel to fold axial traces in the Cobra Syncline suggesting a strong northeast–southwest transpressional stress regime during D_{1e}. Folding in the northwestward extension of the Cobra Syncline is tight with the fold axis marked by a high-strain zone in which silicified siltstone and chert of the Discovery Formation is deformed into steep, double-plunging, bedding-parallel mesofolds.

The typical metamorphic mineral assemblage for siltstones within the southwestern zone is similar to those in the central zone and suggests a low metamorphic grade during M_{1e}.

Palaeoproterozoic Basement

In rocks of the Gascoyne Complex, the effects of the Edmundian Orogeny (D_{1e}/M_{1e}) are mainly evident in late Palaeoproterozoic granites of the Durlacher Supersuite adjacent to Bangemall Supergroup rocks. Deformation mainly consists of southeast- to south-southeast-trending shear zones up to a few tens of metres wide. These structures are parallel to the main structural grain in the overlying Bangemall Supergroup. Within the D_{1e} shear zones, Palaeoproterozoic granite and pegmatite now consists of sericite–quartz(–tourmaline) schist.

Around the Star of Mangaroon mine on MANGAROON there are several southeast-trending shear zones up to a couple of tens of metres wide. Some of the shear zones have narrow (<2 m wide) mylonite zones in their cores. The shear zones dip steeply to the northeast or southwest and locally have a steeply plunging stretching lineation. Sense-of-shear criteria (S–C fabrics, asymmetric porphyroclast tails) suggest northeast side up. Some of the shear zones contain massive quartz veins or blows, one of which cuts a north-northeasterly trending dolerite dyke of the 755 ± 3 Ma Mundine Well dyke swarm. This relationship implies that some veining and deformation is even younger than the Edmundian Orogeny.

About 2 km east-southeast of Red Rock Bore on MAROONAH (MGA 362150E 7408180N), sheared biotite–muscovite granite (*PU-gmv*) contains tourmaline porphyroblasts within a southeast-trending foliation. The porphyroblasts are parallel and oblique to a locally developed mineral-elongation lineation. A weak S–C fabric suggests reverse movement (east side up). Along the eastern edge of the large pluton of muscovite–biotite granite on MAROONAH, thin laminated quartz veins have been emplaced into a south-southeasterly striking foliation that dips steeply to the west-southwest. Slickensides suggest normal fault movement (east side up).

In the southwestern corner of MANGAROON, granitic rocks of the 1830–1780 Ma Moorarie Supersuite adjacent to the Minga Bar Fault, contain a southeast-trending cleavage or zones of brittle fracturing. These structures may be related to D_{1e}/M_{1e}.

Deformation and metamorphism (D_{2e}/M_{2e})

The effects of the second Edmundian deformation event, D_{2e}, are recognized in cover rocks of the Bangemall Supergroup and the Gascoyne Complex basement, although structures formed during this event are less prominent than those resulting from D_{1e}. Three separate episodes are recorded during the D_{2e} event. The first episode involved weak east-southeast to west-northwest compression. This was followed by a period of east-southeast to west-northwest extension, during which time the Mundine Well dyke swarm was emplaced (see **Dolerite dykes (*od*)**). The final episode of D_{2e} deformation post-dated intrusion of the Mundine Well dyke swarm and resulted from dextral strike-slip movement along major basement faults.

Bangemall Supergroup cover

In the Edmund and Collier Basins, the early episode of east-southeast to west-northwest compression during D_{2e} resulted in large- and small-scale, northeast-trending, open, upright folds in the central and southwestern zones. These flexures are responsible for shallow plunge reversals in the F_{1e} folds. Locally the F_{2e} folds are associated with a weak, spaced axial-planar cleavage that dips steeply to the northwest or southeast.

Extension associated with the intrusion of the Mundine Well dyke swarm appears to post-date the development of early F_{2e} folds in the Edmund and Collier Basins. In the Mangaroon Syncline (around MGA 361500E 7378000N) dextral fault movements post-date a prominent dyke belonging to the Mundine Well swarm. Although there is no evidence of folding associated with this movement, F_{1e} folds may also have been tightened during this event.

Palaeoproterozoic basement

The effects of D_{2e}/M_{2e} on basement rocks of the Gascoyne Complex are typically very minor, consisting of localized cleavage development. However, in the large pluton of muscovite–biotite granodiorite and monzogranite (*EU-gmv*) on MAROONAH, a D_{2e} cleavage is common. The cleavage is vertical or steeply dipping, and strikes north to north-northeast. The cleavage overprints S_{1e} and is parallel to a crenulation cleavage in schists along the southwestern side of the pluton. In granitic rocks of the Moorarie Supersuite in the southwestern corner of MANGAROON, narrow, southeast-trending quartz mylonite zones, some of which cut dolerite dykes of the Mundine Well dyke swarm with apparent dextral offset, may also be related to D_{2e}.

Proterozoic and Phanerozoic geology

Dolerite dykes (*od*)

Dolerite dykes (*od*) on MANGAROON may include two discrete ages of intrusion, and possibly more. Most of the dykes are probably Proterozoic in age, but some may be Phanerozoic, hence none of the dykes have been assigned an age.

Mundine Well dyke swarm

Dolerite dykes, which strike north to north-northeast, intrude all the stratigraphic units in the Gascoyne Complex, and rocks of the Wyloo Group, Capricorn Group, and the Bangemall Supergroup. The dykes also cut across dolerite sills intruded into the Edmund Group (*Eod*$_{1,2}$) and Collier Group (*Eod*$_2$), and are mainly concentrated on MANGAROON and MAROONAH. Most post-date movement on Mangaroon Syncline faults. The dolerite dykes are part of the Mundine Well dyke swarm, which was dated at 755 ± 3 Ma by Wingate and Giddings (2000) and 754 ± 5 Ma by Rasmussen and Fletcher (2004). Some of the dykes can be traced for 30 km or more.

The dykes are commonly about 5–25 m wide but some reach nearly 150 m wide. They are commonly marked by sparse vegetation and typically outcrop as fresh boulders and tors amongst weathered rubble. In the southwestern corner of MANGAROON, the dolerites outcrop as boulders and tors in narrow linear valleys bounded by low ridges of contact-metamorphosed granite. At several localities, thick dolerites have caused partial melting of adjacent wall rocks. East of Mullara Well on MAROONAH (MGA 357100E 7408000N), intrusion of a dolerite dyke is associated with anatexis of leucocratic granite. Anatectic melt is present in a zone up to 30 cm wide along the contact. The melted granite is grey, and consists of rounded and embayed crystals of quartz and plagioclase (pseudomorphed by very fine grained albite, sericite, and epidote) in a fine-grained groundmass of quartz, orthoclase, and plagioclase, with minor chlorite and opaques. Micrographic and granophyric textures are common. Northwest of Minga Well on MANGAROON a thick dyke is associated with remelting of medium- to coarse-grained, cream-coloured tonalite. The anatectic rocks are pale pink and fine to medium grained.

The dykes are fine grained, or fine to medium grained, and aphyric to weakly porphyritic (<5% plagioclase phenocrysts up to 10 mm long). The cores of thicker dykes are typically medium grained. The dykes are massive, but locally a spaced cleavage parallel to the dyke walls is present. The dolerites have a subophitic to intergranular texture, and comprise pale-brown augite and plagioclase, and lesser olivine (<10%) and titanomagnetite. Accessory minerals include interstitial quartz, biotite, and apatite, and brown hornblende rims on titanaugite. Low-grade metamorphic recrystallization includes minor epidote and sericite replacement of plagioclase, and iddingsite replacement of olivine along fractures.

Fine-grained pervasive and fracture-related epidote alteration is extensively developed in granites of the Moorarie Supersuite in the southwestern corner of MANGAROON. Epidote alteration is spatially related to the large number of dolerite dykes in the area. Fine-grained pervasive and fracture-related epidote alteration, possibly related to the dolerite dykes, has also been identified at several localities on MAROONAH. In the northwestern part of the sheet area, about 1.9 km south-southwest

of the Monte Carlo workings, epidote alteration is developed in leucocratic monzogranite (*EPU-gpt*) that has intruded amphibolite. About 1.6 km southeast of Dirnelleurby Bore in the southwestern corner of MAROONAH, pervasive epidote alteration is intensively developed in metamorphosed pebbly sandstone (*EP-mtq*). Surrounding porphyritic biotite(–muscovite) monzogranite (*EgUpm*) and metamorphosed feldspathic sandstone (*EP-mtf*) are unaltered.

North-northwest trending dolerite dykes

A smaller number of dolerite dykes on MANGAROON and ELLIOTT CREEK strike roughly north-northwest. Dykes in this orientation are most abundant in the Minnie Creek batholith west of Mangaroon Homestead and in the core of the Wanna Syncline. These dykes are mostly exposed as trains of rubble with scattered low outcrop in a dark-brown soil.

The relationship between the north-northwesterly trending dykes and those of the Mundine Well dyke swarm is exposed at three localities west of Mangaroon Homestead. At each of these localities, dykes of the Mundine Well dyke swarm cut the north-northwesterly trending dykes. At one of the localities (MGA 349260E 7355550N) the north-northwesterly trending dyke is contact metamorphosed by a 150 m-thick dyke belonging to the Mundine Well dyke swarm. Therefore, these north-northwest dykes are older than the Mundine Well dyke swarm. However, in the area south of White Quartz Well on western MANGAROON, a north-northwest dyke appears to truncate a dyke of the Mundine Well dyke swarm. The north-northwesterly trending dykes have not been dated owing to a lack of recoverable zircon and baddeleyite, which is related to their basic composition and fine grain size.

Quartz veins (*zq*)

Quartz veins (*zq*) of various ages cut all the major stratigraphic units on EDMUND.

An extensive system of steep, northwest-trending quartz veins cuts Ashburton Basin rocks in the northeast of the region. Although veins of similar trend cut the Bangemall Supergroup, they are far less abundant in this younger succession, suggesting that most of the veins in the Ashburton Basin pre-date the Bangemall Supergroup. Many Ashburton Fold Belt D_{2a} faults are marked by a line of en echelon quartz veins dipping 30–90° northeast or southwest. Locally they are associated with a second suite of steeply dipping veins that trend between north-northwest and north-northeast. Most consist of equant to prismatic, subhedral to anhedral quartz with irregular goethite vugs (after sulfide). Locally, quartz crystals are kinked as a result of progressive fault movement. Much of the copper, gold, lead, and silver mineralization in the Ashburton Fold Belt is associated with D_{2a} faults and quartz veins.

In the Mangaroon Zone of the Gascoyne Complex, many of the veins strike east-southeast to southeast parallel to the regional structural grain. Several veins in this orientation are intruded by dolerite dykes (for example, about 1.5 km northwest of Shearing Shed Bore, at MGA 356010E 7358600N), whereas other quartz veins cut dolerite dykes (immediately south of the Star of Mangaroon mine, at MGA 372460E 7359480N). In the Boora Boora Zone, and to a much lesser extent in the Mangaroon Zone, veins strike north to north-northeast, parallel to the dolerite dykes (*od*). In some instances, dolerite dykes and quartz veins have utilized the same structure. Some of the veins are associated with mineralization: for instance, at the Monte Carlo Prospect, at the Horse Well prospect about 3 km southwest of Horse Well, and in the Mundong Well Cu–Pb pit. Many of the veins are massive, but epithermal textures — such as bladed quartz, colloform banding, and cavity-fill quartz — are developed in some veins; for example, about 4 km south-southeast of Collins Well on MAROONAH (MGA 351270E 7413470N).

Most of the larger quartz veins that cut Bangemall Supergroup rocks are confined to the central zone of the Edmund Fold Belt (see **Neoproterozoic Edmundian Orogeny**). They are most abundant on south-central MAROONAH and northeastern MANGAROON (between MGA 388700E 7379600N and 367000E 7401000N) where they may reflect the presence of a D_{1e} fault system at shallow depth. The majority of veins are up to a few metres wide (rarely up to 50m), northwest to north-northwest-trending, and dip northeast or southwest at 40–90°. North- to northeast-trending veins are less abundant and cut the lower Edmund Group and associated dolerite sills ($Pod_{1,2}$) in the area on northeastern MANGAROON (around MGA 372300E 7388400N). Most veins are filled either by a mosaic of massive, granular quartz or by brecciated quartz and iron oxide. Late-stage cavities are filled by subhedral quartz crystals and iron oxide cement.

Ferruginous veins (*zi*)

Ferruginous veins and linear alteration zones (*zi*) outcrop within an east-southeasterly trending zone up to 12 km wide in the central part of southern EDMUND (1:100 000 sheet) and cut rocks of the Gascoyne Complex and Edmund Group. This unit corresponds to the 'Yangibana ironstones and ferrocarbonatites' of Pearson (1996). These intrusions, together with the 'Spider Hill sills', 'Bald Hill intrusions', and 'fluidization breccias', were considered by Pearson (1996), Pearson and Taylor (1996) and Pearson et al. (1996) to form a high-level carbonatite-associated intrusive suite. According to Pearson (1996) the carbonatitic affinity of the dykes was initially recognized by Gellatly (1975). The following summary is largely taken from Pearson (1996) who provides details on the mineralogy and mineral and whole-rock chemistry of the veins and associated alteration.

The majority of veins strike between north-northeast and east-northeast, although between the Yanginbana North and Kanes Gossan prospects the veins mostly strike east-southeast. The veins are sinuous in form and individual veins can be traced for several kilometres. Lenses and pods up to 10 m wide of massive to vuggy iron

oxide are contained within the veins. The veins typically intrude subparallel to metamorphic foliations or along lithological contacts. The surface ironstones consist of boxwork structures after carbonate, along with magnetite, ilmenite, phlogopitic mica, apatite, allanite and pyrite (Gellatly, 1975). Three ferrocarbonatite dykes less than 1 m wide are known to be associated with the veins. The dykes consist of dolomite and siderite with accessory magnetite, apatite and phlogopite.

Physiography and Cainozoic deposits

Physiography

The physiography of the study area has been described by Daniels (1969), Payne et al. (1988), and Pye et al. (1998). The following account is largely taken from Pye et al. (1998).

Daniels (1969) divided the region into three main topographic zones, which are equivalent to the Ashburton Valley, Bangemall, and Maroonah Plains Geomorphological Provinces of Payne et al. (1988). These reflect the underlying rock units and correspond to low-grade metasedimentary rocks of the Wyloo and Capricorn Groups, the Bangemall Supergroup, and igneous and metamorphic rocks of the Gascoyne Complex respectively (Fig. 3).

The Ashburton Valley Geomorphological Province occupies a triangular area in the northeastern corner of EDMUND, and consists of undulating low hill country, with sandstones of the Capricorn Group forming higher ranges and isolated hills. Cainozoic alluvium is found along the main river courses (Payne et al., 1988).

The Bangemall Geomorphological Province consists of a broad diagonal strip of northwesterly trending ridges and cuestas across the central part of the region. Muhling and Brakel (1985) noted that prominent ridges and cuestas are formed by chert and sandstone of the Bangemall Group (now Supergroup), with less resistant shale, siltstone, and carbonate underlying valleys and scree slopes. This rugged terrain is dissected by creeks, producing steep-sided valleys and gorges. Dolerite dykes and sills intrude the Bangemall Supergroup, forming more-rounded hills and ridges (Payne et al., 1988). One of these, Mount Palgrave (704 m above sea level), is the highest point on the map sheet area.

The more subdued topography of the Maroonah Plains Geomorphological Province reflects the underlying granitic and metamorphic rocks of the Gascoyne Complex. Payne et al. (1988) divided this province into two land systems. The first system, called Mundong, consists of erosional surfaces of low granitic hills and broad stony plains, which give way downslope to depositional plains of Cainozoic and Quaternary alluvium. The other system, Nadarra, is formed by partially weathered and calcreted Cainozoic valley-fill deposits that overlie sedimentary rocks of the Bangemall Supergroup.

The Ashburton River, which flows northwestwards towards the Indian Ocean, is a relatively mature drainage system showing signs of rejuvenation where it dissects areas of calcrete and hardpan (Muhling and Brakel, 1985). The river is flanked by Quaternary alluvial deposits of deep loam and clay soils forming 3–4 km-wide active floodplains (Payne et al., 1988). The southwesterly flowing Lyons River and its tributaries are less deeply incised into the calcrete, and indicate a more mature river system (Muhling and Brakel, 1985). Payne et al. (1988) recognized a number of other land systems adjacent to major rivers. These include low calcrete plateaus and mesas formed by the dissection of partly consolidated or calcrete-rich Cainozoic colluvial valley-fill deposits.

Cainozoic deposits

Cainozoic deposits within the study area have been described by Daniels (1969), Payne et al. (1988), and Pye et al. (1998). For this present study these deposits have been classified using the scheme of Hocking et al. (2001) which is based on the landform position and principal regolith-forming process, qualified by the composition of the regolith. The classification has a defined set of primary codes that describe the landform setting and process. Within the present study area these are: *R* (residual or relict), *C* (colluvial), *W* (sheetwash), *A* (alluvial), *L* (lacustrine), and *S* (sandplain; mixed and eolian origins). Optional secondary and tertiary code letters can also be used to specify regolith composition and parent rock type respectively. In addition, a system of numbers may be used within the code to differentiate regolith of different relative ages (Plate 1).

The age of the landform elements and associated regolith is mostly poorly constrained. Regolith is shown as Quaternary or undifferentiated Cainozoic depending on whether the regolith is related to present-day processes, or it is likely to be an older feature. In the absence of reliable age data this judgement is based on evidence that includes the position of the unit in the landscape, its degree of induration, and the extent to which it has either been dissected by more recent processes or overlain by younger material. On the basis of these criteria the Relict or Residual units (*R*) are thought to be the oldest regolith units within the study area. Although these units have been assigned to the Cainozoic, it is possible they could be Mesozoic or older (Hocking and Jones, 2002).

