EXPLANATORY NOTES

GOVERNMENT OF WESTERN AUSTRALIA

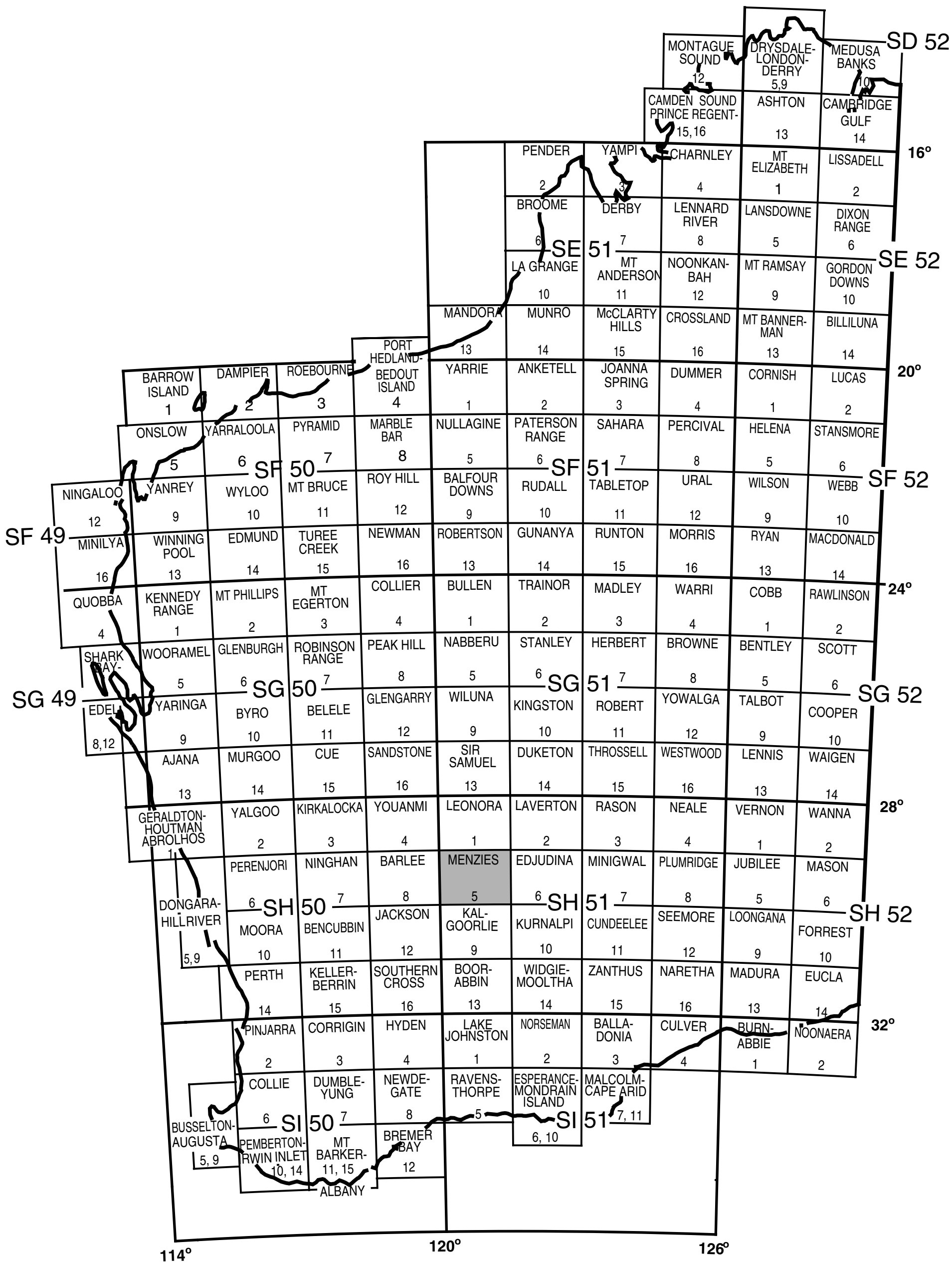
GEOLOGY OF THE MULLINE AND RIVERINA 1:100 000 SHEETS

