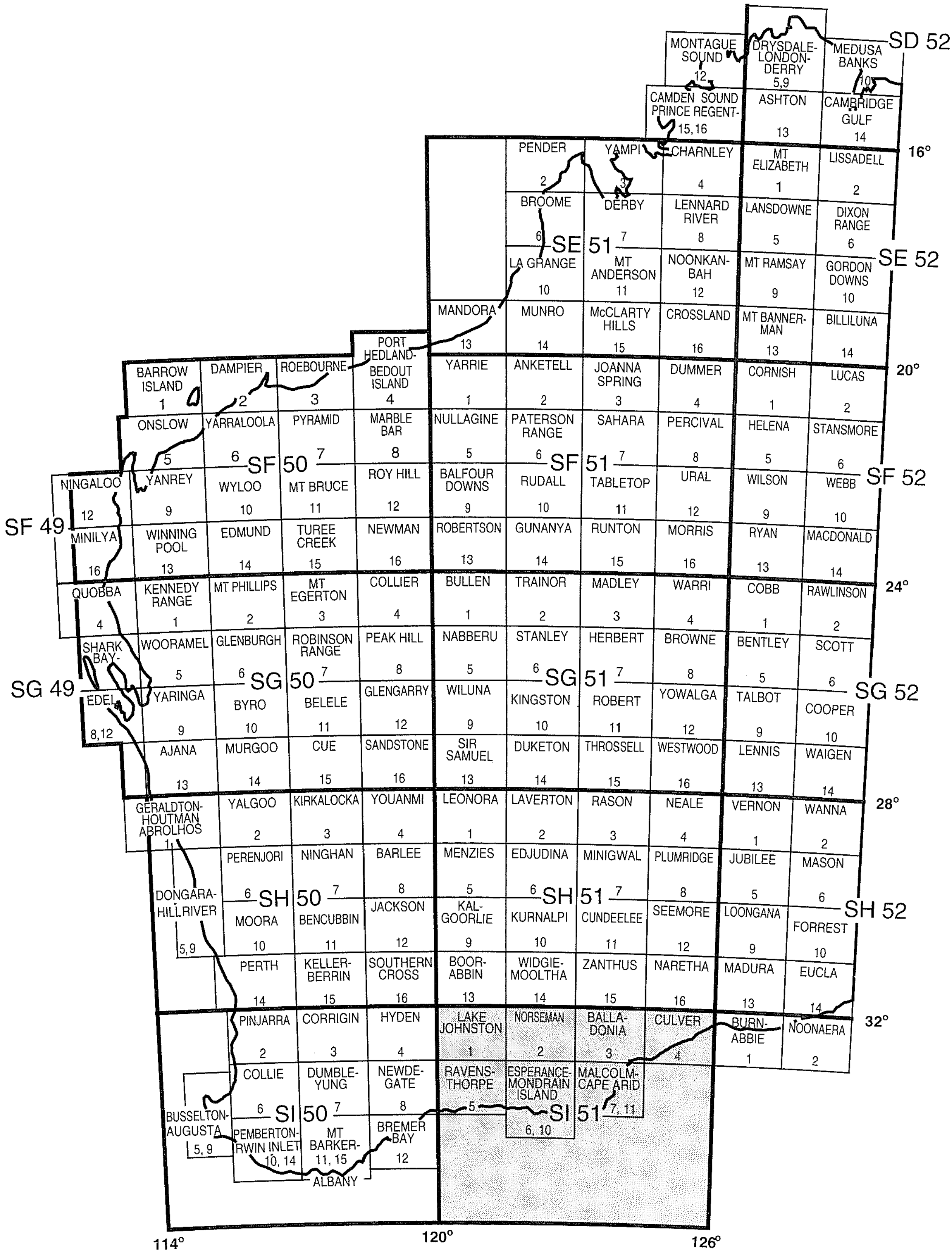
XPLANATORY
NOTES

GEOLOGY OF THE ESPERANCE 1:1 000 000 SHEET

by J.S. MYERS

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY



SD 52
MONTAGUE SOUND 12
DRYSDALE-LONDON-DERRY 5,9
MEDUSA BANKS 10
CAMDEN SOUND PRINCE REGENT 15,16
ASHTON 13
CAMBRIDGE GULF 14
SE 51
SE 52
PENDER 2
YAMPI 3
CHARNLEY 4
MT ELIZABETH 1
LISSADELL 2
BROOME 6
DERBY 7
LENNARD RIVER 8
LANSDOWNE 5
DIXON RANGE 6
LA GRANGE 10
MT ANDERSON 11
NOONKANBAH 12
MT RAMSAY 9
GORDON DOWNS 10
MANDORA 13
MUNRO 14
McCLARTY HILLS 15
CROSSLAND 16
MT BANNERMAN 13
BILLILUNA 14
16°
20°
24°
28°
32°
SF 49
SF 50
SF 51
SF 52
BARROW ISLAND 1
DAMPIER 2
ROEBOURNE 3
PORT HEDLAND-BEDOUT ISLAND 4
YARRIE 1
ANKETELL 2
JOANNA SPRING 3
DUMMER 4
CORNISH 1
LUCAS 2
ONSLOW 5
YARRALOOLA 6
PYRAMID 7
MARBLE BAR 8
NULLAGINE 5
PATERSON RANGE 6
SAHARA 7
PERCIVAL 8
HELENA 5
STANSMORE 6
NINGALOO 12
YANREY 9
WYLOO 10
MT BRUCE 11
ROY HILL 12
BALFOUR DOWNS 9
RUDALL 10
TABLETOP 11
URAL 12
WILSON 9
WEBB 10
MINILYA 16
WINNING POOL 13
EDMUND 14
TUREE CREEK 15
NEWMAN 16
ROBERTSON 13
GUNANYA 14
RUNTON 15
MORRIS 16
RYAN 13
MACDONALD 14
SG 49
SG 50
SG 51
SG 52
QUOBBA 4
KENNEDY RANGE 1
MT PHILLIPS 2
MT EGERTON 3
COLLIER 4
BULLEN 1
TRAINOR 2
MADLEY 3
WARRI 4
COBB 1
RAWLINSON 2
SHARK BAY-EDEL 8,12
WOORAMEL 5
GLENBURGH 6
ROBINSON RANGE 7
PEAK HILL 8
NABBERU 5
STANLEY 6
HERBERT 7
BROWNE 8
BENTLEY 5
SCOTT 6
YARINGA 9
BYRO 10
BELELE 11
GLENGARRY 12
WILUNA 9
KINGSTON 10
ROBERT 11
YOWALGA 12
TALBOT 9
COOPER 10
AJANA 13
MURGOO 14
CUE 15
SANDSTONE 16
SIR SAMUEL 13
DUKETON 14
THROSSELL 15
WESTWOOD 16
LENNIS 13
WAIGEN 14
SH 50
SH 51
SH 52
GERALDTON-HOUTMAN ABROLHOS 1
YALGOO 2
KIRKALOCKA 3
YOUANMI 4
LEONORA 1
LAVERTON 2
RASON 3
NEALE 4
VERNON 1
WANNA 2
DONGARA-HILLRIVER 5,9
PERENJORI 6
NINGHAN 7
BARLEE 8
MENZIES 5
EDJUDINA 6
MINIGWAL 7
PLUMRIDGE 8
JUBILEE 5
MASON 6
MOORA 10
BENCUBBIN 11
JACKSON 12
KALGOORLIE 9
KURNALPI 10
CUNDEELEE 11
SEEMORE 12
LOONGANA 9
FORREST 10
PERTH 14
KELLERBERRIN 15
SOUTHERN CROSS 16
BOORABBIN 13
WIDGIEMOOLTHA 14
ZANTHUS 15
NARETHA 16
MADURA 13
EUCLA 14
SI 50
SI 51
PINJARRA 2
CORRIGIN 3
HYDEN 4
LAKE JOHNSTON 1
NORSEMAN 2
BALLADONIA 3
CULVER 4
BURNABBIE 1
NOONAERA 2
BUSSELTON-AUGUSTA 5, 9
COLLIE 6
DUMBLEYUNG 7
NEWDEGATE 8
RAVENSTHORPE 5
ESPERANCE-MONDRAIN ISLAND 6, 10
MALCOLM-CAPE ARID 7, 11
PEMBERTON-IRWIN INLET 10, 14
MT BARKER-ALBANY 11, 15
BREMER BAY 12
114°
120°
126°

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GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

GEOLOGY OF THE ESPERANCE 1:1 000 000 SHEET

by
John S. Myers

Perth 1995

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Cover photograph:
Thistle Cove, east of Cape Le Grand, showing Esperance Granite, which contains inclusions of older, paler Recherche Granite. These granites were intruded, deformed and recrystallized in the roots of a mountain belt that formed during the collision and amalgamation of a west Australian continent with part of Antarctica.