Three generations of Cainozoic colluvial and alluvial deposits are recognized throughout the study area. The oldest generation (*C*3 and *A*3) consists of deeply dissected, weakly cemented and compacted deposits that often occur above present-day drainage systems, whereas the youngest consists of mostly unconsolidated material (*A1* and *C1*) deposited within the currently active Quaternary colluvial and fluvial systems. An intermediate generation of colluvium and alluvium *(C*2 and *A*2) consisting of partially consolidated and weakly dissected material that is not directly associated with the present-day depositional systems is also recognized locally. In situations where the colluvium and alluvium cannot be assigned a particular relative age, the deposits are grouped as unassigned units (*C* and *A*). All the sheetwash (*W*), lacustrine (*L*), and

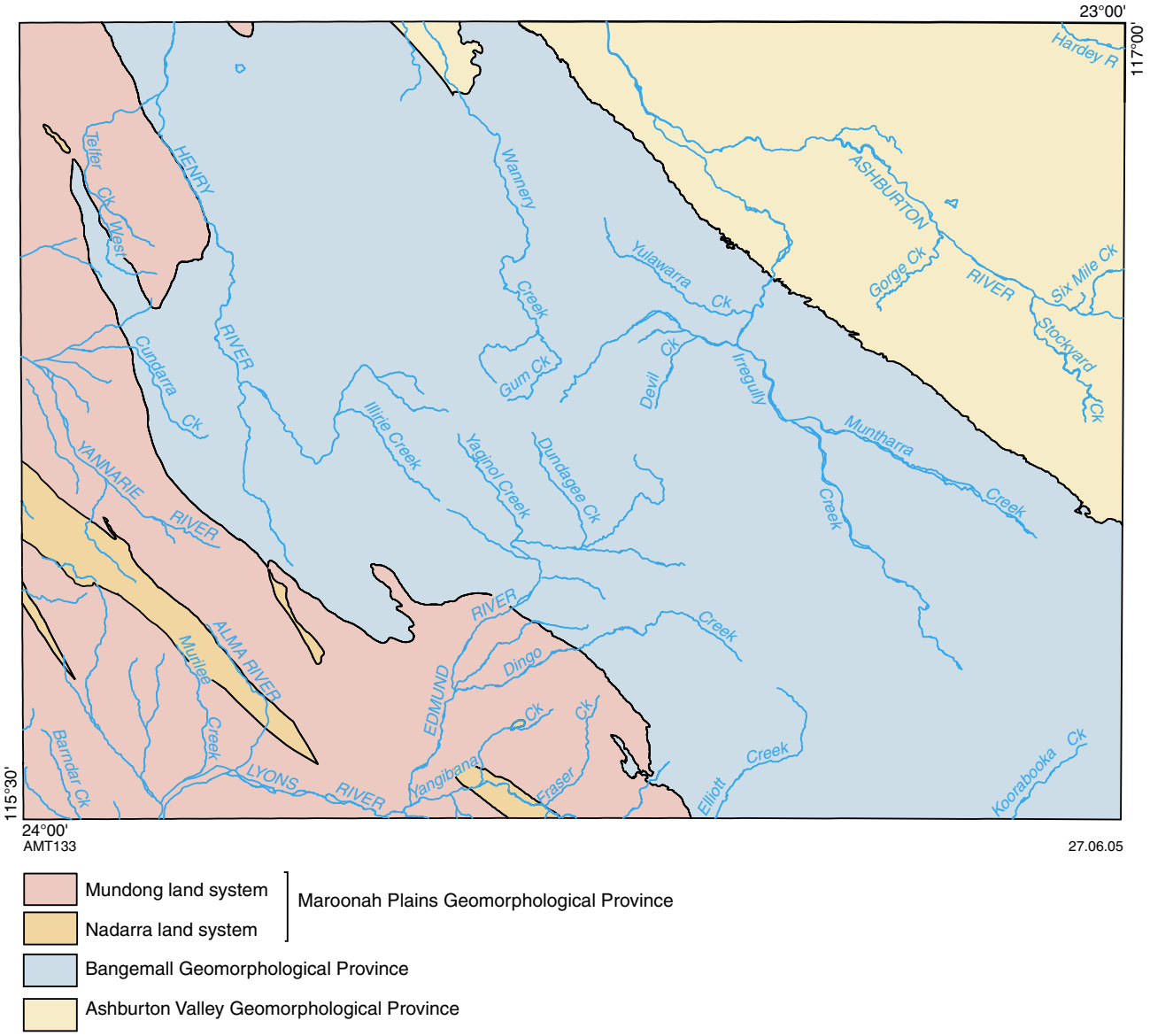


Figure 3. Physiographic regions and drainage systems of the area covered by the EDMUND map sheet. The physiographic subdivision is based on the work of Payne et al. (1988) and Pye et al. (1998)

sandplain (*S*) deposits that occur on the accompanying maps are also grouped into this unassigned relative age category.

In the following description, regolith units are described in terms of their relationship to the three main physiographic provinces recognized within the study area. These are the Ashburton Valley, Bangemall, and Maroonah Plains Geomorphological Provinces (Payne et al., 1988; Pye et al., 1998). Although many depositional units will contain the same code in all three provinces, the nature and composition of the unit will depend to a large extent on local bedrock sources. For example, colluvial units in the Maroonah Plains Geomorphological Province are generally pale-coloured, low-gradient deposits comprising quartz and feldspar grains, reflecting their granitic and metamorphic source rocks. In contrast, colluvial units in the Bangemall Geomorphological Province are commonly dark-coloured, steeply sloping deposits, that often contain abundant sedimentary rock fragments and dolerite or gabbro clasts, in addition to quartz.

Ashburton Valley Geomorphological Province

Relict and residual units (*R*) are comparatively uncommon in the province and consist of small dissected exposures of undivided ferruginous duricrust (*Rf*) in the hills and valleys around O'Grady Creek (e.g. MGA 494200E 7433300N). Nodular and bedded calcrete (*R-k*) is mostly developed along the valley sides in the upper tributaries of Stockyard Creek (around MGA 493400E 7401600N). Although these are grouped with the older Cainozoic deposits, their association with the present-day drainage and lack of deep incision suggests they could be somewhat younger. Silcrete and brecciated siliceous caprock (*Rz*)

is confined to the southern margin of the province, close to the Bangemall Supergroup outcrop, over which these deposits are developed extensively. Ferruginous silcrete (*Rzi*) is confined to two small exposures on northeastern Elliott Creek (around MGA 498400E 7387800N).

Colluvial units (*C, C3, C2, C1*) consist of quartz and rock fragments in a silt and sand matrix. They form small sloping aprons around rocky outcrops of Ashburton Formation and to a lesser extent the Capricorn Group. The oldest, most highly dissected deposits (*C3*) are confined to the southern margin of the province (e.g. MGA 496300E 7487500N). Colluvial deposits belonging to the intermediate generation (*C2*) are more widespread and mantle Ashburton Formation and Capricorn Group rocks west of the Capricorn Range (MGA 468200E 7425000N). Most of the colluvium recognized within the province has been assigned to the youngest generation (*C1*). These deposits overlie the Ashburton Formation and Capricorn Group, and have been subdivided to show material that is especially rich in vein quartz (*C1q*).

Areas of gently sloping sheetwash (*W*) are developed along the margins of Ashburton Formation outcrop north of the Ashburton River. Sheetwash units are poorly dissected by present-day drainage and consist of silt, sand, and gravel. Their top surface may be marked by a deflation lag of vein quartz and rock fragments.

Alluvial units composed of silt, sand, and gravel (*A, A3, A2, A1*) are the most abundant regolith deposit within the Ashburton Geomorphological Province. They form extensive deposits along the Ashburton River valley and its major tributaries including Irregully Creek, Six Mile Creek, and Hardey River (Fig. 3). The oldest alluvial deposits (*A3*) are preserved along the flanks of upland areas in the Capricorn Range and along drainage lines near the Bangemall Supergroup unconformity. Those deposits that have been assigned to an intermediate generation (*A2*) are more widespread. They are recognized in the same areas as the *A3* units and also form partly dissected lobes and sheets in the area north of the Ashburton River (around MGA 457200E 7451100N). The youngest alluvial units (*A1*) are more widespread than the older generations and form significant deposits along most of the major drainage lines. They have not been subdivided during the course of the present mapping.

Bangemall Geomorphological Province

The Bangemall Geomorphological Province is characterized by an extensive system of Relict and Residual deposits (*R*). Ferruginous duricrust (*Rf*) is developed over a wide range of siliciclastic and carbonate rocks in the Edmund Group as well as the associated dolerite sills ($Pod_{1,2}$). The deposits range from thin cappings of bedded or vuggy ironstone with disseminated quartz veins, to pisolitic laterite deposits up to 10 m thick. Dissected calcrete units (*Rk*) up to 30 m thick occur scattered along the major drainage lines where they overlie the *Rf* deposits. Most consist of vuggy calcrete with irregular, lenticular, bedding parallel cavities that give the rock a fenestral appearance. Veins and cavities are also filled by quartz cement, especially in upper parts of the calcrete profile. Dolomitic units within the Edmund Group, particularly the Irregully Formation, are characterized by extensive development of silcrete and brecciated siliceous caprock (*Rz*). Scattered occurrences of ferruginous silcrete (*Rzi*) are also recorded within this province. Daniels (1967) considered that these deposits formed part of the Bangemall Group (now Supergroup); however, they post-date Edmundian folding and intrusion of the Mundine Well dyke swarm. The relationship of *Rz* to the *Rf* and *Rk* units is unknown. Small occurrences of saprolite and saprock of uncertain protolith (*Rl*) are developed over Edmund Group outcrops on northern Mangaroon (around MGA 382900E 7392600N).

Colluvial units (*C, C3, C2, C1*), consisting of locally derived quartz and rock fragments in a silt and sand matrix, form restricted aprons around many Edmund and Collier Group outcrops. The oldest, most indurated and highly dissected deposits (*C3*) are recorded throughout the region but are most abundant on southern Ullawarra and Elliott Creek where they overlie *Rf* units. The intermediate generation of colluvium (*C2*) shows a similar distribution to the *C3* deposits and is most widespread on Ullawarra and Elliott Creek. Colluvium belonging to the youngest generation *(C1*) is less widespread than either the *C2* or *C3* units and is most abundant on Edmund (1:100 000 sheet) and northeastern Mangaroon. Younger colluvial units that are derived from dolerite are often rich in swelling clay minerals and rock fragments ($C1c_b$). More ferruginous material (*C1f*) is also developed locally around dolerite sills and dykes. Material that is especially rich in vein quartz (*C1q*) is also recorded and is especially abundant around the extensive system of quartz veins (*zq*) on northeastern Mangaroon. Unassigned colluvium is subdivided into ferruginous rubble and scree (*Cf*) and quartz-rich silt, sand, and gravel (*Cq*).

Sheetwash units (*W*) consist of silt, sand, and gravel and are poorly dissected by present-day drainage. They are best developed on gentle distal slopes adjacent to major drainage lines in the southwestern part of the province where they may develop a characteristic banded mosaic photo pattern (Wakelin-King, 1999). The upper surface of some sheetwash units may also be marked by a deflation lag of vein quartz and rock fragments (*Wq*). Sheetwash with carbonate cutans and cement (*Wk*) is developed locally over Irregully Formation dolostone.

Extensive alluvial units (*A, A3, A2, A1*) composed of silt, sand, and gravel are present along the main drainage lines of Alma River, Edmund River, Dundagee Creek, Henry River, Irregully Creek, Wannery Creek, and Koorabooka Creek (Fig. 3). The oldest, most widely dissected alluvial deposits (*A3*) are preserved along the upper reaches of tributaries that feed the Henry River and Irregully, Koorabooka, and Wannery Creeks. Ferruginous cemented older alluvium (*A3ti*) also forms a major sheet-like deposit that blankets Edmund Group and Gascoyne Complex rocks along the Edmund River drainage system. Deposits that have been assigned to an intermediate generation (*A2*) are most abundant in the upper reaches of most of the major drainage lines where they form partially dissected terraces above the active channels.

Clay rich deposits ($A2c_b$) are associated with areas of dolerite whereas alluvium rich in lithic fragments derived from the Edmund Group ($A2t$, $A2ts_s$) are preserved in the upper reaches of Dingo Creek (around MGA 434700E 7366000N). The youngest alluvial units ($A1$) form significant deposits along the lower reaches of most of the active drainage lines. They are subdivided into clay-rich deposits derived from dolerite outcrops ($A1c$, $A1c_b$); silt, sand, and gravel deposited on channel banks ($A1k$) or in small drainage depressions ($A1d$); ferruginous deposits, locally associated with dolerite sills or ferruginous relict and residual deposits ($A1f$); and lithic deposits composed of sandstone clasts in an unconsolidated silt and sand matrix ($A1ts_s$). Unassigned Alluvium is divided into clay-rich (Ac, Ac_b) and quartz-rich (Aq) varieties.

Fine-grained, unconsolidated lacustrine deposits (L) occur in isolated claypans, perennial lakes, and swamps; and low-lying areas with internal drainage. They are most abundant in the southwestern part of the province and are usually thickly vegetated.

Maroonah Plains Geomorphological Province

The Maroonah Plains Geomorphological Province comprises two land systems; the areally extensive Mundong land system that overlies granitic and metamorphic rocks of the Gascoyne Complex; and the more restricted Nadarra land system that is developed on outliers of the Bangemall Supergroup (Payne et al., 1988).

Mundong land system

Relict and residual deposits are dominated by dissected calcrete and silicified calcrete (*Rk*) that forms terraces along the major drainage lines. Surface exposures and drillhole sections in the area south of the Lyons River indicate these deposits are up to about 10 m thick and are transitional downwards into clay and silt (Amax Exploration (Australia) Inc., 1974). The calcrete units are characterized by a hard surface layer of brecciated and partly silicified calcrete underlain by softer more friable material. Minor gypsum and botryoidal talc are present locally (Amax Exploration (Australia) Inc., 1974). Calcrete units are commonly partly eroded and degraded, and include variable amounts of calcrete scree and rubble in a lime-rich soil. On southeastern MANGAROON, calcrete forms an extensive planar surface that is incised by the present-day Lyons River and its tributaries. Small, scattered occurrences of ferruginous duricrust *(Rf)* are developed over the metasedimentary rocks of the Pooranoo Metamorphics northwest of the Star of Mangaroon Mine (MGA 398500E 7369000N) and granitic rocks of the Durlacher Supersuite (MGA 401700E 7350150N). Outcrops of Durlacher Supersuite are also covered in places with a veneer of locally derived, weathered quartzofeldspathic rock in a sand and sandy clay matrix *(Rg)*. Areas of saprolite and saprock of uncertain protolith *(Rl)* are developed over outcrops of the Moorarie and Durlacher Supersuites and the Pooranoo Metamorphics on southern MANGAROON (around MGA 362500E 7366800N). Small occurrences of silcrete and brecciated siliceous caprock *(Rz)* are also recorded close to outcrops of the Bangemall Supergroup on MAROONAH and MANGAROON.

Colluvial units, consisting of locally derived quartz, feldspar and rock fragments in a silt and sand matrix (*C3, C2, C1*), are developed around many Gascoyne Complex outcrops. Weakly cemented and dissected deposits belonging to the oldest generation (*C3*) are confined to a small area on southern MANGAROON (around MGA 358300E 7365600N). The intermediate and younger generations of partly consolidated or unconsolidated colluvium (*C*2 and *C*1 respectively) are much more widespread throughout this land system. Units of *C1* have been subdivided into unconsolidated ferruginous rubble and scree (*C1f*) and clay-rich material ($C1c_b$) developed locally on outcrops of Pooranoo Metamorphics, siliciclastic material with calcrete cutans and carbonate cement (*C1k*) derived from calcrete, and quartz-rich material (*C1q*).

Unassigned sheetwash units *(W)* consist of quartzofeldspathic silt, sand, and gravel and are poorly dissected by present-day drainage. They are developed on gentle distal slopes adjacent to major drainage lines throughout the Mundong land system and may develop a distinctive banded-mosaic photo pattern (Wakelin-King, 1999). Clay-rich material derived from saprolite and saprock *(W*c) is present on southern MANGAROON (around MGA 355700E 7258300N). Quartzofeldspathic sand and silt sourced from granitic rocks of the Durlacher Supersuite are confined to an area on central EDMUND (1:100 000 sheet; around MGA 432500E 7360200N). Sheetwash with carbonate cutans and cement *(Wk)* is associated with calcrete terraces near the upper reaches of the Yannerie River (MGA 357400E 7391700N) and along tributaries of the Lyons River (around MGA 374200E 735600N). Material composed mostly of quartz fragments *(Wq)* is recorded near the system of quartz veins (*zq*) on MANGAROON and MAROONAH (around MGA 380100E 7380800N).

Alluvial units (*A, A3, A2, A1*) composed of quartzofeldspathic silt, sand, and gravel have been deposited along the main drainage lines and tributaries of Alma River, Edmund River, Lyons River, Telfer River, and Yannarie River (Fig. 3). The oldest generation of alluvial deposits *(A3ti)* consist mostly of weakly iron-cemented lithic material derived from the nearby Edmund Group. These units form a prominent sheet-like deposit that blankets both the Edmund Group and Gascoyne Complex rocks adjacent to the Edmund River drainage system. The intermediate generation of alluvium (*A2*) forms partially dissected terraces above the active channels along the Alma, Edmund, and Lyons rivers. The youngest alluvial units consisting of unconsolidated, silt, sand and gravel *(A1)* are widespread along the lower reaches of most of the active drainage lines. They are subdivided into units that were either deposited on channel banks ($A1_k$) or in small drainage depressions ($A1_d$).

Fine-grained, unconsolidated lacustrine deposits (*L*) are present in isolated claypans, perennial lakes, and swamps;

and low-lying areas with internal drainage. They are often thickly vegetated and are most abundant along the line of the Edmund River, where they commonly overlie older alluvium *(A3ti)* or sheetwash *(W)* units.

Undivided deposits of quartz sand (*S*) are confined to small areas on southern and eastern Mangaroon (around MGA 378200E 7355800N and MGA 391100E 7367400N, respectively). The origin of this material is uncertain, it could either be a residual deposit or eolian sand.

Nadarra land system

Similarities between the geology of the Nadarra land system and the Bangemall Geomorphological Province have resulted in a similar pattern of regolith distribution. Principal differences relate to the older colluvial and alluvial deposits, and the sheetwash units which are only poorly preserved in the Nadarra land system.