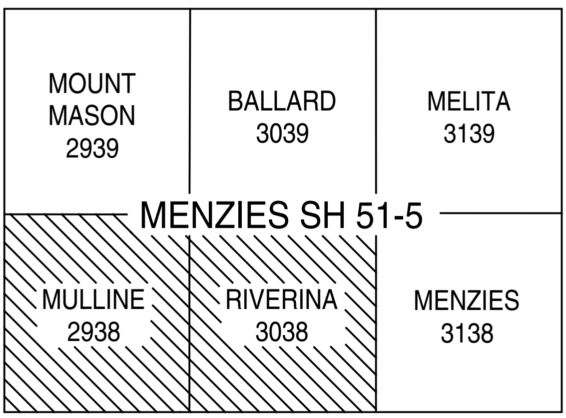
by S. Wyche

1:100 000 GEOLOGICAL SERIES

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
PENDER 2
YAMPI 3
CHARNLEY 4
MT ELIZABETH 1
LISSADELL 2
16°
BROOME 6
DERBY 7
LENNARD RIVER 8
LANSDOWNE 5
DIXON RANGE 6
SE 51
SE 52
LA GRANGE 10
MT ANDERSON 11
NOONKAN-BAH 12
MT RAMSAY 9
GORDON DOWNS 10
MANDORA 13
MUNRO 14
McCLARTY HILLS 15
CROSSLAND 16
MT BANNER-MAN 13
BILLILUNA 14
PORT HEDLAND-BEDOUT ISLAND 4
YARRIE 1
ANKETELL 2
JOANNA SPRING 3
DUMMER 4
CORNISH 1
LUCAS 2
20°
BARROW ISLAND 1
DAMPIER 2
ROEBOURNE 3
ONSLOW 5
YARRALOOLA 6
PYRAMID 7
MARBLE BAR 8
NULLAGINE 5
PATERSON RANGE 6
SAHARA 7
PERCIVAL 8
HELENA 5
STANSMORE 6
SF 50
SF 51
SF 52
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
SF 49
MINILYA 16
WINNING POOL 13
EDMUND 14
TUREE CREEK 15
NEWMAN 16
ROBERTSON 13
GUNANYA 14
RUNTON 15
MORRIS 16
RYAN 13
MACDONALD 14
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
24°
SHARK BAY-
WOORAMEL 5
GLENBURGH 6
ROBINSON RANGE 7
PEAK HILL 8
NABBERU 5
STANLEY 6
HERBERT 7
BROWNE 8
BENTLEY 5
SCOTT 6
SG 49
SG 50
SG 51
SG 52
EDEL 8,12
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
GERALDTON-HOUTMAN ABROLHOS 1
YALGOO 2
KIRKALOCKA 3
YOUANMI 4
LEONORA 1
LAVERTON 2
RASON 3
NEALE 4
VERNON 1
WANNA 2
28°
PERENJORI 6
NINGHAN 7
BARLEE 8
MENZIES 5
EDJUDINA 6
MINIGWAL 7
PLUMRIDGE 8
JUBILEE 5
MASON 6
SH 50
SH 51
SH 52
DONGARA-HILLRIVER 5,9
MOORA 10
BENCUBBIN 11
JACKSON 12
KAL-GOORLIE 9
KURNALPI 10
CUNDEELEE 11
SEEMORE 12
LOONGANA 9
FORREST 10
PERTH 14
KELLER-BERRIN 15
SOUTHERN CROSS 16
BOOR-ABBIN 13
WIDGIE-MOOLTHA 14
ZANTHUS 15
NARETHA 16
MADURA 13
EUCLA 14
PINJARRA 2
CORRIGIN 3
HYDEN 4
LAKE JOHNSTON 1
NORSEMAN 2
BALLA-DONIA 3
CULVER 4
BURN-ABBIE 1
NOONAERA 2
32°
COLLIE 6
DUMBLE-YUNG 7
NEWDE-GATE 8
RAVENS-THORPE 5
ESPERANCE-MONDRAIN ISLAND 6, 10
MALCOLM-CAPE ARID 7, 11
SI 50
SI 51
BUSSELTON-AUGUSTA 5, 9
PEMBERTON-IRWIN INLET 10, 14
MT BARKER-ALBANY 11, 15
BREMER BAY 12
114°
120°
126°