Contents

Figure

Table

Geology of the ESPERANCE 1:1 000 000 sheet

by

John S. Myers

Introduction

The ESPERANCE* 1:1 000 000 geological map sheet covers the southern part of Western Australia south of latitude 32° S, between longitudes 120° and 126° E. The region is sparsely populated and contains only three major towns: Esperance, Norseman, and Ravensthorpe. Most of the region is covered by natural vegetation, but substantial areas have been cleared for wheat farming between Ravensthorpe and Esperance, east towards Cape Arid, and north to the vicinity of Salmon Gums. Sheep grazing occurs in the vicinity of Balladonia and the Fraser Range. Mining activity, mainly gold, is centred around Norseman and Ravensthorpe, but there has been extensive exploration for coal, uranium, nickel, and platinum. The region contains numerous National Parks including Cape Arid, Cape Le Grand, Stokes Inlet, Peak Charles, Frank Hann, and part of the Fitzgerald River National Park, and the extensive Dundas, Nuytsland, and Recherche Archipelago Nature Reserves.

The main geological features of the map are: Archaean granites and greenstones that form part of the Yilgarn Craton in the northwest; Proterozoic gneiss and granite that form part of the Albany–Fraser Orogen exposed in the central and southern part of the map and along much of the coastline and off-shore islands; and Tertiary limestone in the Eucla Basin that overlies gneiss and granite in the east. Other notable rock units are the early Proterozoic Jimberlana layered dyke and the Fitzgerald Peaks Syenite intrusion. Prolonged erosion has led to generally subdued topography that is extensively covered by Cainozoic eolian and residual calcareous clay, sand, and gravel.

The region forms an undulating plateau at a general elevation of 200–500 m west of longitude 123° 30' E. To the east, the plateau is smoother and lower and forms part of the Bunda Plateau containing the Nullarbor Plain, at a general elevation of 100–200 m. In the south, these undulating surfaces were reduced by Quaternary marine erosion to a number of smooth, flat or gently sloping, peneplains that decrease in altitude towards the coast. The Wylie Scarp is the highest of numerous scarps that bound these erosion surfaces. It abruptly terminates the Bunda Plateau, and east of longitude 124° 30' E it forms the coastline as the Baxter Cliffs.

In the northwest, on the Yilgarn Craton, the plateau contains higher, residual hills of greenstones and syenite, whereas on the Albany–Fraser Orogen residual hills are composed of granite, except in the Fraser Range where they consist of pyroxene granulite. Offshore, where this landscape was drowned by the recent postglacial rise in sea level, the granite hills form the numerous small islands of the Archipelago of the Recherche.

There are pronounced changes in the vegetation across ESPERANCE that mainly reflect a marked eastward decrease in rainfall from 500 mm in the southwest to 230 mm in the east. Dense eucalypt woodland in the western two-thirds of ESPERANCE is replaced eastward by open woodland and then by blue bush and salt bush on the limestone of the Nullarbor Plain. Rainfall generally increases southward across the sand and gravel plains that extend 50 km inland from the coast. The dominant mallee-type open woodland north of these sand plains gives way across them to banksia woodland and then coastal heath.

Geological map sheets (1:250 000) and explanatory notes have been completed for the whole region and should be consulted for a more detailed description of the geology than the outline presented here. These map sheets are: LAKE JOHNSTON (Gower and Bunting, 1976), NORSEMAN (Doepel, 1973), BALLADONIA (Doepel and Lowry, 1970), CULVER (Lowry, 1970a), RAVENSTHORPE (Thom et al., 1977), ESPERANCE–MONDRAIN ISLAND (Morgan and Peers, 1973), and MALCOLM–CAPE ARID (Lowry and Doepel, 1974). A first edition ESPERANCE 1:1 000 000 map was compiled from these map sheets by Williams (1976).

The second edition ESPERANCE 1:1 000 000 map was also largely compiled from these map sheets. The interpretation of the geology was supplemented by aeromagnetic data published by the Australian Geological Survey Organization (AGSO, formerly BMR) and by 33 days fieldwork. The Albany–Fraser Orogen appeared to be the least well known geological unit and so the limited fieldwork concentrated on this unit. Most of the easily accessible outcrops within the Albany–Fraser Orogen (that forms 70% of the mainland outcrop) and immediately adjacent Yilgarn Craton were examined, including much of the mainland coastline. Future investigation of the offshore islands should provide additional information about the orogen.

* The ESPERANCE sheet name is printed in capitals to avoid confusion with the town of Esperance.

The geology of the Fraser Complex is based on detailed mapping summarized in Myers (1985), and the geology of the Mount Barren Group is based on recent mapping by Brown (in prep.).

The Tertiary rocks of the Eucla Basin were described in detail by Lowry (1970b) and were not examined during fieldwork for the ESPERANCE map. The greenstones of the Yilgarn Craton at Norseman and Ravensthorpe were being mapped at 1:100 000 scale by the Geological Survey of Western Australia during the compilation of ESPERANCE. However, the results were insufficiently advanced to be incorporated into either the ESPERANCE sheet or these notes.

The mineral resources of ESPERANCE are not discussed because they are the subject of a proposed companion report.

Yilgarn Craton

The Yilgarn Craton on ESPERANCE mainly consists of late Archaean granite and greenstones. The greenstones include basaltic and komatiitic volcanic rocks, mafic and ultramafic plutonic rocks, acid volcanic rocks and sedimentary rocks. The Archaean rocks are metamorphosed in greenschist or amphibolite facies and are heterogeneously deformed. The attitudes of most rock units and tectonic fabrics are steep, and trends north-northwest.

The Yilgarn Craton is cut into three major segments by the Koolyanobbing and Tay Faults. These faults, juxtapose granite–greenstone terranes which, in detail, contain different rock units and show different early tectonic histories. Parts of three more tectonostratigraphic units occur in the vicinity of Norseman bounded by the Mission and Zuleika Faults (Swager et al., 1990).

Greenstones

The greenstones occur in four distinct belts, here informally referred to as the Norseman, Johnston, Forrestania, and Ravensthorpe greenstone belts. The rocks are generally strongly deformed and thoroughly recrystallized, in contrast to most granites which are relatively little deformed and are partly recrystallized. They comprise mappable units of ultramafic (*Au*), mafic (*Ab*), and felsic (*Af*) igneous rocks, and sedimentary rocks (*As*) including BIF, metamorphosed in greenschist or low amphibolite facies, and units of amphibolite (probably derived from mafic igneous rocks) and BIF (together marked as *Ah*) metamorphosed in amphibolite or granulite facies. Some relic igneous and sedimentary structures such as pillow lava structure, cross bedding and graded bedding are preserved.

Many of these rocks have been interpreted as simple stratigraphic sequences, but many rock units are strongly deformed and are tectonically disrupted by thrusts and so the previously developed stratigraphies need reappraisal. Some rock units were also misinterpreted, such as sheets of schistose granite and augen granite in metadolerite/metagabbro that were interpreted as layers of metasedimentary rocks within a sequence of mafic volcanics called the Penneshaw Formation in the Norseman greenstones (Doepel, 1973).

Zircons from rocks described as 'felsic volcanics' from the so-called Penneshaw Formation have given U–Pb SHRIMP ages of c. 2.9 Ga and 3.1 Ga (Campbell and Hill, 1988). They attribute the 2.9 Ga zircons to volcanism and interpret the 3.1 Ga zircons as restite fractions of the source rocks. Campbell and Hill (1988) also determined the U–Pb SHRIMP age of zircons from a 'chert' in the Noganyer Formation and a felsic volcanic rock in the Mount Kirk Formation within the Norseman greenstones. The 'chert' contained 3650–3670 Ma zircons which they interpreted as detrital, and 2706 Ma zircons interpreted as formed by hydrothermal action associated with chert deposition. The felsic volcanics contained c. 2689 Ma zircons and are cut by a granite with c. 2691 Ma zircons.

It has recently been recognized that the Norseman greenstone belt comprises parts of two tectonostratigraphic terranes called the Norseman and Kalgoorlie Terranes (Swager et al., 1990). The Kalgoorlie Terrane itself is subdivided into the Coolgardie tectonic domain to the west of the Mission Fault and the Kambalda tectonic domain to the east of the Zuleika Fault. The terrane boundary faults are cut by c. 2690 Ma granite.

The Johnston greenstone belt contains two distinct components separated by the Tay Fault. West of the Tay Fault the Johnston greenstone belt predominantly comprises clastic metasedimentary rocks and BIF with minor felsic volcanic rocks intruded by mafic and ultramafic sills and overlain by metamorphosed basalt and komatiitic basalt (Gower and Bunting, 1976). To the east of the Tay Fault the Johnston greenstone belt is characterized by metamorphosed basaltic pillow lava with minor mafic and ultramafic intrusive rocks and sedimentary rocks collectively called the Maggie Hays Formation by Gower and Bunting (1976). This, together with heterogeneous granite and migmatite and sheets of massive granite form a distinct tectonostratigraphic unit, here called the Maggie Hays Terrane, bounded by the Tay and Koolyanobbing Faults (Fig. 1).