Small, scattered occurrences of ferruginous duricrust *(Rf)* are best developed over siliciclastic and carbonate rocks in the Yilgatherra and Irregully Formations. The deposits vary from thin cappings of bedded or vuggy ironstone with disseminated quartz veins, to pisolitic laterite deposits up to 10 m thick. Dissected calcrete units *(Rk)* occur scattered along the major drainage lines in the Mangaroon Syncline. They are best developed over carbonate rocks of the Devil Creek and Irregully Formations and consist of vuggy calcrete with irregular, lenticular, bedding parallel cavities that give the rock a fenestral appearance. Veins and cavities are also filled by quartz cement, especially in upper parts of the calcrete profile. In the Nadarra land system the calcrete units appear to post-date the ferruginous duricrust. Outcrops of Irregully Formation are often characterized by extensive development of silcrete and brecciated siliceous caprock and silicified sandstone and conglomerate *(Rz)*. Daniels (1967) considered that these deposits formed part of the Bangemall Group (now Supergroup), however, they post-date Edmundian Folding and intrusion of the Mundine Well dyke swarm. The relationship of *Rz* to the *Rf* and *Rk* units is unknown.

Colluvial units (*C, C2, C1*), consisting of locally derived quartz and rock fragments in a silt and sand matrix, form localized aprons around outcrops of Edmund Group rocks. The oldest generation of indurated and highly dissected deposits (*C3*) that are recorded in the Bangemall Geomorphological Province are not recorded within the Nadarra land system. Similarly, deposits that have been assigned to the intermediate generation of colluvium (*C2*) appear to be poorly preserved within this land system. Colluvium belonging to the youngest generation (*C1*) is, however, widespread within the Mangaroon Syncline and northwestern extension of the Cobra Syncline. Younger colluvial units that are especially rich in vein quartz (*C1q*) are present on the northern limb of the Mangaroon Syncline (around MGA 370500E 7374200N), whereas material with abundant lithic fragments of Edmund Group sandstone and siltstone occur in the Cobra Syncline (around MGA 413900E 7348800N). Unassigned and undivided colluvium (*C*) is also recorded in the Cobra Syncline.

Gently sloping sheetwash units *(W)* consist of silt, sand, and gravel and are poorly dissected by present-day drainage. They are not well developed within the Nadarra land system, probably as a result of the generally steeper slopes associated with the main strike ridges. Sheetwash with carbonate cutans and cement *(Wk)* is developed locally over the Devil Creek Formation in the Mangaroon Syncline.

Alluvial units (*A, A3, A2, A1*) composed of silt, sand, and gravel have been deposited along tributaries of Alma River (MGA 393100E 7364400N), Lyons River (MGA 416200E 7348800N), and Yannarie River (MGA 357400E 7393200N) that drain the Nadarra land system. The oldest generation of weakly cemented and compacted alluvial deposits *(A3)* is only preserved in small exposures near the southern end of the Mangaroon Syncline (MGA 380700E 7361700N) and in the Cobra Syncline (around MGA 413500E 7350000N). The latter area also includes small exposures of ferruginous cemented older alluvium *(A3ti)* derived from the main Bangemall Supergroup outcrop to the north. Alluvium that has been assigned to the intermediate generation *(A2)* is also poorly preserved and has only been identified on alluvial fans draining the northern margin of the Mangaroon and Cobra Synclines. The youngest alluvial units, consisting of unconsolidated, silt, sand and gravel *(A1)* are much more widespread, having been deposited along most of the active drainage lines. A small area of unassigned alluvium *(A)* is present along the banks of the Lyons River where it cuts through the Cobra Syncline (MGA 410100E 7349300N).

Economic geology

There is currently only one operating mine (Mount Mortimer) and one building stone quarry (Sheela Bore) in the area covered by this data package; however, the region has had a history of mining that dates back to the 1890s. The mineral occurrences in the package are recorded in the WAMIN database and are discussed here in terms of the host tectonic unit, mineralization style, and mineral commodity. The occurrences are identified by the WAMIN 'deposit name' and 'deposit number' (or SITEID), shown thus: Star of Mangaroon (**213**).

Ashburton and Blair Basins

Most of the recorded mineralization in the southwestern Ashburton and Blair Basins has come from vein and hydrothermal deposits and the associated regolith material.

Vein and hydrothermal mineralization

Gold and base metal mineralization is locally associated with late D_{2a} quartz veins that cut low-grade metamorphosed siltstone, sandstone, conglomerate, felsic volcanic rock, and dolostone in the Ashburton and Bywash Formations.

Precious metal — gold

Gold mineralization has been recorded from the Ashburton Formation on northern and central CAPRICORN. The gold often occurs in the upper, more weathered parts of late D_{2a} quartz veins, which generally carry a considerable amount of goethite; a little galena may accompany the gold (Simpson, 1926). Most ore was extracted from shallow workings, small shafts, and associated alluvial workings at Big Sarah and Big Sarah North, Hearns Find (O'Gradys), Dead Finish (McKenzies Find), Greggs Find (Star of the West), Dead Finish Northwest, the Gorge, and Mount Mortimer.

The Big Sarah (**7482**) and Big Sarah North (**7483**) prospects are hosted by low-grade metamorphosed siltstones, sandstones and felsic volcanic rocks of the Ashburton Formation that are cut by a dense network of auriferous quartz veins. Department of Industry and Resources records show that Big Sarah produced 6.95 kg of gold from 132 t of ore during the period 1940–41. A reconnaissance grab sample program by Mr M. L. Henry in 1995 returned assay values up to 1.68 g/t Au from old workings.

Simpson (1926) and Wright (1897) stated that Hearns Find (O'Gradys, **1361**)) was located on a tributary of the west branch of O'Gradys Creek (also referred to as The Deep), about 8 miles (13 km) south of Hardey River. An unspecified amount of gold was recovered from a 0.3 m-wide ferruginous quartz vein in siltstone and mudstone.

Dead Finish refers to the area on CAPRICORN which includes McKenzies Find, New Find, and Greggs Find (Star of the West). The principal deposits have been described by Woodward (1891), Maitland (1909), Talbot (1926), Simpson (1926), and Jones and Telford (1939); there is also a brief summary by Johnston (1983) and Thorne and Seymour (1991). Department of Industry and Resources records show that 34.8 kg of gold (excluding alluvial) was produced from this area before 1986. An exploration program at McKenzies Find (**209**) during 1989–90 (Aberfoyle Resources Ltd, 1990) involved geological mapping and rock-chip sampling of an interbedded succession of turbiditic wacke and pelite carrying ubiquitous quartz veins. This program suggested little potential for significant gold mineralization. Little information is available regarding the New Find prospect (**7880**). Jones and Telford (1939, plate 1) indicate that it is an area of alluvial workings about 750 m east of Dead Finish.

Greggs Find (Star of the West **210**, Ivorsens, **1351**), was incorrectly referred to as Star of the East by Jones and Telford (1939) and Thorne and Seymour (1991). Department of Industry and Resources records show that 20.25 kg of gold was extracted in the period 1939–51. During 1984 mining efforts were centered on three quartz veins, (striking 150° and dipping northeast at 25°), which cross-cut chloritic siltstone and mudstone (Thorne and Seymour, 1991). Small amounts of gold have been recovered from these seams; however, the most extensive gold mineralization (5 to 6 g/t Au) is in country rock, close to where veins are cut by two fractures that strike 100°, and dip 65° south and 60° north respectively. Here, the mudstone and siltstone are strongly bleached and contain numerous cubic goethite pseudomorphs (faces up to 10 mm) after pyrite.

The Dead Finish Northwest workings (**1360**) were described by Jones and Telford (1939). They recorded the presence of several auriferous quartz veins that extend approximately 8 km southeast from a conspicuous quartz ridge on central CAPRICORN (MGA 479800E 7438300N). Country rocks are open to tightly folded (axes trend 120°) mudstone, siltstone, and sandstone. Most of the prominent fissures strike slightly south of 120°, thereby cutting fold axes at an acute angle. In addition, numerous smaller veins strike north-northwest to north-northeast. The most significant mineralization (6 g/t from a vein 0.15 m wide) was found at the western end of the belt (Jones and Telford, 1939).

Simpson (1926) referred to a prospect known as the Gorge (**1336**) as being ten miles (16 km) southeast of Mount Mortimer (Mount Dawson). This placed the mined area within the Capricorn Formation outcrop; however, descriptions of prospect geology (Wright, 1897) are more consistent with the Ashburton Formation. Jones and Telford (1939, plate 1) marked the track to the workings further to the southeast, and it is more likely that the Gorge was situated near the headwaters of Gorge Creek, where it is shown on the CAPRICORN map sheet (Thorne et al., 2002). Wright (1897) and Simpson (1926) noted that the area has numerous quartz outcrops, many of which are auriferous, including a gold- and silver-bearing vein up to 1.8 m wide. Although most veins are only weakly mineralized, Simpson (1926) recorded a value of 400 g/t Au from one ore sample. Traces of copper, silver, and lead are present with the gold. Unpublished lead-isotope data from a galena and gold specimen from the Gorge area give a model age of about 1600 Ma (I. R. Fletcher, 1987 quoted in Thorne and Seymour, 1991), based on the Model III curve of Cumming and Richards (1975). Much of the recent exploration in the Gorge area has focused on alluvial gold associated with the quartz veins (Crawford, 2003).

Most of the gold recovered from the Mount Mortimer area (**203**) was obtained from alluvial deposits; however, east-striking, auriferous quartz veins that cut tightly folded mudstone, siltstone and sandstone have also been worked (Woodward, 1891; Wright, 1897; Maitland, 1909; Simpson, 1926; Jones and Telford, 1939). The majority of veins have been mined only to shallow depth. Small amounts of galena occur locally with the gold (Maitland, 1909).

Aberfoyle Resources Ltd (1995) undertook an exploration program at the Sunken Treasure prospect (**1528**) during 1990–95. The two target prospects, Sunken Treasure and Banana, occur in coarse-grained arenites with weak quartz-vein stockworks, and granule conglomerate with conspicuous silica–pyrite–sericite alteration on vein margins. Several phases of rockchip and stream-sediment sampling delineated two anomalous areas (up to 14 g/t Au). RC drilling of these anomalous alteration zones returned only weak gold mineralization beneath the main ridge of quartz stockworks. The most significant intersection was 2 m of 13.26 g/t Au from one hole.

Base metals — copper, lead, and silver

Most copper, lead, and silver production from the Ashburton and Blair Basins has come from quartz veins and shears in the Ashburton Formation and, to a lesser extent, from the Capricorn Group. The principal areas of mineralization are the Kooline and Ashburton Downs centres. These have been described by Low (1963), Blockley (1971), Marston (1979), Thorne and Seymour (1991), and Ferguson (1999).

Kooline centre includes an area 7.2 km long by 2.4 km wide, 7 km east of Kooline Pool. Blockley (1971) listed 17 mines (or groups) and 10 miscellaneous deposits which produced 2679 t of lead and 825 kg of silver between 1948 and 1959. About 65% of production came from the Gift (**229**), June Audrey (**230**), and Bilrose (**231**) Mines. With the exception of Big Chief Mine (**205**), galena-bearing veins occur within Ashburton Formation mudstone, siltstone, and sandstone, on the northern limb of a large, upward-facing D_{2a} syncline. Axes of medium- to large-scale D_{2a}, folds trend about 280°, and axial-plane cleavages are generally vertical or dip steeply southwards. Most mineralized veins are parallel to the axial-plane cleavage, although some smaller fissures cut it at high angle. Within the Kooline centre, there appears to be no correlation between mineralization and the type of country rock. Galena-bearing veins range from a few centimetres to 1.2 m thick and are up to 60 m long. Often, several veins are distributed en echelon. Principal minerals are galena, quartz, cerussite, malachite, calcite, and barite. Ore minerals may be disseminated through quartz, or restricted to narrow seams of massive sulfide or carbonate. The grade of ore mined was in the range 10–12% Pb and 31.1 – 46.6 g/t Ag (Blockley, 1971). Big Chief Mine is 16 km southeast of the main group of Kooline deposits. The mineralized zone is 12 m long, strikes 285°, and dips 60° south, parallel to bedding in the host Bywash Formation. The richest galena and cerussite ore is in a narrow bed of sheared mudstone and siltstone lying beneath a massive quartz sandstone and above a 0.6 m-thick lithic sandstone. Some disseminated cerussite occurs in the footwall and in the hanging wall. Lead-isotope data from 34 galena samples collected from the Kooline centre give an average Pb model age of about 1550 Ma (J. R. Richards, quoted in Thorne and Seymour, 1991), based upon the Model III curve of Cumming and Richards (1975).

The Anticline, Bali High East, Casleys, Ledge, and Stockyard Creek prospects are about 5 km south of Koonong Pool. Most deposits are in shear planes at, or close to, the unconformable contact between the Ashburton Formation and the overlying Capricorn Group. They are described by Low (1963), Blockley (1971), Marston (1979), Thorne and Seymour (1991), and Ferguson (1999).

Casleys (Bali Low, Bali Lo, **1345**) prospect is in a shear-zone close to the hinge of a west-northwest-trending D_{2a} anticline. The dominant mineralization is copper in quartz veins parallel to foliation, disseminations in country rock (felsic tuff, dolomitic slate, and mudstone) and small pods (up to 1 m long by 0.5 m wide) of limonite with disseminated malachite, azurite, chrysocolla, and various copper arsenates. These veins and pods are found in a 240 m-long by 1–3 m-wide brecciated zone that dips steeply southward (Bridge and Pryce, 1978; Marston, 1979; Ferguson, 1999). Metazeunerite (a uraniferous copper arsenate) is present as fracture coatings within the Capricorn Group. Diamond drilling near the eastern end of the prospect intersected the mineralized zone at a depth of 60 m, and assayed 1.2% Cu over a drilled width of 2.8 m (Marston, 1979). Assays of up to 50 ppm Pb, 460 g/t Au, and 370 ppm Ni were also obtained (Marston, 1979). Esso also recorded 219 ppm uranium from the mineralized zone (Ferguson, 1999). During the period 1983–89, Barrack Exploration Pty Ltd (1989) obtained rock chips containing up to 4.93% Pb between Casleys and the Ledge (Ferguson, 1999). On the basis of percussion drilling at Casleys the joint venture estimated an 'inferred resource' of 90 000 t at 1.3% Cu* (Ferguson, 1999).

Bali Hi (Bali High **1281**, Anticline, **9738**) prospect is located 1.2 km east-southeast of the Casleys deposit. The shear zone, which dips south at about 50°, is 1–2 m-wide and sporadically mineralized for 700 m (Marston, 1979). Host rocks consist of kaolinized felsic tuff, sandstone, and minor dolomite of the Capricorn Group and chloritic slate, mudstone, and greywacke of the Ashburton Formation (Ferguson, 1999). A fracture cleavage is associated with the shear. The mineralized zone was encountered in a shaft sunk by Pickands Mather and Co. International (PMI), and consisted of about 12 m of disseminated pyrite, galena, chalcopyrite, bornite, digenite, covellite, tetrahedrite, skutterudite (CoAs), and a copper–antimony sulfide (Marston, 1979). Diamond drilling by PMI encountered mainly pyrrhotite at 76 m vertical depth, assaying up to 300 ppm Cu, 530 ppm Pb, and 2600 ppm Zn, over a true width of 3.9 m. Surface sampling has also revealed anomalous Bi (150 ppm), U (200 ppm), Ag (270 g/t), and As (4.8%). Barrack/UAL conducted mapping, surface and underground sampling and RC drilling during the period 1983–89. They calculated an inferred resource of 95 000 t at 2.8% Pb and 0.2 g/t Au, estimating the core of the mineralized body (>1% Pb) to be 80 m long and up to 4.5 m thick (Ferguson, 1999).

The Bali High East (**1349**) prospect is 2.8 km southeast of the Casleys workings. The mineralized portion of the shear cuts the Ashburton Formation; it is about 280 m long and 1–2 m wide, and contains malachite, azurite, chrysocolla, and traces of chalcocite. Surface material has up to 27% Cu, and gives anomalous levels of Pb, Zn, Bi, As, Ag and U (Marston, 1979). Barrack/UAL obtained maximum copper values of 1.93% during their exploration program between 1983–89 (Ferguson, 1999).

Ledge prospect (**207**) is 2.8 km west of the Casleys deposit and was the source of minor copper production during the 1960s. Country rocks comprise faulted Ashburton Formation fine pebble conglomerate and granular sandstone and Capricorn Group mudstone, siltstone, and fine- to coarse-grained sandstone. These

* This mineral resource estimate is not compliant with the Joint Ore Reserves Committee (JORC) Code.

rocks strike 285° and dip north at about 55° and show bleaching and sericite alteration. Mineralization is in a 1–2 m-wide siliceous shear zone that strikes 285° and dips 80° south. Pods of malachite, chrysocolla, chalcocite, tenorite, cuprite, cerussite, limonite, and quartz are present as breccia matrix in the shear zone (Marston, 1979). Blockley (1971) recorded that lead is most abundant in the western end of the workings. A chip sample from here assayed 31.3% Pb, 0.8% Zn, 6.8% Cu, and 112 g/t Ag.

The Stockyard Creek (**206**) prospect is about 5 km southeast of Casleys prospect. A little malachite forms staining and fracture coatings in Ashburton Formation sandstone, mudstone and conglomerate. Marston (1979) suggested that this may reflect the redistribution of syngenetic copper from the Capricorn Formation by meteoric water. A drilling program by Barrack/UAL during 1983–89 to test the strike extensions of mineralization observed in mine workings failed to intersect mineralization or alteration (WAMEX database).

The WAMIN database records an occurrence of probable Pb vein mineralization (**1330**) in the area 300 m northeast of Star Find in the Mount Mortimer area. No other details are available.

Industrial mineral — barite

Barite is recorded as one of the gangue minerals associated with lead–silver vein and hydrothermal mineralization in the Kooline district (Blockley, 1971; Abeysinghe and Fetherston, 1997). The principal occurrences are at Roebuck (**1529**), South Kooline (**235**), Beadon (**234**) and June Audrey (**230**) mines, although there is no recorded production.

Mineralization in the regolith

The principal areas of regolith mineralization are associated with vein and hydrothermal gold deposits within the Ashburton Formation. There are also minor occurrences of microdiamonds and diamond indicator minerals within these surficial deposits.

Alluvial to beach placers

Precious metal — gold

Most gold recovered from the Ashburton Basin was from alluvial and colluvial deposits overlying the Ashburton Formation (Woodward, 1891; Jones and Telford, 1939, unpublished Department of Industry and Resources records). The principal areas worked on Edmund were the Mount Mortimer area, Dead Finish, and the Gorge.