MOUNT MASON 2939
BALLARD 3039
MELITA 3139
MENZIES SH 51-5
MULLINE 2938
RIVERINA 3038
MENZIES 3138

SW88

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GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

GEOLOGY OF THE MULLINE AND RIVERINA 1:100 000 SHEETS

by
S. Wyche

Perth 1999

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Cover photograph:
Tremolite–chlorite schist in the zone of deformation between the Ida and Ballard Faults in the northern part of RIVERINA (AMG 682341).

Contents

Appendices

Figures

Geology of the Mulline and Riverina 1:100 000 sheets

by

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Abstract

The MULLINE and RIVERINA 1:100 000 sheets lie in the eastern part of the Archaean Yilgarn Craton. The sheets contain substantial parts of the Illaara and Mount Ida greenstone belts, the Ghost Rocks segment of the Menzies – Broad Arrow greenstone belt, and parts of the poorly exposed Yerilgee and Maninga greenstone belts — all separated by areas of granitoid rock of mainly monzogranite composition.

The sheets straddle the boundary between the mainly 2.7 Ga greenstones of the Kalgoorlie Terrane in the Eastern Goldfields Province, and the mainly older (3.0 – 2.7 Ga) greenstones of the Barlee Terrane in the Southern Cross Province. The boundary between the terranes, the Ida Fault, is a moderately easterly dipping, crustal-scale feature that shows as a prominent lineament on aeromagnetic images. The Ida Fault has a long history of movement that may include extension as well as reverse movement and transpression.

Greenstone sequences in the Kalgoorlie Terrane, east of the Ida Fault, are characterized by an abundance of ultramafic and mafic volcanic rocks, and a lack of felsic volcanic and sedimentary rocks. Ultramafic rocks are correlated with those in the Kalgoorlie region to the southeast. Greenstones west of the Ida Fault include abundant tholeiitic mafic volcanic rocks, high-Mg mafic volcanic rocks, common banded iron-formation, and intervals of intermediate volcanic and volcaniclastic rocks. In the northwestern part of the MULLINE sheet, there are abundant quartz-rich sandstones and conglomerates, apparently low in the succession.

Although earlier deformation episodes have been mooted, the best preserved tectonic fabrics and structures in greenstones and granitoids on MULLINE and RIVERINA appear to have developed during a possibly long lived, east–west compressional regime. Structures in granitoid rocks, including the development of gneissic fabrics immediately east of the Mount Ida greenstone belt, suggest that granitoid intrusion both pre-dated and post-dated the main east–west compression. A late-stage compressive event is indicated by dominant north-northeasterly trending faults and subordinate east-southeasterly trending faults in both granitoids and greenstones. These structures overprint all Precambrian elements, except the mainly easterly to northeasterly trending fractures, which are probably filled by Proterozoic mafic and ultramafic dykes.

All greenstones have been metamorphosed, with metamorphic grade typically higher (upper greenschist and amphibolite facies) than in the mainly greenschist facies greenstones to the southeast in the Kalgoorlie region, and to the west in the Marda–Diemals area.

Gold has been found in most greenstone sequences on MULLINE and RIVERINA, but the largest production has been from the Mount Ida greenstone belt.