Granites

The contacts between most granites and greenstones are zones of intense deformation. However, some granites are seen to have intrusive relations with the greenstones and contain angular xenoliths of greenstones. No granitic rocks have been recognized as older than any greenstones.

Most of the granitic rocks are monzogranite in composition and have been subdivided on texture into even-grained (*Age*) and porphyritic (*Agp*) varieties. No attempt has been made to subdivide them into plutons or batholiths, nor into units of different age, although some cross-cutting relations are recorded between the granitic rocks. Details of such subdivisions are shown on the LAKE JOHNSTON and RAVENSTHORPE 1:250 000 map sheets. Regions of heterogeneous granitic rocks and migmatite are designated *Am*.

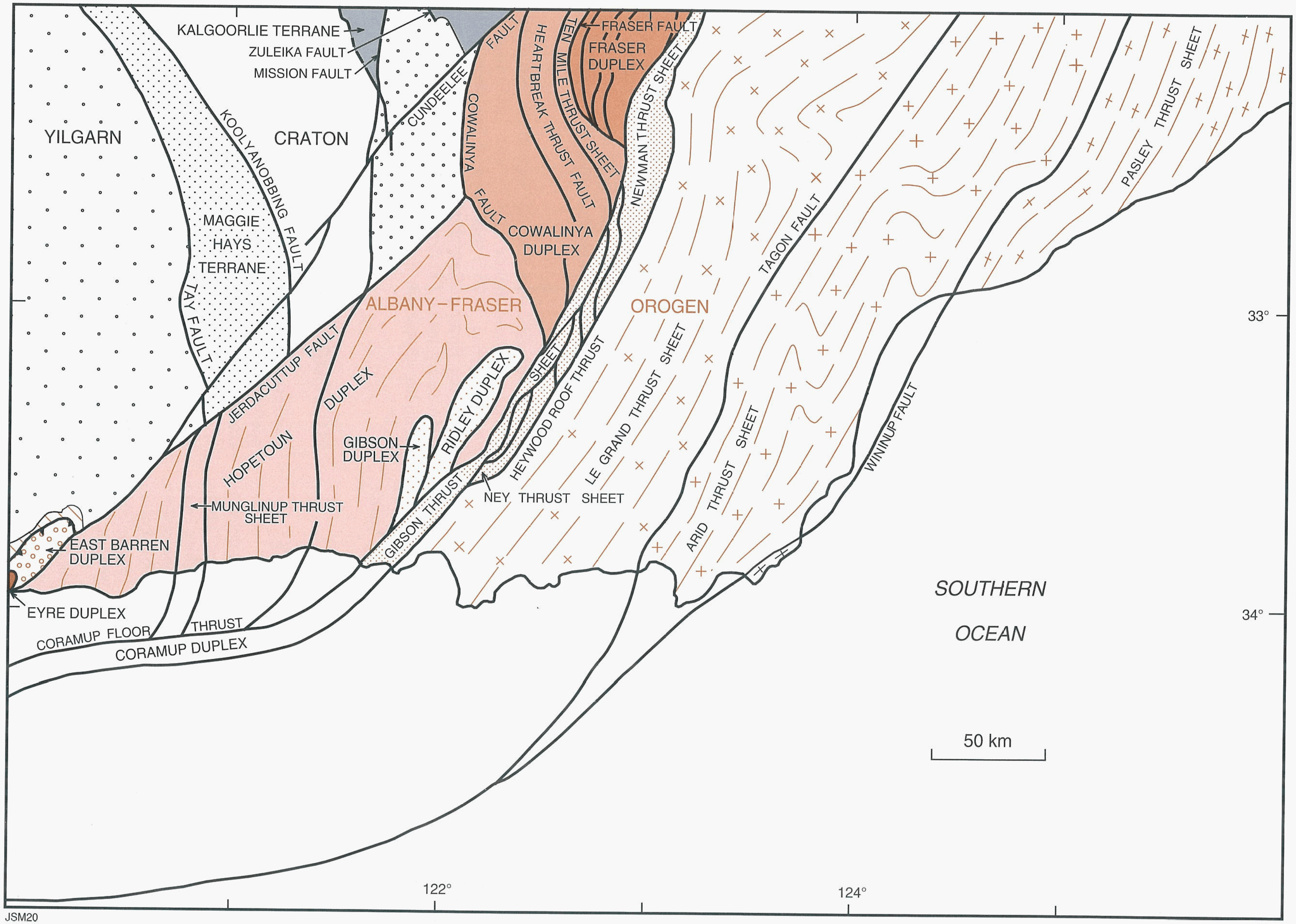

Figure 1. Major Precambrian tectonic units

The U–Pb isotopic age of zircons from some granites have been determined by Hill et al. (1989) on the SHRIMP from Stennet Rock and Buldania Rocks adjacent, respectively, to the southwest and southeast of the Norseman greenstone belt. The igneous age of the granite at Stennet Rock was interpreted as 2691 Ma and that at Buldania Rocks as 2689 Ma. The former also contained zircon cores with ages of c. 3100 to 3196 Ma, interpreted as reflecting the age of the source rock. Zircon ages of 2611 Ma from a granite at Wheeler Rock just east of the Koolyanobbing Fault, east of Lake Johnston were interpreted by Hill et al. (1989) as the age of intrusion.

Widgiemooltha Dyke Swarm

East-southeasterly trending dolerite dykes (*Ed₁*) cut the Archaean Craton in the northwest part of ESPERANCE. They are part of the Widgiemooltha Dyke Swarm that occurs throughout the Yilgarn Craton (Myers, 1990a). The largest dyke on ESPERANCE is called the Jimberlana Dyke. It is up to 2 km wide and locally contains funnel-shaped cumulate layering of norite, gabbro, pyroxenite, and peridotite (Campbell et al., 1970). The Jimberlana Dyke has given identical Rb–Sr isochron and Sm–Nd model ages of 2411 ± 50 Ma (Turek, 1966; Fletcher et al., 1987).

Fitzgerald Peaks Syenite

The Fitzgerald Peaks Syenite outcrops as a cluster of steep-sided hills rising 300 m above the surrounding plain of late Archaean granite. The hills include Peak Charles (651 m) which is the highest point on ESPERANCE. The syenite (*Egy*) forms a heterogeneous crescentic pluton and is mainly composed of quartz syenite with minor syenite that locally contains prominent aegirine. It has a weakly developed foliation that is concentric with the margins of the pluton and dips steeply inwards. The syenite contains small rounded xenoliths of hornblende–diopside–plagioclase granulite. The intrusion has given a Rb–Sr whole rock isochron age of about 2350 Ma (de Laeter and Lewis, 1978).

Albany–Fraser Orogen

The Albany–Fraser Orogen is a belt of repeated deformation, magmatism and sedimentary deposition, about 300 km wide, that extends west from the Darling Fault on the ALBANY 1:1 000 000 sheet, across the eastern two-thirds of ESPERANCE and for a further 800 km to the northeast, where it is truncated by late Precambrian movements in the Paterson Orogen (Myers, 1990b).

The Albany–Fraser Orogen formed between c. 1300 and 1100 Ma during an episode of continent–continent collision along a previously rifted margin of the Yilgarn Craton and what is now eastern Antarctica (Myers, 1993). Substantial volumes of granite were generated, emplaced, deformed, and metamorphosed at this time, and the main tectonic features of the orogen reflect this mid-Proterozoic episode of collision. On ESPERANCE, the main structures strike northeast and are steep. They comprise duplexes and folded thrust sheets that moved upwards towards the west over the margin of the Yilgarn Craton, and indicate overall dextral transpression. The main sequence of events is summarized in Table 1.

On ALBANY, the orogen was subdivided longitudinally into the Biranup and Nornalup Complexes. The outlines of these complexes were based largely on apparent differences in structure shown by aeromagnetic data, and brief observations of mainly coastal outcrops. The ALBANY sheet was compiled without the advantage of associated fieldwork. However, in the production of ESPERANCE, a modest amount of fieldwork was undertaken, supported by minor zircon (SHRIMP) geochronology. Most of the fieldwork was concentrated on the Albany–Fraser Orogen as this appeared to be the most complicated and was the least well known part of the map sheet.

The fieldwork, together with the interpretation of geophysical data, substantiates the broad subdivision of the orogen into the Biranup and Nornalup Complexes. Each complex is a coherent tectonic unit characterized by the dominance of particular rock types and structures. However, the fieldwork indicated that in detail the distinctive aeromagnetic patterns are not in themselves grounds for subdivision of the orogen into two complexes. Similar rocks and structures were found in areas marked by quite different aeromagnetic patterns. The dominant highly magnetic structures indicated by the aeromagnetic data appear to reflect diverse rock types such as magnetite-rich quartzite, BIF, metagabbro, pyroxene granulite, and granite.

The new fieldwork does not support the interpretation of Morgan and Peers (1973) and the suggestion by Thom et al. (1977) that most of the gneisses now called the Biranup Complex were derived from metasedimentary rocks. On the contrary, most of the Biranup Complex appears to have been derived from granitoid rocks.