Department of Industry and Resources (DoIR) records show that 55.5 kg of gold was extracted from the Mount Mortimer area (**203**) prior to 1987; however, this figure does not include the amount removed during the latter part of the 19th century (Thorne and Seymour, 1991). Two large nuggets, one weighing 1.87 kg and the other 1.74 kg, were discovered during the 1890s (Woodward, 1891; Wright, 1897).

Alluvial gold production from the Dead Finish area (**209**) probably amounted to about 30 kg during the early 1890s (Woodward, 1891), and a further 20.5 kg was reported to the Mines Department (now DoIR) between 1983 and 1986 (Thorne and Seymour, 1991). The largest nugget, weighing approximately 0.8 kg, was discovered at Hearns Find (**1361**, Wright, 1897).

There are no production figures available for the Gorge (**208**).

New Finish (**7881**) is reported to be an alluvial gold deposit, occurring 3 km northeast of Greggs Find (WAMIN database). No other details are available.

Precious mineral — diamond

Four occurrences of microdiamonds and diamond indicator minerals have been reported from the Ashburton and Blair Basins. They are the O'Grady Creek occurrence on eastern Capricorn and three unnamed occurrences in the central and southern part of that map sheet.

At O'Grady Creek (**7481**) numerous dolerite dykes and lamproitic/kimberlitic bodies have been reported to intrude the sedimentary succession (Mason, 1998, WAMEX database). Stream-sediment samples showed abundant indicator minerals and some microdiamonds were recovered. A number of leucite lamproite diatremes were also identified.

Stockdale Prospecting (1996) investigated an unnamed diamond occurrence (**1583**) 7 km south of the Dead Finish Northwest gold prospect. Heavy mineral analysis of stream-sediment samples returned several chromite crystals and one small diamond. Follow-up investigation of chromite mineralogy failed to reveal any positive affinity to a kimberlitic source.

During the period 1992–97 Stockdale Prospecting Ltd conducted an exploration program for diamonds, lead, and zinc on the southern part of Capricorn. They reported the presence of one fine diamond and four fine spinel crystals from a sample taken from an unnamed site (**2005**) south of the Capricorn Range (MGA 482290E 7401750N). A sample taken from another unnamed site (**2004**) 6.5 km to the northwest (MGA 478340E 7406650N) yielded one medium diamond. No follow-up work was carried out for either of these occurrences.

Gascoyne Complex

A number of vein and hydrothermal mineral occurrences of gold, base metals, uranium, and barite are located in Gascoyne Complex rocks on Edmund, but to date there has been very little production. Most of the hard-rock occurrences in the Gascoyne Complex are located between the Minga Bar Fault and the Mangaroon Syncline on Mangaroon. This area has a greater amount of shearing related to the Mangaroon Orogeny (D_{2m}) relative to the Mangaroon Zone north of the Mangaroon Syncline. There are also a number of occurrences in the Boora Boora Zone on Maroonah. In addition, on the southern part of Edmund (1:100 000 sheet), there are numerous occurrences of mineralization associated with alkaline intrusions.

Vein and hydrothermal mineralization

Precious metal — gold

The only two mines on MANGAROON, Diamond Gold Mine (**1288**) and Star of Mangaroon (**213**), both of which are abandoned, are related to vein and hydrothermal gold mineralization. Of the two, only Star of Mangaroon has any recorded production; 4742 t of ore were mined between 1960 and 1983 for 3.197 kg Au (Sullivan, 2001). In the 1990s, Welcome Stranger Mining Company NL (1995) drilled 18 angled RC holes (1050 m total) and estimated a 'measured, indicated, and inferred resource' to 150 m depth of 79 467 t at 9.3 g/t Au for a total of 23 856 oz*.

Mineralization at Star of Mangaroon consists of an anastomosing quartz vein with a strike of about 010°, and which dips to the east at an average of about 50° (Sullivan, 2001). The gold-bearing vein system is reportedly about 200 m long and 2–4 m wide. Mineralization is associated with pyrite, pyrrhotite, and arsenopyrite. Sullivan (2001) also reported mineralized zones running north from the mine consisting of stockworks rich in galena, malachite, barite, covellite, azurite, cuprite, gold, pyrite, pyrrhotite, and arsenopyrite.

Mineralized veins cut S_{2m}, and the strike of the mineralization at Star of Mangaroon is nearly perpendicular to that of the main structural grain in the region formed during D_{2m}. It is, however, subparallel to two milky quartz veins near Two Peaks–Mangaroon (**1441**) 9 km to the north-northwest. This orientation is also common to dolerite dykes of the c. 755 Ma Mundine Well dyke swarm. On MAROONAH, quartz veins and dykes in this orientation have been locally intruded along the same structures. It is, therefore, possible that some of the hydrothermal gold mineralization is Neoproterozoic (or younger) in age. The 010° trending structures could be antithetic (R_2) Riedel faults related to a southeast-trending dextral strike-slip shear zone active during the late stages of the Edmundian Orogeny (D_{2e}).

At the Diamond Gold Mine, gold mineralization is hosted by foliated to massive, medium-grained strongly pophyritic biotite monzogranite in the Minnie Creek batholith. Mineralized zones are 1–10 m wide and 20–200 m long (Regional Resources NL, 1987), with quartz veins striking east-southeast subparallel to the foliation. In outcrop, chrysocolla and malachite coatings are visible on foliation and fracture surfaces. The main ore minerals reported are galena, malachite, covellite, azurite, cuprite, pyrite, gold, and chrysocolla (Regional Resources NL, 1987). The age of the east-southeasterly and southeasterly striking shear zones and foliation in the Minnie Creek batholith is unknown. These structures also host barite mineralization (see **Industrial mineral — barite**), and may form a conjugate array related to dextral strike-slip faulting either during the Mangaroon Orogeny (D_{2m}) or the Edmundian Orogeny (D_{1e}).

* This mineral resource estimate is not compliant with the Joint Ore Reserves Committee (JORC) Code.

Base metals — copper, lead, and silver

In the immediate area around the Star of Mangaroon mine there is a cluster of polymetallic mineral occurrences, of which Star of Mangaroon South (**1437**) and Mangaroon (Pb)(**214**) are the most notable. Of similar style is Two Peaks–Mangaroon (**1441**) about 9 km to the northwest of the Star of Mangaroon. The Monte Carlo Mine (**221**) in the northwestern part of MAROONAH is the other main occurrence.

At Mangaroon (Pb) mineralization is hosted in strongly sheared metasedimentary rock and weakly sheared biotite granite. The foliation strikes east-southeast and dips steeply to the north. Small-scale tight folds with S-vergence plunge shallowly to the southeast and, along with an S–C fabric, suggest northeast-side up reverse faulting. Mining from 1956 to 1960 produced 11.61 t of concentrate containing 8.43 t Pb, 0.1418 t Cu, 2.924 kg Ag, and 1.524 kg Au (Blockley, 1971). Blockley (1971) reported that ore was mined from three en echelon quartz veins that strike north and dip 10–15° to the east; that is, in a similar orientation to the vein system at Star of Mangaroon. At Star of Mangaroon South, an east-southeast-striking quartz vein dips moderately to the north and contains malachite, pyrite, and chalcopyrite. At Two Peaks–Mangaroon, east-southeast-trending quartz veins that dip moderately to the north are hosted by megacrystic biotite monzogranite. The highest values from four rock-chip samples being 65% Pb, 10.5% Cu, 284 g/t Ag, and 100 g/t Au.

Monte Carlo consists of Pb–Ag–Cu(–U–Zn) mineralization in a steeply dipping quartz vein nearly 3 km long and striking north-northeast. Several shallow shafts and pits extend over about 120 m strike length in the southern half of the vein, and with more workings over a length of 90 m farther north (Ferguson, 1999). Production between 1948 and 1953 consisted of 47.7 t Pb and 8211 g Ag (Ferguson, 1999). Mineralization is developed in foliated granodiorite (*EmggGAB*), muscovite–biotite granite (*EU-gmv*), and muscovite–tourmaline pegmatite (*EU-gpt*). Some quartz displays colloform banding, and locally cavity fill textures are present. The age of mineralization is not known, but is younger than granites of the Durlacher Supersuite (i.e. less than c. 1620 Ma).

The Horse Well Cu–U prospect (**2156**) consists of three small pits each about 1 m deep and 5 m in diameter amongst sheetwash. Cuprite, chalcopyrite, chalcocite, malachite, chrysocolla, pyrite and minor chalcopyrite are associated with a vertical quartz vein that strikes east-northeast. The orientation of the vein is similar to that at Monte Carlo.

At the Mundong Well Northeast Cu prospect (**10507**) malachite veins are exposed in the walls of a small pit. Host rocks are variably sheared and consist of quartz-veined amphibolite (*EmwaGAB*) and muscovite–tourmaline pegmatite and monzogranite (*EU-gpt*). The foliation strikes east-southeast and dips steeply to the south-southwest parallel to regional S_{2n}. Laminated quartz veins contain seams of fine-grained tourmaline suggesting that mineralization may be related to granite of the Durlacher Supersuite.

At the Walker's Cu–U prospect (**1448**) two costeans contain exposures of weathered gneissic granodiorite (*EmggGAB*) intruded by veins and dykes of muscovite–tourmaline pegmatite (*EU-gpt*). Excavated material contains extensive copper staining in gossanous and strongly weathered material only; no copper staining was identified in fresher rock in the costeans.

In addition, there is minor copper mineralization exposed in a small bulldozed pit about 2 km southeast of White Quartz Well (MGA 361570E 7374800N). This mineralization is associated with a stockwork of quartz veins hosted by schlieric inclusion-rich granodiorite (*EU-ggvs*).

Energy mineral — uranium

Hydrothermal uranium mineralization is confined to the northern part of MAROONAH. The Mundong Well U(–Cu–Pb) prospect (**223**) consists of an east-southeasterly trending shear that dips steeply to the south-southwest in gneissic granodiorite (*EmggGAB*). At the Laura U–Cu–Pb prospect (**2157**) minor autunite, metatorbernite, torbernite, malachite, chrysocolla, chalcopyrite, and pyrite are developed over 600 m in a southeast-striking, steeply dipping ?shear zone. Milky quartz veins with epidote alteration are hosted in muscovite–biotite granite (*EU-gmv*) and muscovite–tourmaline pegmatite (*EU-gpt*). The strike of mineralization at Mundong Well and Laura is parallel to S_{2m}, a feature shared by the strong foliation at Mundong Well east.

The Pete and Georges Shear U–Cu–Pb prospect (**1445**) consists of a small pit with quartz veined and sheared muscovite–tourmaline pegmatite (*EU-gpt*), gneissic granodiorite (*EmggGAB*) and amphibolite (*EmwaGAB*). The quartz veins strike north-northeast and dip steeply to the north-northwest, similar to the quartz veins at Monte Carlo and Horse Well.

Industrial mineral — barite

A vein of barite (**1524**) was reported in Abeysinghe and Fetherston (1997), but its location is not precisely known. The barite outcrop is about 4 m wide and 90 m long, and strikes 160° with a steep dip to the west (Beesley, 1971 in Abeysinghe and Fetherston, 1997). At the reported coordinates no evidence of drilling is apparent, but there are several southeast- and east-southeast-striking shear zones and quartz veins with minor barite in the vicinity.

Mineralization associated with carbonatitic and alkaline igneous intrusions

Speciality metals — rare earth elements

Rocks of the Gascoyne Complex in the centre of the southern part of EDMUND (1:100 000 sheet) are host to numerous REE prospects related to ferruginous veins (*zi*) (namely, the Yangibana ironstones and ferrocarbonatites of Pearson (1996)). The ironstones are associated with haloes, up to 100 m wide, of K-feldspar(–magnetite) alteration and veinlets. The ironstones contain anomalous amounts of lead, zinc, barium and rare earth elements. Drilling results were used to estimate an 'ore block' of 3.5 million tonnes at an average grade of 1.7% rare earth oxides* (Hurlston Pty Ltd, 1989). Most of the individual prospects have ore zones ranging from about 100 to 500 m in strike length, with resources of 1300–7000 tonnes of rare earth oxide, and grades of 0.85 – 2.3% total REE oxide† (WAMIN database). The Yangibana North prospect (**1146**) is somewhat larger than the remainder, consisting of four separate pods totalling about 18 500 tonnes of REE oxide†.

Pearson (1996) has interpreted the veins as the high-level expression of a deeper, inferred carbonatite–alkaline silicate magma intrusion. The age of magmatism, and hence mineralization, is interpreted to be c. 1250 Ma; this age is based on SHRIMP U–Pb analysis of a single zircon crystal from an intrusion at Bald Hill with which the ferrocarbonatites are thought to be associated (Pearson, 1996).

Orthomagmatic mafic and ultramafic mineralization

On MANGAROON there is only one occurrence (**1981**) of this type, where rock-chip samples with anomalous Pt, Pd, Au, Cu, and Ni were collected from the margin of a 40 m-thick dolerite dyke. Mineralization at the Diamond Gold Mine was previously considered part of this mineralization style (Cooper et al., 1998b), but it is hosted in granitic rocks and is probably unrelated to much younger nearby dolerite dykes.

Pegmatitic mineralization

Precious mineral — beryl

One occurrence of this mineralization style on EDMUND is an unconfirmed occurrence of Beryl (**227**) south of Maroonah Homestead. The occurrence was shown on the first edition of EDMUND (Daniels, 1967), but no details regarding its host rock or origin are known.

Mineralization in the regolith

Alluvial to beach placers

Precious metal — gold

Two unnamed occurrences of gold in alluvium or sheetwash (**1442**, **1443**) are present in the Pritchard Well area on southern MANGAROON.

Calcrete

Energy mineral — uranium

Calcrete-hosted uranium occurrences over Gascoyne Complex rocks are present at Fraser Creek (**2163**) on

* This mineral resource estimate is not compliant with the Joint Ore Reserves Committee (JORC) Code.

† This reserve estimate is not compliant with the Joint Ore Reserves Committee (JORC) Code.

EDMUND (1:100 000 sheet), and at Pooranoo Well (**2160**) and Alma Well (**2161**) on MANGAROON.

Bangemall Supergroup

The Bangemall Supergroup on EDMUND hosts numerous prospects and occurrences of a variety of commodities including base metals, gold, manganese, talc, asbestos, uranium, and diamonds, and one operating building-stone quarry. Mineralization styles include vein and hydrothermal, stratabound sedimentary, calcrete-hosted, alluvial placer, undivided sedimentary, orthomagmatic, kimberlite- and lamproite-hosted mineralization, and mineralization in the regolith.

Vein and hydrothermal mineralization

Base metals — copper, lead, and silver

Copper mineralization, with or without associated lead and silver, is typically found in pyritic black shales of the Kiangi Creek and Discovery Formations (Blue Rocks **7478**, Mount Palgrave **219**, High Range **1408**), but also occurs in dolostones of the Irregully Formation (Joy Helen). The Blue Rocks prospect (Cu) consists of secondary malachite veins exposed in costeans and shafts excavated in the Kiangi Creek Formation during the 1960s. The cupreous ore was mainly used for agricultural purposes. In the Mount Palgrave area (Pb, Ag, Cu), quartz veins containing galena and chalcopyrite were originally considered to be within the Kiangi Creek Formation (Blockley, 1971), but are now known to be hosted within the Discovery Formation. One sample assayed 66.2% Pb, 195.01 g/t Ag, and 0.79% Cu (Blockley, 1971). Minor copper staining is exposed in two pits in the Kiangi Creek Formation at High Range (Cu), and uranium and copper are associated with veinlets in a shear zone in the Irregully Formation (Ferguson, 1999). The Joy Helen prospect (Cu, Pb, Ag) (**88**) has generally been interpreted as a Mississippi Valley-type deposit, with drill intersections up to 1.5 m at 13.7% Pb and 1.6% Cu. Mineralization in several shallow shafts occurs as three separate lodes comprising quartz, azurite, chrysocolla, galena, cuprite, cerussite, malachite, sphalerite, and chalcopyrite. At Latham prospect (Pb, Cu, Ag) (**87**), a quartz vein up to 0.5 m wide is enriched in chrysocolla, galena, and malachite. Rock-chip samples returned grades of 3.53% Pb, 0.03% Zn, and 13.06 g/t Ag (Daniels, 1969; Ferguson, 1999).

Stratabound sedimentary mineralization

Base metals — copper, lead, zinc, and silver

Stratabound base metal mineralization is by far the most common style within the Bangemall Supergroup, and is typically hosted in pyritic carbonaceous shales in the Irregully, Gooragoora, Kiangi Creek, and Discovery Formations.

Drill intersections in the Irregully Formation on the Pingandy Shelf include 4 m at 0.56% Pb in drillhole ICO28 (Pb) (**243**) and 6 m at 0.5% Pb in pyrite in drillhole ICO12 (Pb) (**244**). In the same area, patchy ironstone gossans are associated with pyritic black shales in the Gooragoora Formation, with anomalous base metals over a thickness of 85 m (Zn, Cu) (**2007**). Base metal values in the associated shales are low, with the best values of 4 m at 0.54% Zn and 703 ppm Cu coming from drillhole CAP8. Ore minerals include pyrite, pyrrhotite, sphalerite, and antimony. However, the majority of this style of mineralization occurs in the Mount Palgrave (Prospects 1, 2, and 3A) and Illirie Creek (Illirie Creek and Anomalies A, C(A), and C(B)) areas.

In the Mount Palgrave area, copper and minor associated zinc mineralization is hosted by pyritic black shales of the Kiangi Creek Formation (Prospect 3A) and Discovery Formation (Prospect 1, 2). Prospect 3A (Cu, Zn) (**1468**) is located in pyritic black shale near the contact with the Discovery Formation. Copper is mainly found in oxidized surface rocks, whereas zinc is present at depth with the best intersection in DH36 of 2 m at 1.3% Zn. Grades of sporadic surface mineralization in the vicinity of Prospect 1 (Cu) (**1469**) range from 1–5% Cu in disseminations and joint fillings of malachite and azurite. Prospect 2 (Cu, Zn) (**217**) is characterized by near surface enrichment of stibarsen, diopside, malachite, azurite, chalcopyrite, marcasite, pyrite, covellite, and sphalerite in pyritic black shales to a depth of 15 m. Surface chip samples yielded 5 m at 1.2% Cu, and the best intersection in diamond drillhole DDH12 was 6 m at 3% Cu (Blockley, 1971; Davy, 1980). In the same area, a drillhole collared in Kiangi Creek Formation west of Mount Palgrave (Cu) (**220**) yielded 6 m at 3% Cu and 1 m at 2.4% Zn.