Biranup Complex

The Biranup Complex can be subdivided into three major gneiss complexes here called Munglinup Gneiss, Dalyup Gneiss and Coramup Gneiss (Table 1).

The Munglinup Gneiss (*AEng*) was derived mainly from granite, granodiorite, tonalite, and pegmatite. Zircons from four samples of these rocks have given a U–Pb age of c. 2630 Ma (Nelson et al., in press), and Richards et al. (1966) obtained a U–Pb zircon age of c.2800 Ma from another sample by the Oldfield River. The rocks were heterogeneously deformed. They appear to have been relatively little deformed by D_0, an episode of deformation prior to mid-Proterozoic orogenesis, and were generally more severely deformed by D_1 and D_2 at c.1300 Ma during the main tectonic development of the Albany–Fraser Orogen (Table 1).

Table 1. Sequence of events in the Albany–Fraser Orogen

Time (Ma)		*New rock units*		*Deformation*		*Metamorphism*
c. 1200–1100	NORNALUP COMPLEX	**Esperance Granite** (*Ᵽge*, *Ᵽgp*)	D_3	Westward transport of thrust sheets onto Yilgarn Craton regional weak to moderate foliation, local mylonite	(brittle) ↑ M_3 (ductile)	Greenschist facies ↑ Amphibolite facies
					M_2	Granulite facies and partial melting
c. 1300		**Recherche Granite** (*Ᵽne*, *Ᵽno*) with synplutonic mafic dykes	D_2	Heterogeneous deformation just before and during peak metamorphism		
			D_1	Heterogeneous deformation during and after plutonism, weaker in west, stronger in east, leading to thrust stacking and crustal thickening	M_1	Granulite facies
c. 1300		**Coramup Gneiss** (*Ᵽnc*) component derived from Recherche Granite				
c. 1300		**Fraser Complex** (*Ᵽa*$_{1-5}$) and dolerite dykes (*Ᵽd*$_2$)				
		Malcolm Gneiss (*Ᵽnm*) derived from granite, granodiorite (?c. 1450 Ma) and paragneiss (?c. 1550 Ma)				
?c. 1550–1300		Metasedimentary rocks (*Ᵽq*, *ᵽBq*, *ᵽBS*)				
?c. 1700–1600	BIRANUP COMPLEX	**Coramup Gneiss** (*Ᵽnc*) component derived from granite and granodiorite				
c. 1700–1600		**Dalyup Gneiss** (*Ᵽng*, *Ᵽnp*) derived from granite and granodiorite	D_0	Heterogeneous deformation		?Amphibolite facies
c. 2630		**Munglinup Gneiss** (*AᵽPng*) derived from granite, granodiorite and tonalite				

The Dalyup Gneiss was derived mainly from heterogeneous granite, granodiorite and pegmatite (collectively *Ᵽng*) and relatively uniform porphyritic granite (*Ᵽnp*). Zircons from 5 samples of these rocks have given U–Pb ages between c. 1700 and 1600 Ma (Nelson et al., in press). Like the Munglinup Gneiss, the protoliths of the Dalyup Gneiss appear to have been relatively little deformed by D_0 before mid-Proterozoic orogenesis. They were heterogeneously deformed by D_1 and D_2. In many places, relic igneous textures are preserved, but in some places the rocks are strongly deformed and gneissose.

The Coramup Gneiss (*Ᵽnc*) was mainly derived from Recherche Granite, interleaved with orthogneiss (?c. 1700–1600 Ma) and paragneiss (?c. 1550 Ma). These rocks were strongly deformed together by D_1 and generally form a heterogeneous finely banded gneiss. In some lenticular zones, the deformation was less intense and relic igneous textures survive in Recherche Granite.

The gneisses of the Biranup Complex form a number of thrust sheets and duplex structures (Fig. 1). During the first major episode of mid-Proterozoic deformation (D_1) the rock units were tectonically interleaved by thrusting and isoclinal folding. The deformation generally decreased towards the west, but zones of relatively low D_1 deformation also occur as strips and lenses between zones of intense D_1 deformation in the east. Strong D_1 deformation converted the heterogeneous granitoid rocks and pegmatite veins into pegmatite-banded gneiss. Dykes and sheets of dolerite and gabbro (*Ᵽd*$_2$) were intruded into the protoliths of the Munglinup and Dalyup Gneisses. They were isoclinally folded and strongly deformed (mainly D_1) and metamorphosed (M_1) with the gneiss, and generally became subparallel layers of amphibolite. These dyke remnants may be part of the Gnowangerup Dyke Swarm that is well preserved in the margin of the Yilgarn Craton adjacent to the orogen.

Mount Barren Group

Part of the Mount Barren Group occurs in the southwest corner of ESPERANCE between Hopetoun and Ravensthorpe. It largely comprises allochthonous sheets of folded quartzite, phyllite and quartz–mica schist metamorphosed in greenschist facies (*EBq, EBs*).

Brown (in prep.) recognized two major allochthons: an upper allochthon comprising flat-lying thrust sheets of quartzite that forms the Eyre Range, resting on a lower allochthon of quartzite, semi-pelitic schist and phyllite. The lower allochthon consists of an imbricate sequence of southward-dipping thrust sheets that form a duplex structure. Imbricate thrust sheets are bounded by mylonite zones in greenschist facies. The metamorphic grade within the thrust sheets of the lower allochthon increases southward and the southernmost thrust sheet contains kyanite–sillimanite–staurolite–garnet schists. Within the thrust sheets of the lower allochthon, southeast-plunging folds with pronounced axial-plane cleavage and associated transposition of bedding are folded by southwest-plunging folds.

The thrusts transported rocks northwestward onto the edge of the Yilgarn Craton. Immediately to the north, the allochthons are thrust over gently dipping, little deformed and metamorphosed quartzite, conglomerate and dolomite of the Mount Barren Group that appear to rest unconformably on the greenstones and granitoid rocks of the Yilgarn Craton. To the southeast the allochthonous metasedimentary rocks are truncated by the Jerdacuttup Fault. This fault transported granulite and retrograded granulite facies gneisses of the Biranup Complex over both the lower and upper allochthons.

The precise age of the Mount Barren Group is unknown. It conformably overlies Archaean granites and greenstones, and its tectonic structures and metamorphism are thought to relate to mid-Proterozoic deformation and metamorphism within the Biranup and Nornalup Complexes. Rb–Sr isotopic data are presented and discussed by Thom et al. (1981).

Other metasedimentary rocks

Other metasedimentary rocks (*Eq*) include:

1. Thin sheets of quartzite, pelitic schist and BIF tectonically interleaved (by the first major episode of mid-Proterozoic deformation D_1) with metagabbroic rocks of the Fraser Complex. They were repeatedly intensely deformed and were attenuated into thin parallel layers. They were metamorphosed in granulite facies (during the first two major episodes of mid-Proterozoic metamorphism M_1 and M_2) and partly retrogressed to amphibolite facies during M_3.

2 Quartz-rich metasedimentary rocks that form prominent hills in the eastern part of the Nornalup Complex at Mount Ragged, Mount Dean, Mount Esmond, The Diamonds Hill, and Price Hill. They comprise mainly quartzite and quartz–mica schist, with a minor component of pelitic schist.

   Doepel, in Lowry and Doepel (1974), proposed the name 'Mount Ragged Beds' for these rocks and thought that they were unconformable upon the granitic rocks, although the contact relations are not exposed. The rocks have suffered D_2 deformation and M_2 metamorphism and so must predate the Esperance Granite. They are broadly similar to rocks of the Mount Barren Group, but their stratigraphy and structure have not been studied in detail. The name 'Mount Ragged Beds' is best abandoned. A name such as Mount Ragged schist would be more appropriate.

3. Metasedimentary gneisses interleaved with granitoid gneisses (together forming the Malcolm Gneiss) between Point Malcolm and Cape Pasley, and on islands in the eastern part of the Archipelago of the Recherche. They comprise pelitic, semi-pelitic and psammitic schists with various amounts of quartz, biotite, muscovite, cordierite, sillimanite, staurolite, and garnet. The interleaved granitoid gneiss is heterogeneous and includes both granodioritic and granitic protoliths. Zircons from a granitic sample have given a poorly defined U–Pb age of c. 1450 Ma (Nelson, D. R., 1991, pers. comm.).

   The metasedimentary rocks are intruded by the protoliths of the orthogneiss. They appear to pre-date remnants of basic dykes and are intruded by granite and pegmatite of the Recherche Granite complex. Eighteen zircons from a quartzo-feldspathic paragneiss define groups with U–Pb ages of c. 1560, 1810, 2035, 2175 and 2735 Ma (Nelson et al., in press).

4. Rubble of quartzite and quartz–mica schist that occurs within the Biranup Complex to the north and east of Esperance. Similar rocks may be a more widespread component of the Biranup Complex than appears from the outcrops. Magnetite-rich quartzite such as that known at Southdown in the Biranup Complex on ALBANY may contribute to the prominent magmatic layering seen on aeromagnetic maps covering the Biranup Complex.