Mineralization in the Illirie Creek area is hosted within carbonaceous pyritic shale of the Discovery Formation, and the associated oxidized zone. The Illirie Creek occurrence (Cu) (**10610**) consists of three costeans that intersect stratabound secondary copper mineralization consisting of malachite and azurite on bedding planes and along joint surfaces in laminated siltstone and fine-grained sandstone. Surface mineralization in veins up to 5 mm thick at Anomaly A (Cu) (**1467**) and Anomaly C(A) (Cu, Zn) (**48**) has returned surface values up to 5.6% Cu. The best drillhole intersection at Anomaly C(A) in drillhole CA5 was 7 m at 3% Cu, and drilling at the nearby Anomaly C(B) (Cu, Zn) (**216**) returned values of up to 0.37% Zn in the oxidized zone. Minor stratiform mineralization in the Kiangi Creek Formation is also present at High Range (Cu, Zn, U) (**1408**) in the Mangaroon Syncline where surface samples containing 0.56% Cu, 0.01% Pb, and 0.05% Zn have been reported (Daniels, 1966; Ferguson, 1999).

Construction material — marble

Green, stromatolite-bearing dolomitic marble, suitable as a dimension stone, occurs in the contact aureole of a dolerite sill intruded into the Irregully Formation on MAROONAH. There are two operating open pits at Sheela Bore (**15555**) that produced 434 t in 2002–03, and further resources are present at the nearby Maroonah prospect (**15554**).

Industrial minerals — talc and asbestos

In addition to green dolomitic marble, the margins of dolerite sills in the Sheela Bore area also locally contain small occurrences of talc and asbestos. The main occurrences are at Sheela Bore Talc (Talc, Asbestos) (**226**), Sheela Bore north (Talc, Asbestos) (**829**), and Henry River West 1 and 2 (Talc) (**15645**, **15646**). In this area, stromatolitic dolostones of the Irregully Formation host small lenses and veins of talc, serpentine, chrysotile and wollastonite, none of which are of commercial quality (Daniels, 1969; Abeysinghe, 1996). Asbestos also occurs in dolomitic rocks of the Devil Creek Formation on Elliott Creek (**2151**) and Edmund (1:100 000) (**211**) (Daniels, 1969).

Mineralization in the regolith

Regolith — calcrete

Energy mineral — uranium

Calcrete-hosted uranium deposits are common in the Telfer River area on Maroonah (Telfer River (**2166**), Telfer South (**2158**), PDH50 Anomaly (**224**), Zone 4 (**225**), and Maroonah (**13409**)), and along the Lyons River on Edmund (Gifford Creek (**2162**)). The main ore mineral is carnotite which occurs in calcrete or carbonaceous shale in Tertiary channels and in fractures in underlying carbonaceous siltstones. Autunite is present as an accessory mineral at Zone 4. The primary source is inferred to be Gascoyne Complex granites and basal Bangemall Supergroup sandstones. The highest grab sample in a trench at Telfer River contained 8691 ppm U_3O_8, whereas a surface sample from Maroonah assayed 292 ppm U_3O_8 with 10.2% Cu and 600 ppm Pb. Diamond drillhole PDH106 at the PDH50 Anomaly intersected 7 m at 700 ppm U_3O_8 including 1 m at 1180 ppm, and drillhole DDH11 at Zone 4 intersected 2 m at 809 ppm U_3O_8.

Regolith — alluvial placer

Precious mineral — diamond

Microdiamonds have been recovered from stream-sediment samples in three localities on Edmund (Cooper et al., 1998b). One fine diamond was recovered from a 20 kg stream-sediment sample in the Godfrey Range (**212**). Detailed follow-up sampling did not identify the source or any other diamonds. Placer diamonds on Edmund have been found in close association with the Eersteling Lamproites (Rohde, 1993; Cooper et al., 1998b). One macrodiamond as well as chromite and pyrope crystals were recovered from a stream draining the Kiangi Creek Formation (**1938**) and containing abundant lamproitic siltstone float. Chromite crystals and one microdiamond were also recovered from a second sample in this area (**1937**) which was taken within 100 m of a lamproite dyke.

Regolith — residual and supergene

Steel industry metal — manganese

There are numerous small occurrences of manganese in the Bangemall Supergroup, mainly associated with the weathering of laminated ferruginous siltstones or ferroan dolostone. The most conspicuous occurrences are associated with the Devil Creek Formation (**2150**, **2147**, **2148**) and Ullawarra Formation (**2149**, **242**) (Daniels, 1969).

Base metal — lead

Although the Joy Helen prospect (Cu, Pb, Ag) (**88**) has generally been interpreted as a Mississippi Valley-type deposit, most of the galena at surface is hosted within calcrete and silcrete developed on top of the Irregully Formation. This observation supports the interpretation of Chuck (1984) that the mineralization is hosted within an ancient weathering profile. Surface samples contain up to 35% Pb, 5% Cu, and 19 g/t Ag; however, drill intersections are less encouraging with 1.5 m at 13.7% Pb and 1.5 m at 11.5% Pb and 1.6% Cu having been reported (Ferguson, 1999).

Mineralization associated with kimberlite and lamproite intrusions

Precious mineral — diamond

One microdiamond, weighing 0.000017 carat, has been recovered from a thin kimberlitic dyke (<0.5 m) intruded en echelon into the Devil Creek Formation over a strike length of 2 km (**2009**) on Maroonah (Duncan, 1993).

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Appendix 1

1:100 000 Geological Information Series Western Capricorn Orogen — Datasets

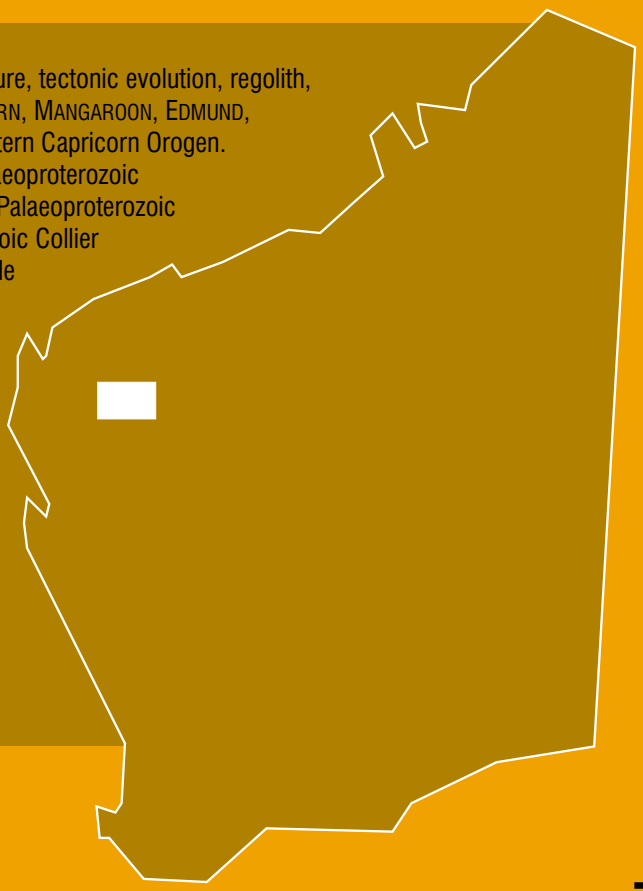
Geology
Surface geology and structure
GSWA geochronology sample locations, and summaries
Interpreted bedrock geology and structure
Petrographical sample locations, and summaries
Project area
Extracts from WAROX database
Cross section geology
Tectonic units

Mineralization and exploration
Mineral exploration activity (EXACT) database points, lines, and polygons
Mineral deposits from MINEDEX database
Tenements from TENEGRAPH database
Mineral deposits and occurrences from WAMIN database
Indexes of aeromagnetic data from the MAGIX database

Topography
WA coast and State boundary
Contour lines
Cultural localities
Major rivers and drainage lines
Major water bodies
Hydrographical point features
1:100 000 map sheet index
1:250 000 map sheet index
Major topographical localities
Major roads and tracks
Major townsite locations

Georeferenced images
Aster satellite data bands 8, 3, and 1 covering the project area
1:100 000 Geological series map images
1:250 000 Geological series map image
Gravity image at 800 m pixels covering the project area
Landsat TM satellite image covering the project area
Total magnetic intensity image at 125 m spacing covering the project area
SPOT image covering the project area

These Explanatory Notes describe the stratigraphy, structure, tectonic evolution, regolith, and mineralization of the MAROONAH, ULLAWARRA, CAPRICORN, MANGAROON, EDMUND, and ELLIOTT CREEK 1:100 000 map sheet areas in the western Capricorn Orogen. The major tectonic units within the study area are the Palaeoproterozoic Ashburton and Blair Basins, and Gascoyne Complex, the Palaeoproterozoic to Mesoproterozoic Edmund Basin, and the Mesoproterozoic Collier Basin. The Ashburton and Blair Basins comprise low-grade metasedimentary and metavolcanic rocks. The Gascoyne Complex is composed of meta-igneous and metasedimentary rocks, which are extensively intruded by large volumes of granite. The Edmund and Collier Basins are composed of sedimentary rock interlayered with two generations of dolerite sills. Rocks of the Ashburton and Blair Basins and the Gascoyne Complex have been deformed during The 1830–1780 Ma Capricorn Orogeny. Gascoyne Complex rocks have also been affected by the 1680–1620 Ma Mangaroon Orogeny. The area is prospective for gold, copper, lead, silver, zinc, barite, uranium, and diamond.



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Geology of the Maroonah, Ullawarra, Capricorn, Mangaroon, Edmund, and Elliott Creek 1:100 000 sheets

These Explanatory Notes are published in digital format (PDF) and are available online at: www.doir.wa.gov.au/gswa/onlinepublications. Laser-printed copies can be ordered from the Information Centre for the cost of printing and binding.

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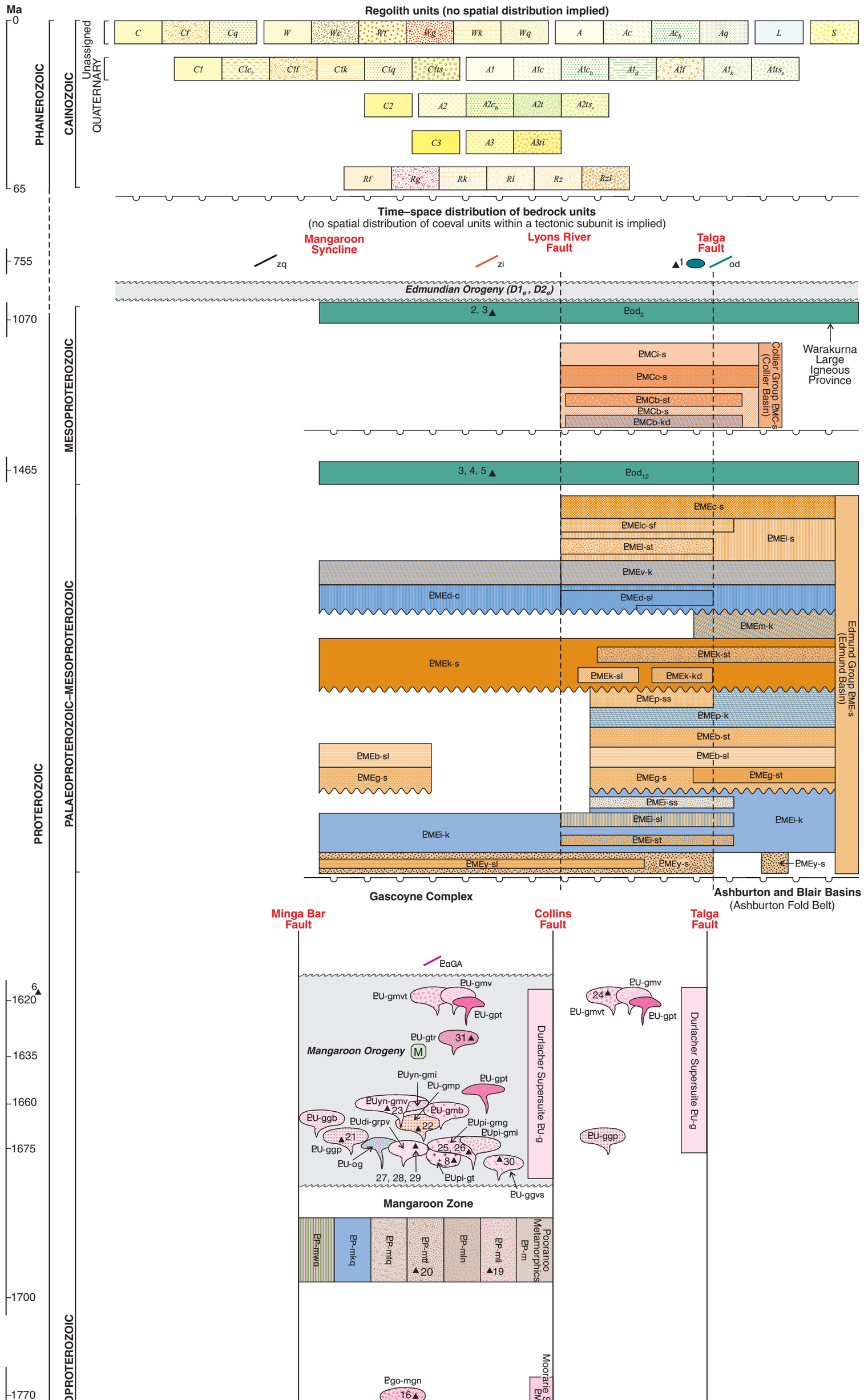
EXPLANATORY NOTES



Rock unit descriptions

Colluvial units, generation unassigned

C	Proximal mass-wasting deposits in an unconsolidated to partly consolidated, weakly cemented and compacted silt and sand matrix; includes ferruginous deposits
Cf	Ferruginous rubble and scree, unconsolidated
Cq	Predominantly quartz-rich silt, sand, and gravel, derived from quartz veins and quartz-rich rock

Sheetwash units, generation unassigned

W	Sandy and clayey distal sheetwash and slope deposits, no clearly defined drainage
Wc	Clay, silt, and sand from saprolite and saprock
Wf	Ferruginous sand and silt
Wg	Quartzofeldspathic sand and silt
Wk	Distal sheetwash with calcrete cutans and carbonate cement
Wq	Predominantly quartz-rich silt, sand, and gravel, derived from quartz veins and quartz-rich rock

Alluvial units, generation unassigned

A	Silt, sand, and gravel in drainage channels and adjacent to floodplains; includes ferruginous deposits
Ac	Clay-rich alluvium
Acb	Swelling clay (gilgai)
Aq	Alluvium with abundant vein-quartz fragments

Lacustrine unit, generation unassigned

L	Unconsolidated, fine-grained deposits in claypans, perennial lakes, and swamps; low-lying areas with internal drainage; usually thickly vegetated

Sandplain unit, generation unassigned

S	Quartz sand of mixed origin; includes residual and eolian sands

Colluvial units, third generation

C1	Quartz and rock fragments in an unconsolidated silt and sand matrix; includes ferruginous deposits
C1cb	Swelling clay (gilgai) and rock fragments, mostly developed over dolerite
C1f	Unconsolidated ferruginous rubble and scree
C1k	Quartz and rock fragments in an unconsolidated silt and sand matrix; contains calcrete cutans and carbonate cement
C1q	Ferruginous rubble and scree, unconsolidated
C1tss	Sandstone fragments in a silt and sand matrix

Alluvial units, third generation

A1	Unconsolidated silt, sand, and gravel in active drainage channels; includes ferruginous deposits
A1d	Unconsolidated, mainly fine-grained deposits in drainage depressions
A1t	Silt, sand, and gravel as stream-bank deposits marginal to active channels, incised by present-day drainage
A1c	Clayey alluvium developed on alluvial flats
A1cb	Swelling clay (gilgai) developed on alluvial flats
A1f	Unconsolidated ferruginous silt, sand, and gravel
A1tss	Sandstone fragments in an unconsolidated silt and sand matrix

Colluvial unit, second generation

C2	Quartz and rock fragments in a partly consolidated silt and sand matrix

Alluvial units, second generation

A2	Partly consolidated silt, sand, and gravel; partly dissected by present-day drainage
A2cb	Swelling clay (gilgai), commonly developed near dolerite
A2t	Alluvium with abundant lithic clasts
A2tss	Sandstone fragments in a weakly cemented and compacted silt and sand matrix

Colluvial unit, first generation

C3	Quartz and rock fragments in a weakly cemented and compacted silt and sand matrix; deeply dissected valley-fill deposits

Alluvial units, first generation

A3	Weakly cemented and compacted silt, sand, and gravel; deeply dissected by present-day drainage
A3ti	Sand and gravel with ferruginous cement; deeply dissected by present-day drainage

Residual or relict units

Rf	Ferruginous deposits, including lateritic, ferruginous, and manganiferous duricrust
Rg	Weathered quartzofeldspathic rock with locally derived sand and sandy clays
Rk	Calcrete developed in and adjacent to alluvial channels; locally silicified; disected by major present-day drainage lines
Rl	Saprolite and saprock of uncertain protolith
Rz	Silcrete and brecciated siliceous caprock
Rzi	Ferruginous silcrete and brecciated siliceous caprock

zq	Quartz veins, of various ages
zi	Ferruginous veins and linear alteration zones containing hematite–magnetite–chalcedony rock, saussiterized feldspar–quartz–phlogopite–geothite–hematite–chalcedony rock, and quartz–sericite–phlogopite rock with both clay and opaque minerals
od	Dolerite dykes, sills, and small intrusions, of various ages; one suite dated at c. 755 Ma[1]; includes minor quartz diorite, tonalite, and biotite monzogranite

Epod2	Dolerite and gabbro sills intruded into **Edmund and Collier Groups**

EMC-s	**Collier Group:** undivided; thin- to thick-bedded sandstone, quartz sandstone, conglomerate, siltstone, mudstone, thin- to thick-bedded dololutite, dolomitic siltstone, and dolarenite; minor chert
EMCi-s	**ILGARARI FORMATION:** siltstone, mudstone, and fine-grained sandstone
EMCc-s	**CALYIE FORMATION:** quartz sandstone, siltstone, mudstone, conglomerate, and dolostone
EMCb-s	**BACKDOOR FORMATION:** siltstone, mudstone, and thin- to thick-bedded sandstone; minor chert and dolostone
EMCb-st	Thin- to thick-bedded sandstone and siltstone
EMCb-kd	Thin- to thick-bedded dololutite, dolomitic siltstone, dolarenite, and siltstone

Epod1,2	Dolerite and gabbro sills intruded into **Edmund Group**; oldest suite (Epod1) dated at c. 1465 Ma, and youngest suite (Epod2) dated at c. 1070 Ma[3,4]

EME-s	**Edmund Group:** undivided; sandstone, siltstone, mudstone, dolostone, and chert; minor conglomerate
EMEc-s	**COODARDOO FORMATION:** thin- to very thick bedded lithic quartz sandstone; minor siltstone and mudstone
EMEl-s	**ULLAWARRA FORMATION:** siltstone, fine-grained sandstone, dolostone, and chert; intruded by numerous dolerite sills (Epod1,2)
EMEic-sf	**Curran Member:** siltstone and fine- to course-grained sandstone; locally intuded by dolerite sills; has gradational contacts with underlying **ULLAWARRA FORMATION** and overlying **COODARDOO FORMATION**
EMEl-st	Sandstone, conglomerate, siltstone, and dolostone
EMEv-k	**DEVIL CREEK FORMATION:** laminated dolostone and dolomitic siltstone; local thick-bedded dolorudite
EMEd-c	**DISCOVERY FORMATION:** massive or laminated chert, silicified mudstone, and siltstone; local silicified sandstone and conglomerate
EMEd-sl	Siltstone
EMEm-k	**MUNTHARRA FORMATION:** thin- to thick-bedded dolostone and stromatolitic dolostone, and sandstone and siltstone
EMEk-s	**KIANGI CREEK FORMATION:** siltstone, mudstone, and thin- to very thick bedded quartz sandstone; minor dolostone and conglomerate
EMEk-st	Medium to very thick bedded quartz sandstone and siltstone
EMEk-kd	Dolostone, siltstone, and sandstone
EMEk-sl	Siltstone; minor fine-grained sandstone
EMEp-k	**CHEYNE SPRINGS FORMATION:** dololutite, dolarenite, dolorudite, mudstone, siltstone, and minor sandstone
EMEp-ss	Thin- to thick-bedded sandstone and siltstone; minor dolostone
EMEb-sl	**BLUE BILLY FORMATION:** siltstone and mudstone; minor thin- to thick-bedded sandstone; locally sulfidic
EMEb-st	Medium- to thick-bedded sandstone and siltstone; locally sulfidic
EMEg-s	**GOORAGOORA FORMATION:** fine- to coarse-grained sandstone and siltstone; minor conglomerate, dolostone, and dolomitic siltstone
EMEg-st	Medium- to thick-bedded sandstone and siltstone
EMEi-k	**IRREGULLY FORMATION:** stromatolitic and non-stromatolitic dolostone, dolomitic siltstone, quartz sandstone, and conglomerate
EMEi-ss	Sandstone and siltstone; minor dolostone
EMEi-st	Sandstone, conglomerate, siltstone, and dolostone
EMEi-sl	Siltstone, sandstone, and dolomite
EMEy-s	**YILGATHERRA FORMATION:** sandstone, siltstone, conglomerate, and dolostone
EMEy-sl	Siltstone and sandstone

EaGA	Ultramafic sills and dykes

EU-g	**Durlacher Supersuite:** undivided; monzogranite and granodiorite, and minor tonalite and syenogranite
EU-gpt	Tourmaline–muscovite pegmatite and coarse-grained granite, and fine-grained, leucocratic tourmaline–muscovite monzogranite
EU-gmv	Cream, medium-grained muscovite–biotite granodiorite and monzogranite; equigranular or weakly porphyritic
EU-gmvt	Cream, medium-grained muscovite–tourmaline(–biotite) monzogranite; locally garnet bearing
EU-gtr	Biotite–muscovite–cordierite tonalite with abundant inclusions of pelitic schist, biotite schist, and calc-silicate gneiss
EUyn-gmv	**YANGIBANA GRANITE:** equigranular to locally weakly porphyritic, medium-grained biotite–muscovite monzogranite; locally contains tourmaline; may contain inclusions of metasedimentary rock or porphyritic granodiorite
EUyn-gmi	Equigranular to weakly porphyritic, medium-grained biotite–muscovite(–tourmaline) monogranite with abundant inclusions of metasedimentary rock or porphyritic granodiorite
EU-gmb	Equigranular, medium-grained biotite monzogranite
EU-ggb	Mesocratic, medium-grained, equigranular biotite granodiorite
EU-gmp	Cream, massive, medium-grained, porphyritic biotite(–muscovite) monzogranite
EU-ggp	Grey, massive, medium-grained, porphyritic biotite granodiorite
EU-og	Massive metagabbro with xenocrysts of quartz and K-feldspar
EUdi-grpv	**DINGO CREEK GRANITE:** porphyritic biotite–muscovite granite; fine- to medium-grained with thin, tabular K-feldspar phenocrysts defining a trachytic texture
EUpi-gmg	**PIMBYANA GRANITE:** massive, medium-grained, megacrystic and porphyritic biotite(–muscovite) monzogranite; tabular megacrysts of K-feldspar up to 7-cm long; minor fine- to medium-grained biotite tonalite and granodiorite
EUpi-gmi	Porphyritic, medium- to coarse-grained biotite–muscovite granodiorite to syenogranite, with abundant xenoliths of metasedimentary and metamafic rocks; abundant large tabular phenocrysts of K-feldspar; contains even textured, fine- to medium-grained biotite monzogranite to tonalite and quartz diorite
EUpi-gt	Equigranular, fine- to medium-grained biotite tonalite and granodiorite
EU-ggvs	Schleiric, medium-grained biotite–muscovite granodiorite with abundant inclusions of metasedimentary rock and augen gneiss; minor flow-banded biotite–muscovite monzogranite with inclusions

EP-m	**Pooranoo Metamorphics:** undivided; pelitic gneiss and granofels and metamorphosed feldspathic sandstone and psammitic schist
EP-mli	Migmatitic pelitic gneiss (diatexite and metatexite migmatite)
EP-mln	Pelitic gneiss and granofels composed of biotite–muscovite–quartz–plagioclase–sillimanite; also includes migmatitic pelitic gneiss
EP-mtf	Metamorphosed felspathic sandstone and psammitic schist; includes interbedded pelite, quartzite, and metamorphosed granule conglomerate
EP-mtq	Metamorphosed cobble and pebble conglomerate, quartz sandstone, and pebbly quartz sandstone
EP-mkq	Calc-silicate gneiss and schist
EP-mwa	Amphibolite and actinolite–plagioclase schist

EM-g	**Moorarie Supersuite:** undivided; monzogranite, granodiorite, and tonalite
Ego-mgn	**GOOCHE GNEISS:** strongly foliated, porphyritic granodiorite and monzogranite, and augen gneiss
EM-gma	Fine-grained, leucocratic biotite monzogranite
EM-gml	Massive, equigranular, medium-grained, leucocratic biotite monzogranite
EM-gmp	Massive, medium-grained, porphyritic biotite monzogranite; round phenocrysts of K-feldspar up to 5 cm in diameter; minor fine- to medium-grained, sparsely porphyritic monzogranite
EM-gge	Equigranular to sparsely porphyritic, medium-grained biotite(–muscovite) granodiorite
EM-gti	Medium- to coarse-grained tonalite with abundant mafic clots; lesser medium-grained granodiorite with scattered mafic clots
EmggGAB	Foliated and gneissic granodiorite and tonalite; weakly pegmatite banded
EmgmGAB	Pale grey, foliated and gneissic monzogranite

EmsqmGAL	Quartz–mica schist and metamorphosed, fine-grained sandstone

EmdGAB	Undivided metasedimentary rock and amphibolite
EmlsGAB	Pelitic to psammitic schist; includes muscovite–quartz–andalusite–garnet–plagioclase–biotite schist
EmkqGAB	Calc-silicate gneiss and schist
EmiGAB	Metamorphosed banded and granular iron-formation
EmwaGAB	Amphibolite and hornblende schist

ER-s	**Capricorn Group:** undivided; conglomerate, ferruginous and quartzitic sandstone, ferruginous siltstone and mudstone, dolostone, and felsic volcanic rock
ERm-s	**MOOLINE FORMATION:** fine to very coarse grained sandstone, siltstone, conglomerate, dolostone, dolomitic siltstone, and felsic volcaniclastic sandstone
ERm-kd	Thin to very thick bedded dolostone, dolomitic sandstone, dololutite, dolorudite, and quartz sandstone
ERm-sc	Polymictic, clast- and matrix-supported pebble to cobble conglomerate, pebbly sandstone, coarse-grained sandstone, dolomitic sandstone, and dolostone
ERm-sl	Siltstone and fine-grained sandstone, medium to very coarse grained sandstone, dolomitic siltstone, dolostone, and felsic volcaniclastic sandstone
ERbk-f	**Koonong Member:** thin- to thick-bedded, massive to planar laminated felsic volcaniclastic rock, and accretionary lapilli tuff
ERb-s	**BYWASH FORMATION:** thin to very thick bedded, medium to very coarse grained sandstone, dolomitic sandstone, dolostone, dololutite, dolorudite, and felsic volcanic rock
ERb-sl	Siltsone dolostone, and fine- to coarse-grained sandstone

EW-s	**Wyloo Group:** undivided; siltstone, mudstone, sandstone, dolostone, conglomerate, felsic and mafic volcanic rock, and banded iron-formation; lower greenschist facies
EWa-mh	**ASHBURTON FORMATION**, metamorphosed: interbedded psammite and pelite; includes quartz–muscovite–biotite–cordierite–andalusite–garnet schist and quartz–muscovite–biotite–staurolite schist; upper greenschist to amphibolite facies
EWa-s	**ASHBURTON FORMATION:** siltstone, thin to very thick bedded lithic quartz sandstone, pebble to cobble conglomerate, and felsic volcanic rock; lower greenschist facies
EWa-sc	Pebble to cobble conglomerate, thin to very thick bedded sandstone, and siltstone; lower greenschist facies
EWa-f	Thin to very thick bedded, massive to laminated felsic volcaniclastic sandstone, and siltstone; lower greenschist facies
EWa-st	Thin- to very thick bedded lithic sandstone, and siltstone, pebbly sandstone, and conglomerate; lower greenschist facies
EWd-k	**DUCK CREEK DOLOMITE:** thin- to thick-bedded laminated dolostone

Metamorphic grade
L Low
M Medium

Orogeny
Unconformity
Disconformity

TIME–SPACE PLOT FOR THE MAROONAH, ULLAWARRA, CAPRICORN, MANGAROON, EDMUND, AND ELLIOTT CREEK 1:100 000 SHEETS

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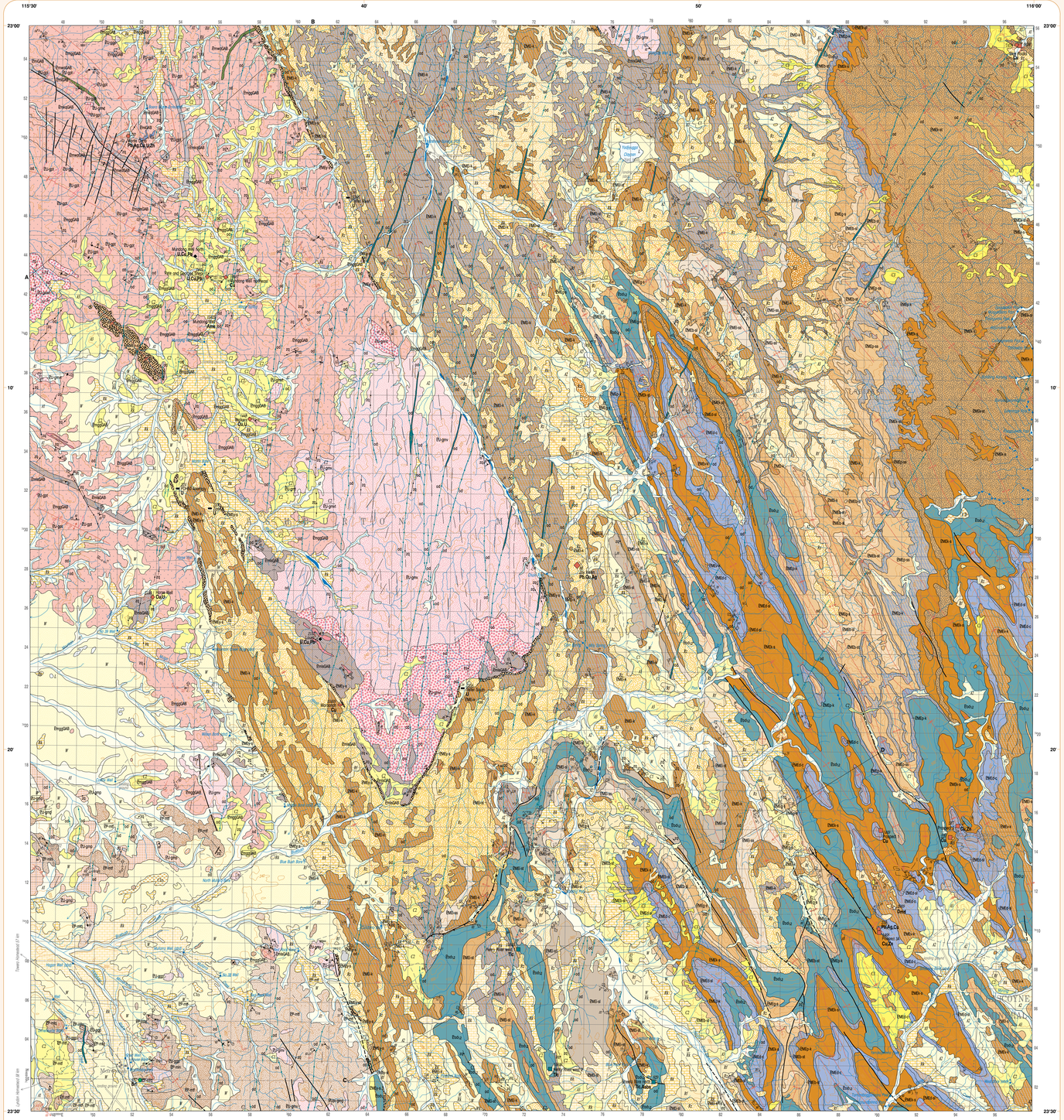
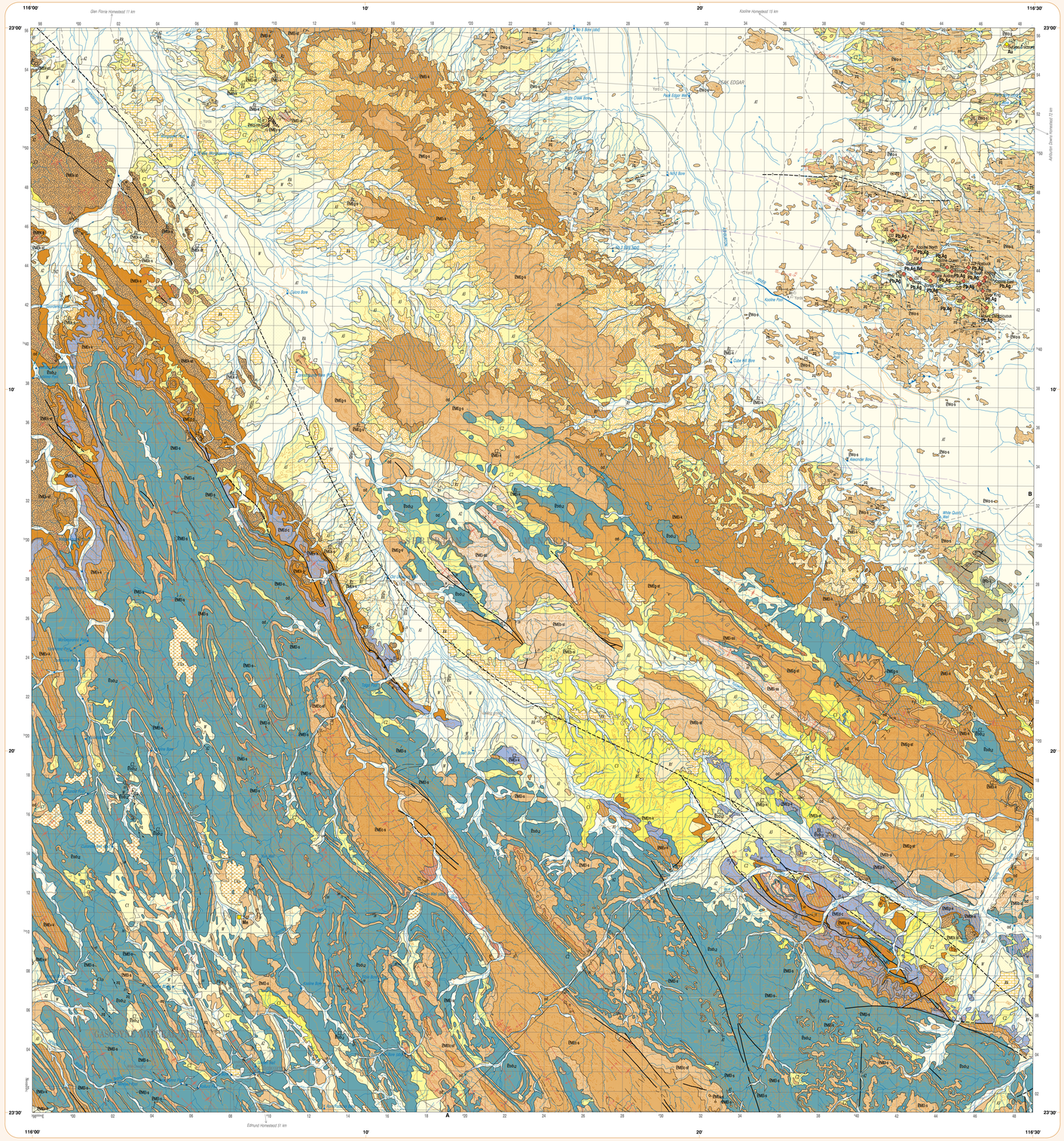
MAROONAH