Fraser Complex

The Fraser Complex is derived largely from gabbro with minor components of anorthosite, leucogabbro, melanogabbro and ultramafic rocks. It represents one or a number of large layered intrusions emplaced into, or at the base of, the lower crust. The rocks occur at thrust sheets, mostly between 2 and 5 km thick and over 100 km long, that were tectonically interleaved with thin strips of metasedimentary rocks (*Eq*), mainly quartzite, psammitic and pelitic schist and BIF, and recrystallized in granulite facies (D_1, M_1).

They were subsequently intruded by sheets of granite and pegmatite and strongly deformed while still at a deep crustal level (D_1, M_1).

Most of the rocks are now pyroxene granulites (*Ᵽa*$_2$, *Ᵽa*$_4$) with equigranular post-tectonic textures, or garnet amphibolite (*Ᵽa*$_1$). Tectonostratigraphic unit *Ᵽa*$_3$ (Myers, 1985) does not occur on ESPERANCE. It mainly consists of leucogabbro and anorthosite and lies between units *Ᵽa*$_2$ and *Ᵽa*$_3$ to the northeast on the KALGOORLIE 1:1 000 000 sheet. The eastern tectonostratigraphic unit of metagabbro (*Ᵽa*$_5$) is much less deformed and widely preserves relic igneous textures and minerals in lensoids of low deformation enclosed by anastomosing networks of strongly deformed metagabbro converted to pyroxene granulite. Igneous minerals from one of these undeformed rocks has given a Sm–Nd isochron of 1291 ± 21 Ma, thought to reflect the igneous crystallization age of the Fraser Complex (Fletcher et al., 1991).

The Fraser Complex forms part of a duplex structure (Cowalinya Duplex, Fig. 1) that also incorporates Dalyup Gneiss (including granitic augen gneiss (*Ᵽnp*) and heterogenous granitoid gneiss (*Ᵽng*)) of the Biranup Complex. It was transported northwestward onto the margin of the Yilgarn Craton and was overridden from the east by the Coramup Duplex of Coramup and Dalyup Gneiss (Fig. 1).

Nornalup Complex

The Nornalup Complex on ESPERANCE can be subdivided into the Recherche Granite and Esperance Granite complexes and Malcolm Gneiss (Table 1).

The Malcolm Gneiss (*Ᵽnm*) occurs in the easternmost exposed part of the orogen. It comprises a mixture of heterogeneous granitoid gneiss, mainly derived from (?c. 1450 Ma) granite, granodiorite and pegmatite, interleaved with paragneiss (?c. 1550 Ma). It was generally strongly, but heterogeneously, deformed by D_1 and D_2.

The Recherche Granite is subdivided into even-grained units (*Ᵽne*) and porphyritic units (*Ᵽno*). It was intruded as sheets together with synplutonic mafic dykes, and was boudinaged during D_1. Deformation (D_2) continued during high-grade metamorphism, and partial melt patches developed in the older gneiss, especially in the attenuated limbs of some asymmetric D_2 folds. Recrystallization (M_2) outlasted deformation and formed mineral assemblages in granulite facies with orthopyroxene, garnet, and strained, dark grey-green quartz and feldspar of waxy appearance.

The Esperance Granite (*Ᵽge*, *Ᵽgp*) was emplaced as sheets and plutons into the Recherche Granite and contains angular xenoliths of the older granites. Where these components are intimately mixed and form roughly equal proportions of the outcrop, they have been mapped as *Ᵽgm*.

Zircons from a porphyritic example of the Esperance Granite at Esperance have given a U–Pb SHRIMP age of 1138 ± 38 Ma. Zircons from the Recherche Granite indicate intrusion ages of c. 1300 Ma (Nelson et al., in press). These include: a porphyritic granodiorite from Israelite Bay, 1314 ± 21 Ma; a porphyritic granite at Poison Creek east of Cape Arid, 1330 ± 14 Ma; a fine, even-grained granite on the headland north of Observatory Island west of Esperance, 1288 ± 12 Ma; a granite gneiss from Coramup Hill, north of Esperance, 1283 ± 13 Ma; and a granite from Mount Burdett, north of Esperance, 1299 ± 18 Ma.

Regional structure

The main northeasterly tectonic grain reflects mid-Proterozoic deformation (c. 1300 to 1100 Ma) superimposed on both mid- and early Proterozoic and Archaean rocks. The main structures observed on the scale of the map (Fig. 1) are thrust sheets and duplex structures that transported the high-grade metamorphic rocks of the orogen northwestward onto the low-grade granite greenstone terranes of the Yilgarn Craton. This deformation process started at deep to mid-crustal levels in ductile conditions (D_1, D_2 and early D_3) with associated recrystallization in amphibolite or granulite facies (M_1, M_2 and early M_3), and was eventually superseded by brittle deformation (late D_3) (Table 1). Throughout most of the orogen, these brittle structures and cataclastic fabrics are parallel to previous ductile D_3 structures and fabrics. The last movements on major fault zones were entirely brittle and led to substantial brittle fracturing.

The major evolution of the thrust systems is shown schematically on the cross sections. The Ridley Duplex occurs in the core of the folded Hopetoun Duplex (Fig. 1). The latter consists of an isoclinally folded stack of thrust sheets, too complex to show at the scale of 1:1 000 000. It is overridden by the Cowalinya Duplex and associated Fraser Duplex. The Hopetoun Duplex itself was transported northwestward on a ramp over the East Barren and Eyre Duplexes of the Mount Barren Group, which were themselves thrust northwestward over an autochthonous part of the Mount Barren Group resting unconformably on the Yilgarn Craton.

These lower duplex structures were overridden by the Coramup Duplex of early and mid-Proterozoic gneiss and granites which carries the main bulk of the Nornalup Complex westward. Shear-sense indicators are widespread and show that the dominant movements were dextral with both individual thrust sheets, duplexes and the rocks of the orogen as a whole moving southwestward relative to the craton. Such transpressive movements were already in operation during the M_2 metamorphic peak in granulite facies as indicated by the widespread occurrence of small asymmetric folds with shear-zone limbs and associated partial melting. They suggest that the main direction of compressive stress during at least the later stages of mid-Proterozoic orogenic activity were oblique to the length of the orogen. This may reflect the oblique convergence of the Yilgarn Craton with another craton to the southeast.

Bremer Basin

Bremer Basin is the name given to a region of Phanerozoic deposition that extends along the southern margin of Western Australia as far east as Cape Pasley on ESPERANCE, and offshore across the continental shelf to the continental margin (Hocking, 1990a). The rocks exposed on land are Eocene and form an extensively eroded veneer, mostly less than 60 m thick, infilling palaeodrainage valleys and depressions and blanketing the smooth low topography on the Albany–Fraser Orogen and adjacent Yilgarn Craton.

The exposed rocks are part of the Pallinup Siltstone (*Tpp*) of the Plantagenet Group of Sequence Cz2 (Hocking, 1990a). They comprise marine siltstone, sandstone, and spongolite that, in the south, are locally richly fossiliferous with bivalves, gastropods, echinoids, bryozoans, and sponges. Inland there is a facies change to less fossiliferous rocks.

The Upper Eocene sea level was about 300 m above present sea level and so covered much of ESPERANCE, except the northwest part. A prominent erosional bench at an elevation of 300 m on the flanks of Mount Ragged and adjacent hills is thought to be a wave-cut platform that formed during the upper Eocene (Lowry and Doepel, 1974).

The Pallinup Siltstone is underlain by the 20–50 m thick Werillup Formation which does not outcrop on ESPERANCE but is known from extensive drilling to comprise siltstone and sandstone with a number of coal-bearing horizons (Le Blanc Smith, 1990). At Scadden, north of Esperance, the main coal seam is 12 m thick.

Eocene and Miocene sedimentary rocks occur in the vicinity of Norseman in the palaeodrainage basin of Lake Cowan. The outcrops are too small to be shown on the ESPERANCE 1:1 000 000 map, but are indicated on the NORSEMAN 1:250 000 map (Doepel, 1973). They were called the Eundynie Group and described by Cockbain (1968) and Doepel (1973). The stratigraphy has recently been revised by Clarke (1993) and correlated with deposits elsewhere in the Bremer and Eucla Basins. Around Norseman he distinguished Eocene and Miocene groups overlain by Pliocene evaporites.

Eucla Basin

Eocene and Miocene rocks exposed in the eastern part of ESPERANCE are part of the Eucla Basin, which extends as a veneer over the central southern part of the Australian continent eastward from Israelite Bay. The western part of the Eucla Basin is described by Lowry (1970b) and Hocking (1990b).

The lowest formation exposed on ESPERANCE is the Toolinna Limestone (*Tt*), a late Eocene bryozoan calcarenite, generally about 60 m thick, that forms prominent cliffs in the vicinity of Point Culver and Toolinna Cove. It is part of depositional Sequence Cz2 (Hocking, 1990b). It is overlain in turn by the early Miocene Abrakurrie Limestone (*Ta*), a bryozoan calcirudite and calcarenite with a maximum thickness of about 100 m, and the 30 m thick Nullarbor Limestone (*Tn*), a foraminiferal calcarenite, that together are part of depositional Sequence Cz3.