AUSTRALIA 1 : 100 000 GEOLOGICAL SERIES — **GEOLOGICAL SURVEY OF WESTERN AUSTRALIA** — **SHEET 2051**


115°30'
40'
50'
116°00'
23°00'
20'
10'
23°30'
Mundong Well
Mundong Well Outhouse
Mundong Well Airstrip
Mundong Well Tank
Mundong Well Dam
Mundong Well Bore
Mundong Well Yard
Mundong Well Quarry
Mundong Well Windpump
Mundong Well Yard Bore
Mundong Well Yard Windpump
Mundong Well Yard Tank
Mundong Well Yard Dam
Mundong Well Yard Quarry
Mundong Well Yard Airstrip
Mundong Well Yard Outhouse

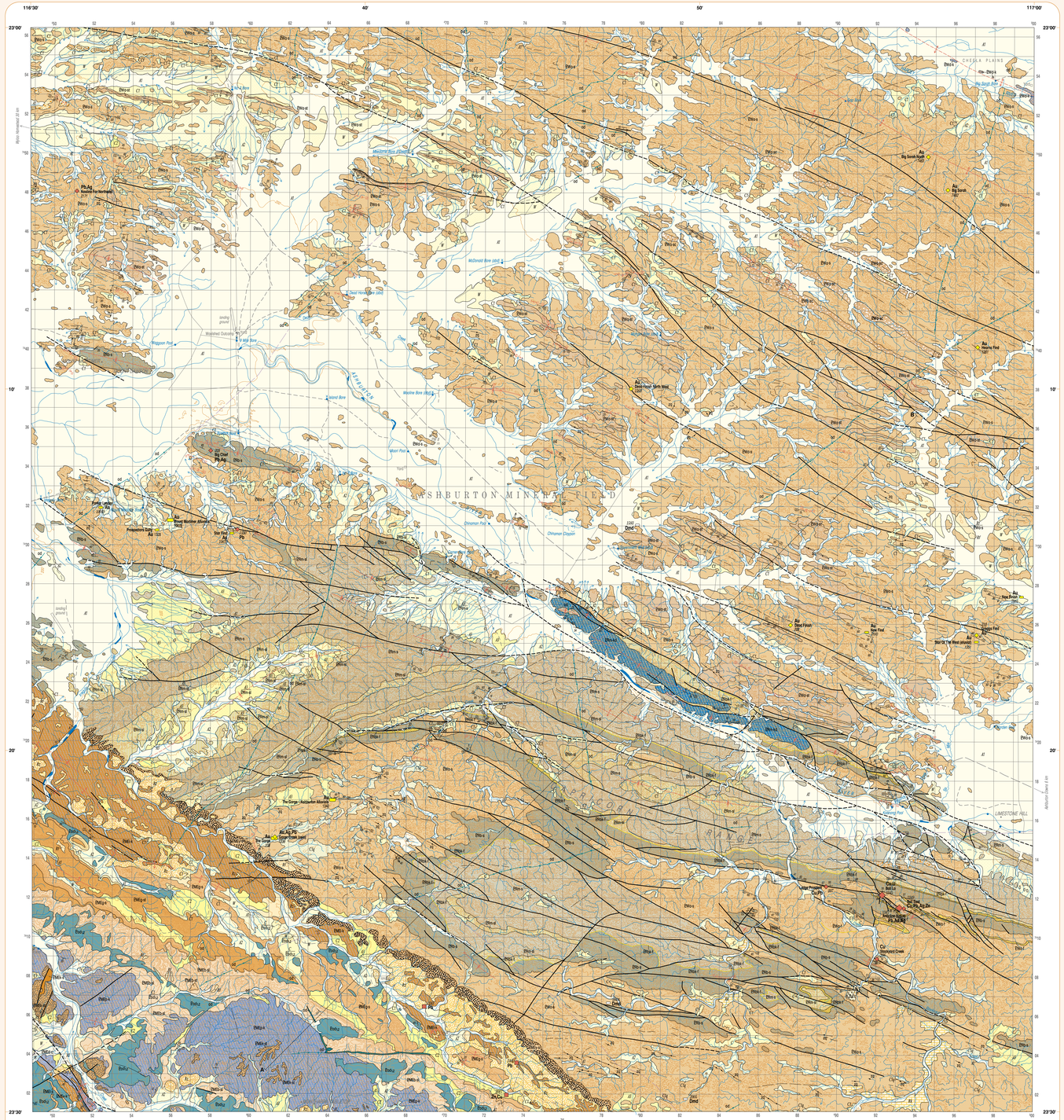
ULLAWARRA

AUSTRALIA 1 : 100 000 GEOLOGICAL SERIES — **GEOLOGICAL SURVEY OF WESTERN AUSTRALIA** — **SHEET 2151**


116°00'
10'
20'
116°30'
23°00'
10'
20'
23°30'
Glen Florie Homestead 11 km
Koolline Homestead 18 km
Edmund Homestead 51 km
Ullawarra Dam
Yerbo
Yerbo Creek
Peak Edger Well
Peak EDGAR
Wells Creek Bore
Kirk Bore
Kirk Well
Big Tank
Big Tank Well
Quarry Bore
Quarry Well
Koolline Pool
Koolline Pool Yards
Koolline Well
Koolline Queen
Koolline Queen Well
Koolline Queen Bore
Koolline Queen Yards
Koolline Queen Dam
Koolline Queen Tank
Koolline Queen Yards

CAPRICORN

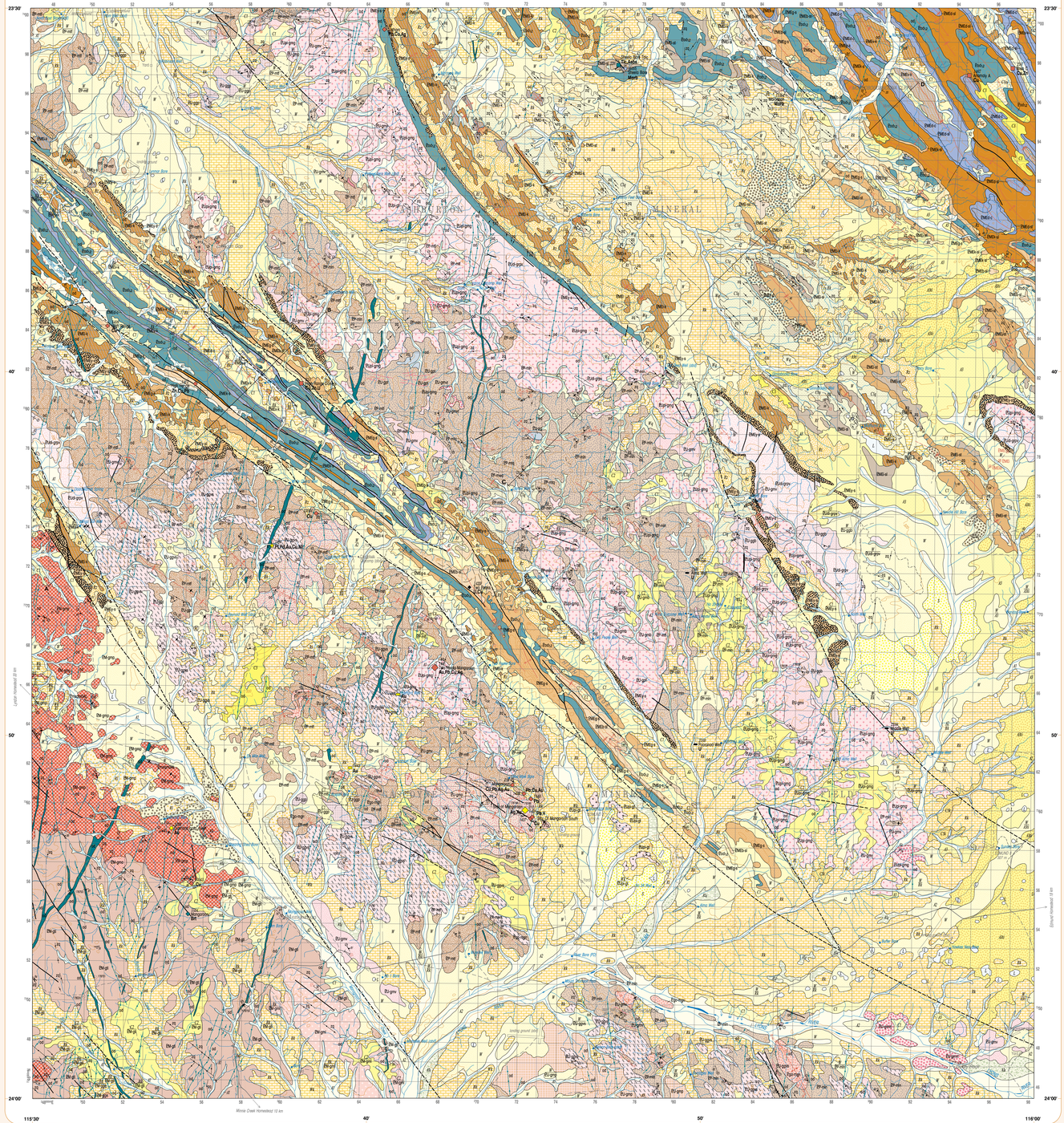
AUSTRALIA 1 : 100 000 GEOLOGICAL SERIES | **GEOLOGICAL SURVEY OF WESTERN AUSTRALIA** | **SHEET 2251**


116°30'
40'
50'
117°00'
23°00'
23°30'
20'
10'
CHESLA PLAINS
ASHBURTON MINERAL FIELD
LIMESTONE WALL
Ashburton Downs 4 km
Wyloo Homestead 20 km
Mt Sholl Bore
Mt Sholl Bore (Disused)
Wyloo Bore
McDonald Bore (disused)
Mt Sholl Bore (disused)
Mt Sholl Bore (disused)
Piggoon Pool
Mt Sholl Bore
Mooline Bore (disused)
Wood Bore
Wood Pool
Chinaman Pool
Chinaman Deposit
Mt Sholl Bore (disused)
Mt Sholl Bore (disused)
Mt Sholl Bore (disused)

MANGAROON

AUSTRALIA 1 : 100 000 GEOLOGICAL SERIES — **GEOLOGICAL SURVEY OF WESTERN AUSTRALIA** — **SHEET 2050**

115°30' 40' 50' 116°00' — 23°30' 24°00'



DIAGRAMMATIC SECTIONS

A — Mingo Bor Fault — Doorawarrah Creek — LYNDON RIVER — HIGH RANGE — B

C — MARDIWAH SOUTH ROAD — HENRY RIVER — D

PHANEROZOIC

CAINOZOIC — QUATERNARY

Unassigned

W — Sandy and clayey distal sheetwash and slope deposits; no clearly defined drainage

Wc — Clay, silt, and sand derived from saprolite and saprock

Wk — Distal sheetwash with colcrete cutans and carbonate cement

Wq — Predominantly quartz-rich silt, sand, and gravel derived from quartz veins and quartz-rich rock

Lacustrine unit

L — Unconsolidated, fine-grained deposits in claypans, perennial lakes, and swamps; low-lying areas with internal drainage; typically thickly vegetated

Sandplain unit

S — Quartz sand of mixed origin; includes residual and eolian sands

Colluvial units, third generation

C1 — Quartz and rock fragments in an unconsolidated silt and sand matrix; includes ferruginous deposits

C1s — Swelling clay (gilgai) and rock fragments, mostly developed over dolerite

C1k — Quartz and rock fragments in an unconsolidated silt and sand matrix; contains colcrete cutans and carbonate cement

C1q — Quartz fragments in an unconsolidated silt and sand matrix, derived from quartz veins and quartzose rocks

C1s — Sandstone fragments in a silt and sand matrix, derived from sandstone

Alluvial units, third generation

A1 — Unconsolidated silt, sand, and gravel in active drainage channels; includes ferruginous deposits

A1p — Unconsolidated, mainly fine-grained deposits in drainage depressions

A1s — Silt, sand, and gravel as stream-bank deposits marginal to active channels, incised by modern drainage

Colluvial units, second generation

C2 — Quartz and rock fragments in a partly consolidated silt and sand matrix

Alluvial units, second generation

A2 — Partly consolidated silt, sand, and gravel; partly dissected by present-day drainage

Colluvial units, first generation

C3 — Quartz and rock fragments in a weakly cemented and compacted silt and sand matrix; deeply dissected valley-fill deposits

Alluvial units, first generation

A3 — Weakly cemented and compacted silt, sand, and gravel; deeply dissected by present-day drainage

A3ri — Sand and gravel with ferruginous cement; deeply dissected by present-day drainage

Residual or relict units

R — Ferruginous deposits, including laterite, ferruginous, and manganiferous duricrust

Rk — Colcrete, developed in and adjacent to alluvial channels; locally silicified; dissected by major present-day drainage lines

Rf — Saprolite and saprock of uncertain protolith

Rz — Silcrete and brecciated siliceous outcrop

MESOPROTEROZOIC

Qtz — Quartz veins, of various ages

Do — Dolerite dykes, sills, and small intrusions, of various ages; one suite dated at c. 755 Ma[1]; includes minor quartz diorite, tonalite, and biotite monzogranite

Edmundian Orogeny (1070–750 Ma?)

Enx1u — Dolerite and gabbro sills intruded into **Edmund Group**; oldest suite (Pn2u) dated at c. 1465 Ma[1,4]; and youngest suite (Pn3u) dated at c. 1070 Ma[1,4]

PALAEOPROTEROZOIC — MESOPROTEROZOIC

Bangemall Supergroup — Edmund Group

EMEs-k — **DEVIL CREEK FORMATION:** laminated dolostone and dolomitic siltstone; local thick-bedded dolorudite

EMEd-c — **DISCOVERY FORMATION:** massive or laminated chert, silicified mudstone, and siltstone; local silicified sandstone and conglomerate

EMEd-si — Siltstone

EMEs-x — **KIANG CREEK FORMATION:** siltstone, mudstone, and thin to very thick bedded quartz sandstone; minor dolostone and conglomerate

EMEs-si — Siltstone; minor fine-grained sandstone

EMEp-k — **CHEYNE SPRINGS FORMATION:** dolosilite, dolorenite, dolorudite, mudstone, siltstone, and minor sandstone

EMEs-st — Medium- to thick-bedded sandstone and siltstone; locally sulfidic

EMEs-si — **BLUE BILLY FORMATION:** siltstone and mudstone; minor thin- to thick-bedded sandstone; locally sulfidic

EMEs-s — **GOONAGOORA FORMATION:** fine- to coarse-grained sandstone and siltstone; minor conglomerate, dolostone, and dolomitic siltstone

EMEs-k — **IRREGULLY FORMATION:** stromatolitic and non-stromatolitic dolostone, dolomitic siltstone, quartz sandstone, and conglomerate

EMEs-ss — Sandstone and siltstone; minor dolostone

EMEd-si — Siltstone, sandstone, and dolomite

EMEs-st — Sandstone, conglomerate, siltstone, and dolostone

YILGATHERRA FORMATION: sandstone, siltstone, conglomerate, and dolostone

EMEy-si — Siltstone and sandstone

c. 1620 Ma[1]

Mangaroon Orogeny (1680–1620 Ma)

1695–1620 Ma[4,11]

Dutcher Supersuite

Bu-ggb — Mesocratic, medium-grained, equigranular biotite granodiorite

Bu-ggg — Grey, massive, medium-grained, porphyritic biotite granodiorite

Bu-ggpa — Schlieric, medium-grained biotite-muscovite granodiorite with abundant inclusions of metasedimentary rock and augen gneiss; minor flow-banded biotite-muscovite monzogranite with inclusions

Bu-grb — Equigranular, medium-grained biotite monzogranite

Bu-grg — Cream, massive, medium-grained, porphyritic biotite±muscovite monzogranite

Bu-grv — Cream, medium-grained muscovite-biotite granodiorite and monzogranite; equigranular or weakly porphyritic

Bu-grmt — Cream, medium-grained muscovite-tourmaline±biotite monzogranite; locally garnet bearing

Bu-gpt — Tourmaline-muscovite pegmatite and coarse-grained granite, and fine-grained, leucocratic tourmaline-muscovite monzogranite

Bu-ggv-gmp — **DINGO CREEK GRANITE:** porphyritic biotite-muscovite granite; fine to medium grained with thin, tubular K-feldspar phenocrysts defining a trachytic texture

Bu-gp-gmg — **PIRRYANA GRANITE:** massive, medium-grained, megacrystic and porphyritic biotite±muscovite monzogranite; tubular megacrysts of K-feldspar up to 7 cm long

Bu-gb-gd — Equigranular, fine- to medium-grained biotite tonalite and granodiorite

Bu-mg — Massive metagabbro with xenocrysts of quartz and K-feldspar

Mangaroon Orogeny (1680–1620 Ma)

Bu-ggb | Bu-ggpa | Bu-ggv | Bu-gpb | Bu-gmg | Bu-grv | Bu-grmt | Bu-gpt | Bu-ggv-gmp | Bu-gp-gmg | Bu-gb-gd | Bu-mg

Paperona Metamorphics

c. 1680 Ma[11]

BP-mt — Migmatitic pelitic gneiss (stromatic and metatexite migmatite)

BP-mm — Pelitic gneiss and granofels composed of biotite-muscovite-quartz-plagioclase-sillimanite; also includes migmatitic pelitic gneiss

BP-mst — Metamorphosed feldspathic sandstone and psammitic schist; includes interbedded pelitic, quartzite, and metamorphosed granule conglomerate

BP-mq — Metamorphosed quartzite and pebble conglomerate; quartz sandstone, and pebbly quartz sandstone

BP-mmaf — Amphibolite and actinolite-plagioclase schist

BP-mst | BP-mm | BP-mmf | BP-mq | BP-mmaf

c. 1770 Ma[1]

Tgp-mgg — **GOOCHE GNEISS:** strongly foliated, porphyritic granodiorite and monzogranite, and augen gneiss

Capricorn Orogeny (1830–1780 Ma?)

1795–1785 Ma[4,14]

Moorarie Supersuite

BM-gmc — Fine-grained, leucocratic biotite monzogranite

BM-ggp — Equigranular to sparsely porphyritic, medium-grained biotite±muscovite granodiorite

BM-gmt — Massive, equigranular, medium-grained, leucocratic biotite monzogranite

BM-gmg — Massive, medium-grained, porphyritic biotite monzogranite; round phenocrysts of K-feldspar up to 5 cm in diameter; minor fine- to medium-grained, sparsely porphyritic monzogranite

BM-gt — Medium- to coarse-grained tonalite with abundant mafic clots; lesser medium-grained granodiorite with scattered mafic clots

BM-gmc | BM-ggp | BM-gmt | BM-gmg | BM-gt

c. 1840 Ma[2]

Bmsgs/GAB — Quartz-mica schist and metamorphosed, fine-grained sandstone

1806–1784 Ma[4]

Bmsg/GAB — Foliated and gneissic granodiorite and tonalite; weakly pegmatite banded (Section only)

Bmsc/GAB — Pelitic to psammitic schist; includes muscovite-quartz-andalusite-garnet-plagioclase-biotite schist (Section only)

EDMUND BASIN

Yerrida Zone — Yelma Zone — Lyndon Zone — Boora Boora Zone — Mangaroon Zone — GASCOYNE COMPLEX

Geological boundary

exposed
concealed

Structural symbols are labelled according to the sequence of deformation events, where known

Edmundian Orogeny (1070–750 Ma)
Edmund Fold Belt
D_{ed}
D_{ed}
D_{ed}

Mangaroon Orogeny (1680–1620 Ma)
D_{mn}
D_{mn}

Fault
exposed
concealed
concealed, position uncertain

Fold, showing axial trace and generalized plunge direction
anticline; exposed, concealed
syncline; exposed, concealed
antiform; exposed, concealed
synform; exposed, concealed

Small-scale fold axial surface, showing strike and dip
inclined
vertical

Small-scale fold axis, showing trend and plunge
anticline
syncline
antiform
S-vergence
M-vergence
Z-vergence

Locality of superposed fold

Bedding, showing strike and dip
inclined
vertical
overturned

trend of bedding

Igneous layering, showing strike and dip
inclined
vertical

Igneous flow banding, showing strike and dip
inclined
vertical

Igneous contact, showing strike and dip
inclined

Way-up indicator
graded bedding

Metamorphic foliation, showing strike and dip
inclined
vertical

Gneissic banding, showing strike and dip
inclined

Trend of foliation or gneissic banding

Cleavage, showing strike and dip
inclined
vertical

Crenulation cleavage, showing strike and dip
inclined
vertical

Shear-sense indicator
dextral
sinistral

showing dip of foliation
dextral
inclined
vertical
sinistral
inclined
vertical

Mineral lineation, showing trend and plunge
inclined

Axis of crenulation, showing trend and plunge
inclined

Bedding-cleavage intersection lineation, showing trend and plunge
inclined

Cleavage-cleavage intersection lineation, showing trend and plunge
inclined

Sickensticle, showing direction and plunge of striation

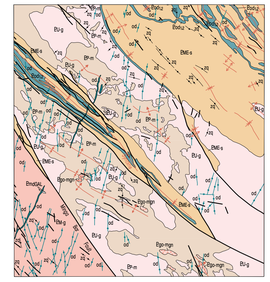
Aciphotic lineament
unspecified

Isotopic age determination site with identification number — 1870

Formed road
Track
Fence, generally with track
Homestead — Mangaroon
Locality — Minthorna
Building
Yard — Yard
Horizontal control; major, minor
Contour line, 20 metre interval — 420
Watercourse with ephemeral pool or waterhole
Pool — Pool
Spring — Spring
Bore, well — Bore — Well
Windpump, solar pump
Dam, tank — Dam — Tank
Abandoned — abnd
Position doubtful — (P2)

Mineral field boundary
Mine, abandoned mine, deposit or prospect — Star of Mangaroon
Mineral exploration drillhole showing subsurface data — DM5

INTERPRETED BEDROCK GEOLOGY



MINERAL OCCURRENCES

MINERALIZATION STYLES*

- Vein and hydrothermal
- Stratabound Sedimentary
- Orthomagmatic
- Regolith hosted
- Undivided

MINERAL AND ROCK COMMODITY GROUPS

- Precious metal
- Base metal
- Industrial mineral
- Energy mineral
- Construction material

MINERAL AND ROCK COMMODITIES

Asbestos, serpentine (chrysotile)	Asbs
Barite	Brt
Copper	Cu
Gold	Au
Lead	Pb
Marble	Marb
Nickel	Ni
Palladium	Pd
Platinum	Pt
Silver	Ag
Talc	Tlc
Uranium	U
Vanadium	V
Zinc	Zn

OPERATING STATUS AND SITE IDENTIFICATION NUMBER

Operating mine	e.g. 15555
Abandoned mine	e.g. 1442
Mineral deposit	e.g. 1441
Mineral occurrence or prospect	e.g. 2429

Mineral occurrences and numbers are from the GSWA MINEDEX database

*Larger symbols represent mines or deposits also in the DoIR MINEDEX database

Bangemall Supergroup geology by D. McB. Martin and A. M. Thorne 1998–1999
Gascoyne Complex geology by S. Sheppard 2002

Geochronology by:
(1) M. T. D. Wingate and J. W. Giddings, 2000, Precambrian Research, v. 100, p. 335–357.
(2) M. T. D. Wingate, 2002, GSWA Record 2002/4.
(4) D. R. Nelson, 2001, GSWA Record 2001/2, p. 15–20
(5) D. R. Nelson, 1998, GSWA Record 1998/2, p. 194–197.
(6) D. R. Nelson, in prep., GSWA Record.
(7) D. R. Nelson, 2002, GSWA Record 2002/2, p. 35–42.
(8) D. A. D. Evans et al., 2003, Australian Journal of Earth Sciences, v. 50, p. 853–864.

Interpreted Geochronology by:
(2) D. McB. Martin and A. M. Thorne, 2004, Precambrian Research, v. 128, p. 385–409.
(9) S. Sheppard et al., 2001, GSWA Record 2001/3, p. 3–4.

Edited by F. Ellaham and G. Lizin

Cartography by G. Wright, A. Fronzes, and K. Greenberg

Published by the Geological Survey of Western Australia. Digital and hard copies of this map are available from the Information Centre, Department of Industry and Resources, 100 Plain Street, East Perth, WA, 6004. Phone (08) 9222 3459, Fax (08) 9222 3444
Web: www.doir.wa.gov.au/gswa/ Email: geological.survey@doir.wa.gov.au

The recommended reference for this map is:
SHEPPARD, S., MARTIN, D. McB., and THORNE, A. M., 2004, Mangaroon, W.A. Sheet 2050: Western Australia Geological Survey, 1:100 000 Geological Series

DATA DIRECTORY

Theme	Data Source	Data Currency	Agency
Geology	GSWA	1996 – 2002	Dept of Industry and Resources
Structural data	WARCH	FEB 2004	Dept of Industry and Resources
Mineral occurrences (non-confidential)	MINEDEX	FEB 2004	Dept of Industry and Resources
	MWIN	FEB 2004	Dept of Industry and Resources
Cadastre	TENGRAPH	APR 2004	Dept of Industry and Resources
Horizontal control	GEOMAR	MAY 2004	Dept of Land Information
Topographic nomenclature	GEONOMA	APR 2004	Dept of Land Information
Topography	DLI and GSWA field survey	2002	Dept of Land Information

CLIVE BROWN, M.L.A. — MINISTER FOR STATE DEVELOPMENT
JIM LIMERICK — DIRECTOR GENERAL
Department of Industry and Resources
Geological Survey of Western Australia
TIM GRIFFIN — DIRECTOR

SCALE 1:100 000

1000 0 1 2 3 4 5 6 7 8 9 10 Metres / Kilometres

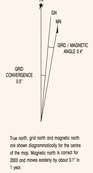
UNIVERSAL TRANSVERSE MERCATOR PROJECTION
HORIZONTAL DATUM: GEOCENTRIC DATUM OF AUSTRALIA 1994
VERTICAL DATUM: AUSTRALIAN HEIGHT DATUM

Grid lines indicate 1000 metre interval of the Map Grid Australia Zone 50

GDA — The Map Grid Australia (MGA) is based on the Geocentric Datum of Australia 1994 (GDA94)
GDA94 positions are compatible within one metre of the datum WGS84 positions

SHEET INDEX

1:100 000 maps shown in black
1:250 000 maps shown in brown
Non-series maps used in compilation shown in green
See current GSWA map catalogue for full range of published products



True north, grid north and magnetic north are shown diagrammatically for the centre of the map. Magnetic north is correct for 2003 and moves westerly by about 0.1° in 1 year.

MANGAROON

SHEET 2050 — **FIRST EDITION 2004** — Version 1.0 — June 2004

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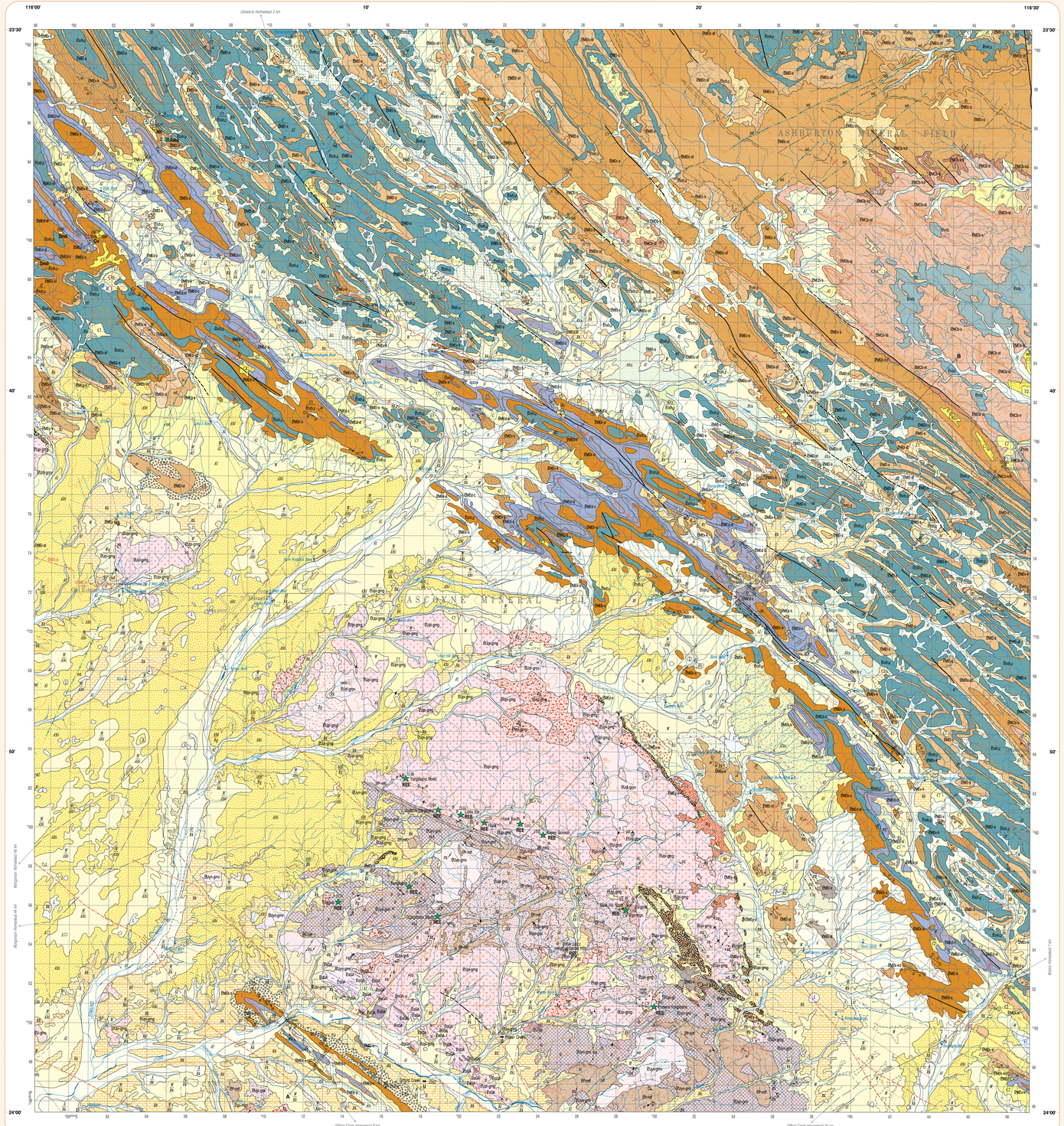
EDMUND

AUSTRALIA 1 : 100 000 GEOLOGICAL SERIES — **GEOLOGICAL SURVEY OF WESTERN AUSTRALIA** — **SHEET 2150**


116°00'
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20'
116°30'
23°30'
40'
50'
24°00'
ASHBURTON MINERAL FIELD
ASCONE MINERAL FIELD
Ullawarra Homestead 2 km
Mangaroon Homestead 40 km
Minilya Homestead 7 km
Gifford Creek Homestead 8 km
Gifford Creek Homestead 20 km
Lyons River
Barlee Range
Ningaloo
Coral Bay
Exmouth
Onslow
Learmonth
Giralia
Bullara
Yanrey
Yarraloola
Nanutarra
Wittenoom
Tom Price
Paraburdoo
Pannawonica
Karratha
Dampier
Roebourne
Wickham
Point Samson
Port Hedland
Whim Creek
Marble Bar
Nullagine
Newman
Jigalong
Meekatharra
Wiluna
Leinster
Leonora
Laverton
Mount Magnet
Sandstone
Yalgoo
Mount Gibson
Mount Jackson
Mount Adams
Mount Clarke
Mount Phillips
Mount Augustus
Kennedy Range
Elliott Creek
Edmund
Collier
Ashburton Downs
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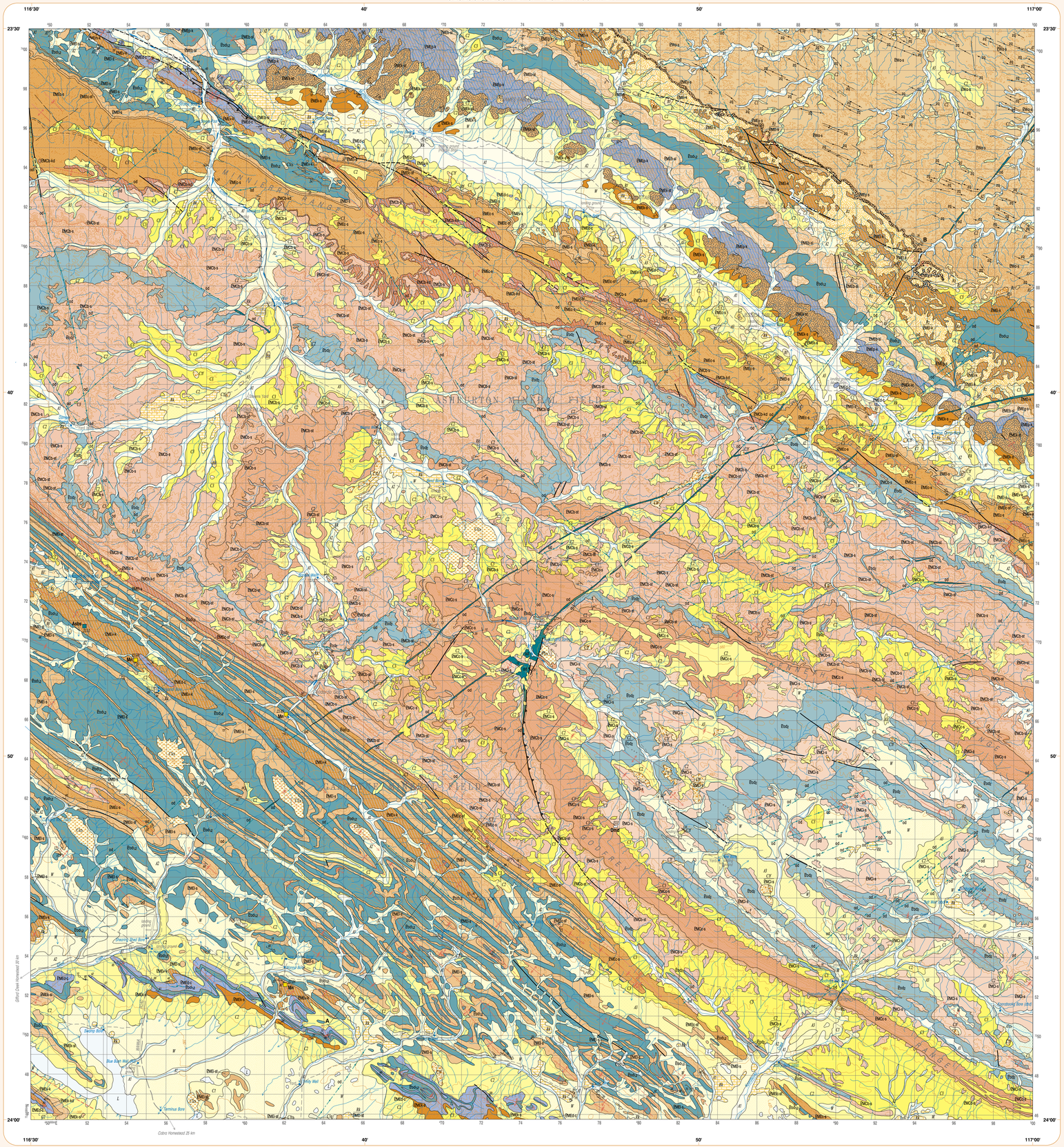
ELLIOTT CREEK

AUSTRALIA 1 : 100 000 GEOLOGICAL SERIES

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

SHEET 2250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24°00'
ASHBURTON MINERAL FIELD
Ashburton Mine
Mn
Mt Minnierra
Minnierra Bore
Terminus Bore
Cobra Homestead 25 km
Gifford Creek Homestead 20 km
Highway
Swamp Well Bore
Swamp Well
Blue Bush Well Bore
Blue Bush Well
Windy Well
Yarraloola Bore
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