Drilling indicates that these rocks are underlain by granulite-facies granitic gneiss covered by early Cretaceous Loongana Sandstone (>33 m thick), part of deposition sequence Mz3, and the Neocomian to Santonian Madura, Toondi and Nurina Formations of shale and siltstone (>315 m thick) that are part of depositional Sequences Mz4 and Mz5. These rocks are overlain by the thin Middle Eocene Hampton Sandstone and Upper Eocene Wilson Bluff Limestone (Lowry, 1970a; 1970b; Hocking, 1990b).

Regolith

Most of the rocks of ESPERANCE are covered by a veneer of unconsolidated or partly consolidated deposits called regolith.

Weathering products

Laterite, silcrete, and ferricrete (*Czl*) occur as small scattered outcrops in the west and northwest of ESPERANCE. They are locally abundant to the north of Ravensthorpe where they formed as weathering products of Archaean granite and greenstones. Although these deposits (*Czl*) have traditionally been referred to as Cainozoic on Geological Survey maps, Clarke (1993, 1994) has recently demonstrated that in the vicinity of Kambalda, on the KALGOORLIE 1:1 000 000 sheet just north of Norseman, these deposits are incised by Eocene palaeodrainage channels, and may have originated between Late Permian and Middle Jurassic time.

White and yellow sand and limonite gravel (*Czs*) cover extensive areas in the western part of ESPERANCE and in a belt 40 km wide inland from the coast. Some sand contains layers of limonitic pisoliths, some contains basal layers of cemented ironstone nodules, and some passes downward into weathered rock. In the west, this sand overlies laterite (*Czl*) and may have formed in association with the laterite. Towards the south and east there is a sharp decrease in the occurrence of laterite, and the white and yellow sand and gravel (*Czs*) rests directly on either weathered or fresh bedrock. This could reflect a variation in climatic conditions from being wetter in the north and west to drier in the south and east during the formation of the laterite, that led to a southeastward decrease in the formation of laterite. Alternatively laterite could have been more uniformly developed over the whole region but have been more extensively eroded towards the south and east, and the bedrock blanketed by largely eolian sand, before being buried by the loess-like deposit of *Cze*.

The deposits of sand (*Czs*) in the 40 km-wide belt along the coast cover two distinct peneplains at altitudes of about 75–145 m and 50–80 m. These plains are thought to have formed in the Miocene (Morgan and Peers, 1973). However, much of the lower plain approximately corresponds in height with the 80 m wave-cut platform on East Mount Barren, just west of Hopetoun, that is thought to have formed during a Pleistocene interglacial period. If this similarity is not coincidental then the 50–80 m peneplain covered by sand (*Czs*) may have been modified, or formed by erosion, from the higher sand plain during the Pleistocene.

Rock platforms noted by Morgan and Peers (1973) at altitudes of 225–240 m and 160–170 m probably predate the formation of the sand plain (*Czs*) at an altitude of 75–145 m and postdate the upper Eocene rock platform at 300 m on Mount Ragged (Lowry and Doepel, 1974).

Calcareous clay (*Czr*) with concretions called kankar (Lowry, 1970b) covers much of the Nullarbor Limestone (*Tn*) as a residual weathering product. Calcareous clay, silt, and sand (*Cze*) is even more widespread and forms the dominant soil over undulating topography across most of ESPERANCE. It is a buff, sandy to calcareous loam containing sheet-like and nodular calcareous concretions (kankar). It is thought to be residual over Tertiary limestone and elsewhere to be largely eolian, having been derived as a loess from calcareous dust blown westward from soil overlying the Tertiary limestones of the Eucla Basin during arid conditions (Doepel and Lowry, 1970), probably during the Pleistocene (Lowry, 1970b).

Unit *Cze* overlies quartz sand (*Czs*) and laterite (*Czl*). It decreases in abundance towards the western part of ESPERANCE where it is restricted mainly to drainage valleys and basins. This appears to have been the western limit of its original distribution as it does not occur on ALBANY. It may have been concentrated in the valleys and basins by erosion of a thin widespread cover before being overlain by alluvial (*Cza*) and eolian (*Czd*) deposits. It is absent in a 40 km wide belt along the south coast where it appears to have been completely removed by more vigorous erosion during the late Pleistocene and Holocene.

Drainage-related deposits

The valleys and flood plains contain both alluvial and lacustrine sedimentary deposits. Alluvial sand, silt, clay, and gravel, and minor lacustrine deposits, transported and deposited by flowing water, are grouped as *Cza*. The palaeodrainage system of Lakes Cowan and Dundas was recently studied by Clarke (1993, 1994) around Kambalda, north of Norseman. He found that it developed between the Middle Jurassic and early Eocene and was overlain by gypsum-bearing deposits and dunes during Pliocene aridity. A late Pleistocene to Holocene low sea level caused rejuvenation of rivers in the coastal region and the dissection of alluvial flood plains.

Eolian sand, silt, and clay form prominent deposits (*Czd*) around many lakes, especially on their eastern sides. These deposits are largely derived by wind erosion from dry lake beds and occur as dunes and sheets. They are generally gypsiferous and saline as a result of repeated Pliocene–Recent evaporation from the lakes.

Coast-related deposits

East of Cape Arid an extensive marine erosion surface, called the Israelite Plain by Lowry (1970b), is overlain by marine limestone deposits (*Qpl*) up to several metres thick. This limestone contains fossil bivalves and in some localities chert flakes worked by humans. It may be late Pleistocene and is extensively overlain by Pleistocene and Holocene quartz sand dunes (*Qpd* and *Qhs*). It appears to be equivalent to the Roe Calcarenite described by Lowry (1970b) on a similar marine erosion surface called the Roe Plains extending eastward beyond ESPERANCE.

Quartz sand (*Qpd*) occurs as coastal dunes, stabilized by a cover of vegetation, whereas quartz and calcareous sands (*Qhs*) are mobile, or in part lithified, beach and dune sands.

Deposits of cemented wind-blown calcareous sand (eolian calcarenite) (*Qpt*) and overlying residual sand occur along the whole coastline from Hopetoun eastward to Cape Arid. They were probably derived from former beach lines and sand flats south of the present coastline that were exposed during periods of low sea level associated with peaks of Pleistocene glaciation.

Marine Quaternary erosion surfaces

Quaternary marine erosion surfaces occur along the whole of the south coast between altitudes of about 10 and 30 m. They are partly eroded and covered by sand dunes (*Qpd*, *Qhs*) and, west of Cape Arid, by calcarenite (*Qpt*). The best preserved of these surfaces forms the Israelite Plain, northeast of Cape Pasley and below the Wylie Scarp, and is overlain successively by marine limestone (*Qpl*) and sand dunes (*Qpd* and *Qhs*).

Remnants of older marine wave-cut platforms can be seen along much of the coast, especially between altitudes of 60 and 80 m, such as the 80 m high platform on East Mount Barren. Rock platforms and drowned shorelines have also been observed offshore (Morgan and Peers, 1973) at depths of around 6–8 m, 11–13 m, 16–21 m and 54–100 m. They reflect stands in the shoreline during changes in sea level related to the expansion and contraction of the Pleistocene ice caps, and/or tectonic movements.

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ESPERANCE

AUSTRALIA 1:1 000 000 GEOLOGICAL SERIES

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

SHEET SI 51

SYMBOLS

Geological boundary
- exposed
- concealed
- interpreted, partly based on aeromagnetic data

Fault
- exposed
- concealed, partly based on aeromagnetic data
- thrust

Shear sense indicator, steep or vertical, D_1 D_2

Bedding, igneous layering, or foliation, showing strike and dip
- inclined
- vertical

Fold axis or lineation, showing direction of plunge

Subsurface trend of steep or vertical layering in Albany-Fraser Orogen indicated by aeromagnetic data

Highway with national route marker

Formed road

Railway

Townsite
- population 1000—10 000 — NORSEMAN
- population less than 1000 — Grass Patch, Balladonia

Homestead

National park, major nature reserve boundary

Horizontal control, major

Watercourse, ephemeral

Bathymetric contour, depth in metres

Mineral field boundary

Major mine (gold, unless otherwise indicated)

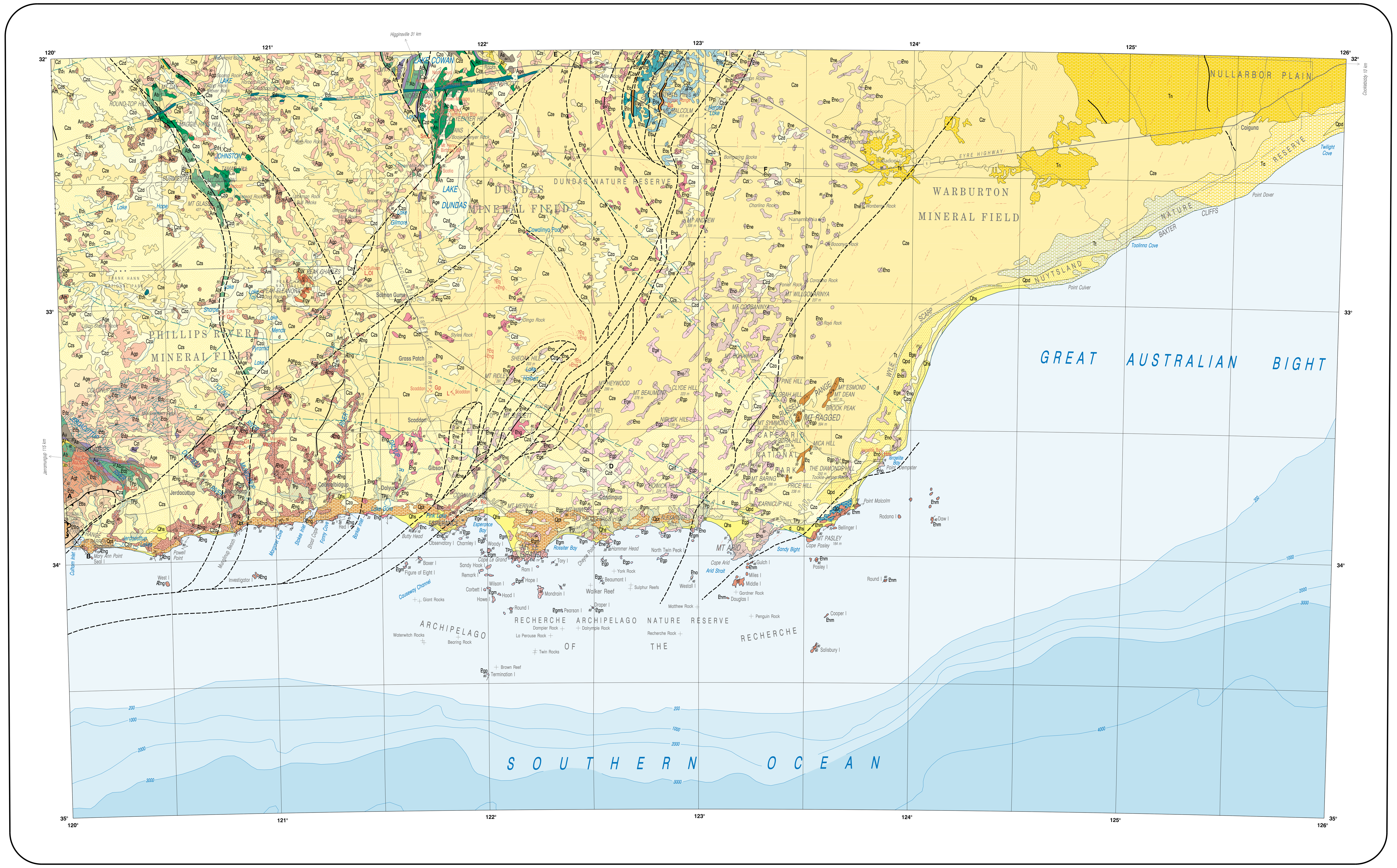
Mine

Major openout

Openout

Prospect

Mineral occurrence
- Building stone, facing stone
- Copper — Cu
- Gold — Au
- Graphite — Gr
- Gypsum — Gp
- Heavy-mineral sands — Hm
- Lignite — L
- Lithium — Li
- Magnesite — Ma
- Manganese — Mn
- Nickel — Ni
- Oil shale — Ol
- Rock aggregate, crushed — Rc
- Salt — Na
- Silver — Ag
- Talc — T
- Tin — Sn
- Vanadium — V
- Vermiculite — Ve



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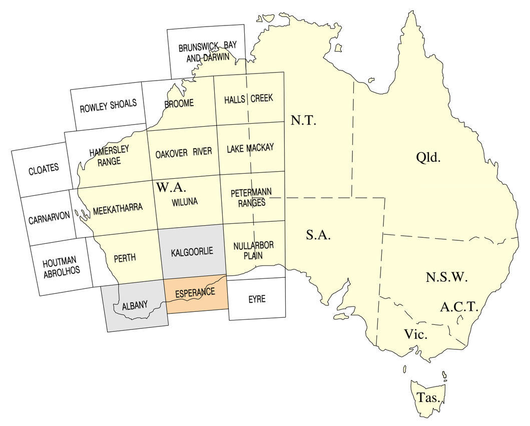

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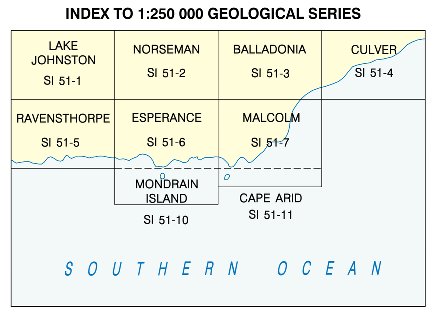
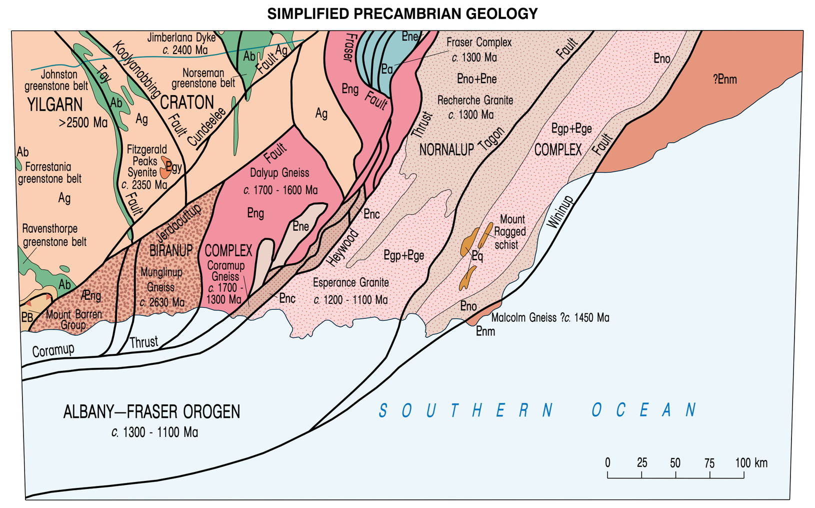


SIMPLIFIED PRECAMBRIAN GEOLOGY



DEPARTMENT OF MINERALS AND ENERGY

HON. GEORGE CASH, J.P., M.L.C.
MINISTER FOR MINES

K.R. PERRY, DIRECTOR GENERAL

PIETRO GUJ
DIRECTOR, GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

SCALE 1:1 000 000

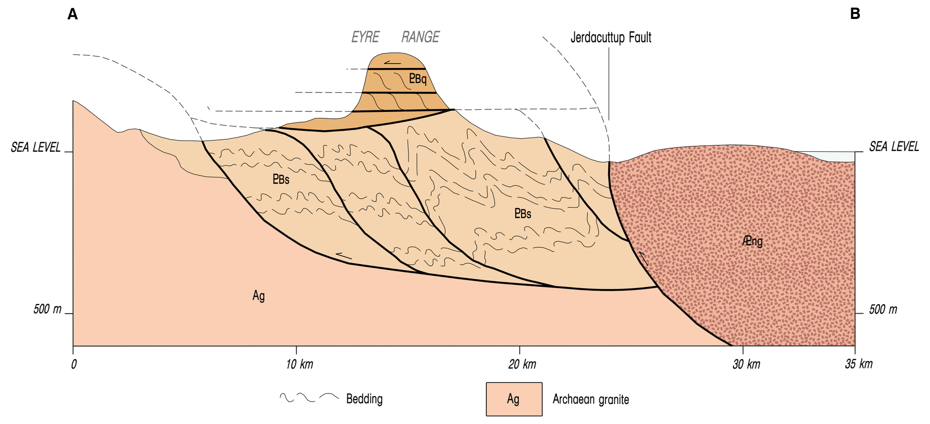
LAMBERT CONFORMAL CONIC PROJECTION
STANDARD PARALLELS 32° 40' and 35° 20'

MAIN FEATURES OF THE REGOLITH AND GEOMORPHOLOGY

- River channel with active Quaternary erosion
- Inland extent of active Quaternary erosion
- Holocene and Pleistocene quartz sand dunes on Pleistocene marine limestone
- Late Pleistocene cemented calcareous dune sand
- Pleistocene calcareous loess
- ?Holocene to Pliocene alluvial and lacustrine deposits
- Dominantly ?Oligocene to Miocene gravel and quartz sand
- Tertiary limestone
- Precambrian rocks

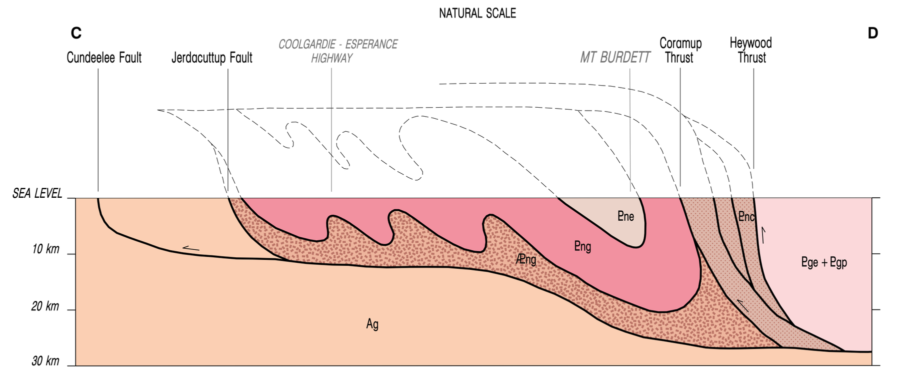
SIMPLIFIED SECTIONS

SCALE EXAGGERATION: HORIZONTAL x 4, VERTICAL x 60

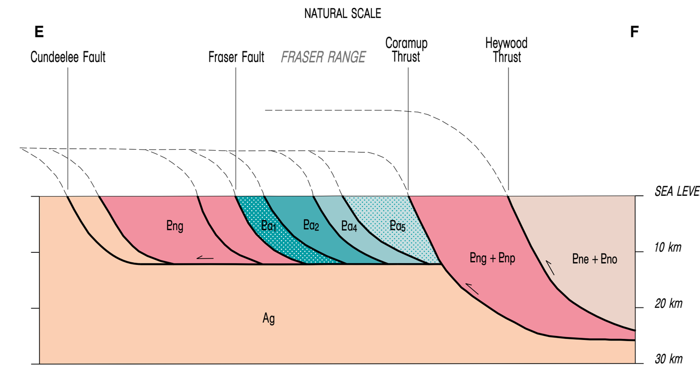


Bedding — Ag Archaean granite

NATURAL SCALE



NATURAL SCALE



REFERENCE

PHANEROZOIC — CAINOZOIC

HOLOCENE	Qhs	Quartz and calcareous sand; mobile or in part lithified beach and dune deposits
PLEISTOCENE	Qpt	Eolian calcarenite and overlying residual quartz sand
	Qpd	Quartz sand in fixed coastal dunes
	Qpl	Marine limestone; south of Israelite Bay
	Czd	Eolian sand, silt and clay, partly gypsiferous; in dunes and sheets around playa lakes
	Cza	Sand, silt, clay, and gravel; alluvium and other valley and playa lake deposits, mainly saline and gypsiferous
	Cze	Calcareous clay, silt, and sand; eolian and residual deposits with locally developed sheet and nodular kankar
	Czr	Calcareous clay and kankar; residual deposits over NULLARBOR LIMESTONE
	Czs	Quartz sand and gravel; residual and transported deposits
	Czl	Laterite, silcrete, ferricrete, and associated clastic rocks; residual and transported deposits, and deeply weathered rock
MIOCENE	Tn	**NULLARBOR LIMESTONE:** foraminiferal calcarenite
	Ta	**ABRAKURRIE LIMESTONE:** bryozoan calcirudite and calcarenite
EOCENE	Tt	**TOOLINNA LIMESTONE:** bryozoan calcarenite
	TPp	**PLANTAGENET GROUP** — **PALLINUP SILTSTONE:** siltstone, sandstone, conglomerate; with fossil sponges and molluscs
	d	Dolerite dykes, intruded into Precambrian rocks; interpreted from aeromagnetic data where dashed

REGOLITH; EUCLA BASIN; BREMER BASIN

PROTEROZOIC — ALBANY — FRASER OROGEN

Nornalup Complex

ESPERANCE GRANITE — c. 1200 - 1100 Ma

Weakly to moderately deformed (D_3) and recrystallized (M_3) in prograde amphibolite facies or retrograde greenschist facies

Unit	Description
Ꝑge	Granite, even-grained
Ꝑgp	Granite, porphyritic
Ꝑgm	Mixture of Ꝑge or Ꝑgp with Ꝑne and Ꝑno; Ꝑge or Ꝑgp with abundant xenoliths of Ꝑne and Ꝑno, or Ꝑne and Ꝑno with abundant sheets of Ꝑge or Ꝑgp

RECHERCHE GRANITE — c. 1300 Ma

Moderately to strongly deformed (D_1 $+D_2$ $\pm D_3$) and recrystallized (M_1 $+M_2$ $\pm M_3$) in prograde granulite facies, or retrograde amphibolite or greenschist facies

Unit	Description
Ꝑne	Granite, heterogeneous, even-grained
Ꝑno	Granite, heterogeneous, porphyritic

Fraser Complex

c. 1300 Ma

Moderately to strongly deformed (D_1 $\pm D_2$ $\pm D_3$) and recrystallized (M_1 $+M_2$ $\pm M_3$) in prograde granulite facies, or retrograde amphibolite or greenschist facies

Unit	Description
$Ꝑa_1$	Garnet amphibolite, unit 1
$Ꝑa_2$	Pyroxene granulite, unit 2
$Ꝑa_4$	Pyroxene granulite, unit 4
$Ꝑa_5$	Metagabbro, unit 5

MALCOLM GNEISS

Moderately to strongly deformed (D_1 $+D_2$ $\pm D_3$) and recrystallized (M_1 $+M_2$ $\pm M_3$) in prograde granulite facies, or retrograde amphibolite or greenschist facies at c. 1300 - 1100 Ma

Unit	Description
Ꝑnm	Mixture of heterogeneous granitoid gneiss; derived from ?c. 1450 Ma granite, granodiorite and pegmatite, and paragneiss (?c. 1550 Ma)
$Ꝑd_2$	Dolerite and metadolerite dykes; interpreted from aeromagnetic data where dashed

Metasedimentary rocks

Moderately deformed (D_1 $\pm D_2$ $\pm D_3$) and mainly recrystallized (M_1 $+M_2$ $\pm M_3$) in prograde greenschist or amphibolite facies at c. 1300 - 1100 Ma

Age	Unit	Description
?c.1550 Ma	Ꝑq	Quartzite, quartz-mica schist, pelitic schist, and banded iron-formation
		MOUNT BARREN GROUP
	ꝐBq	Quartzite
	ꝐBs	Phyllite and quartz-mica schist

Biranup Complex

Moderately to strongly deformed and recrystallized (M_1 $+M_2$ $\pm M_3$); in prograde granulite facies or retrograde amphibolite or greenschist facies at c. 1300 - 1100 Ma

CORAMUP GNEISS

Age	Unit	Description
c. 1700 - 1300 Ma	Ꝑnc	Granitoid gneiss, heterogeneous; mainly derived from Recherche Granite, deformed (D_1 $+D_2$ $\pm D_3$) with orthogneiss (c. 1700 - 1600 Ma) and paragneiss, including quartzite (?c. 1550 Ma)

DALYUP GNEISS

Deformed by D_0 $+D_1$ $+D_2$ $\pm D_3$

Age	Unit	Description
c. 1700 - 1600 Ma	Ꝑnp	Granitic augen gneiss (c. 1660 Ma)
	Ꝑng	Granitoid gneiss, heterogeneous; mainly derived from granite, granodiorite, and pegmatite (c. 1700-1600 Ma), with some Recherche Granite

ARCHAEAN

MUNGLINUP GNEISS

Deformed by D_0 $+D_1$ $+D_2$ $\pm D_3$

Age	Unit	Description
c. 2630 Ma	ÆPng	Granitoid gneiss, heterogeneous; mainly derived from granite, granodiorite, tonalite and pegmatite (c. 2630 Ma), with some Recherche Granite

PROTEROZOIC

Age	Unit	Description
c. 2350 Ma	Ꝑgy	**FITZGERALD PEAKS SYENITE:** syenite and quartz syenite
c. 2400 Ma	$Ꝑd_1$	Mafic dykes; dolerite or layered norite, gabbro, pyroxenite, and peridotite (Widgiemooltha Dyke Swarm); partly interpreted from aeromagnetic data where dashed

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Granitoid rocks

c. 2690 - 2550 Ma

Undeformed to weakly deformed; unrecrystallized or recrystallized in prograde greenschist facies

Unit	Description
Agt	Tonalite and granodiorite
Age	Granite, even-grained
Agp	Granite, porphyritic

c. 3000 - 2640 Ma — Recrystallized in prograde amphibolite or granulite facies, or retrograde amphibolite facies

Unit	Description
Agn	Heterogeneous granite and migmatite, moderately deformed

Greenstones

c. 3000 - 2690 Ma — Strongly deformed greenstones; recrystallized in greenschist or low amphibolite facies

Unit	Description
As	Sedimentary rock
Af	Felsic igneous rock
Ab	Mafic igneous rock
Au	Ultramafic igneous rock

c. 3000 - 2690 Ma — Strongly deformed greenstones, recrystallized in amphibolite or granulite facies

Unit	Description
Ab	Mainly mafic igneous rocks and banded iron-formation

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