KEYWORDS: Archaean, regional geology, greenstone, granite, gneiss, Eastern Goldfields, Southern Cross, Kalgoorlie Terrane, Barlee Terrane, Ida Fault, gold

Introduction

The MULLINE* (Swager and Wyche, 1996) and RIVERINA (Wyche, 1995) 1:100 000 sheets occupy the southwestern and south-central parts of the MENZIES 1:250 000 sheet, between latitudes 29°30' and 30°00'S and longitudes 120°00' and 121°00'E.

There are very few published studies over the area. Gibson (1904) and Feldtmann (1915, 1916) described gold workings in the southern part of the Mount Ida greenstone belt in the early 20th century, which was the period of most intensive mining activity. At that time, there were settlements at the Mulwarrie (AMG 640792)† and Mulline (AMG 595005) mining centres on RIVERINA. The first edition of the MENZIES 1:250 000 geological sheet was published in 1971 (Kriewaldt, 1970). Results of a regional geochemical sampling and associated regolith mapping program over the MENZIES 1:250 000 sheet area have also been published (Kojan and Faulkner, 1994).

During an extensive nickel–copper exploration program between 1966 and 1975, CRA Exploration Pty Ltd produced detailed outcrop and interpretive maps over a large part of the Mount Ida greenstone belt (e.g. Tuite, 1970). Unpublished maps and data produced as a result of mineral exploration are available through the Western Australian Mineral Exploration (WAMEX) open-file system at the Department of Minerals and Energy's library in Perth, and at the Geological Survey of Western Australia's (GSWA's) Kalgoorlie Regional Office.

The Ghost Rocks area in northeastern RIVERINA was mapped by C. P. Swager in 1988, and descriptions of the greenstone succession and structural geology are included in the Explanatory Notes for the MENZIES 1:100 000 geological map sheet (Swager, 1994). Field mapping on MULLINE and RIVERINA was carried out between August 1990 and November 1993. Rocks within, and adjacent to, the greenstones between Mulwarrie and Blue Well were mapped using 1:25 000-scale colour aerial photographs taken in 1990 for the Western Australian Department of Lands Administration (DOLA). Other areas were mapped using 1:50 000-scale black-and-white aerial photographs taken in 1984 for DOLA. Geological interpretation was assisted by 200-m line-spaced aeromagnetic data collected by World Geoscience Corporation Ltd.

Access

The town of Menzies lies about 2 km east of the eastern boundary of RIVERINA, and a sealed road and railway line run from Menzies south to Kalgoorlie (130 km) and north to Leonora (100 km).

The Riverina Homestead is in the central-western part of RIVERINA (AMG 645060; Fig. 1). There are no other homesteads on either of the map sheets, but parts of the Credo, Walling Rock, Mount Owen, and Goongarrie pastoral stations lie within the sheet areas. Short- and long-term camps are established periodically as a result of mining and exploration activity.

Access through the region is provided by the formed Evanston–Menzies Road, which runs from Menzies to Diemals Homestead, about 70 km west of the western boundary of MULLINE (Fig. 1). The Menzies–Sandstone Road traverses the northeastern part of RIVERINA, providing access to the Ghost Rocks area (AMG 955283). A road from the Davyhurst mining district, via Mulwarrie in the south, runs along the greenstone belt that straddles the boundary between the MULLINE and RIVERINA map sheets, and joins the Menzies–Sandstone Road on BALLARD to the north. Access to the western greenstone belt on MULLINE is by an exploration track that runs north from Hospital Rocks off the Evanston–Menzies Road, or along a track from the Menzies–Sandstone Road on MOUNT MASON to the north. The southwestern corner of MULLINE is accessible via a track from the Evanston–Menzies Road, just west of the sheet boundary.

Climate, physiography, and vegetation

The region has a semi-arid climate. Menzies has an average annual rainfall of 247 mm, and Diemals has an annual average of 276 mm. Rain may fall at any time during the year, but summer rains tend to be more episodic. The hottest months are from December to March when temperatures regularly exceed 40°C, and the coldest months from June to August when there are occasional frosts.

Relief is low (<200 m across the study area), with the highest points around Mount Morley (541 m above the Australian Height Datum), north of Riverina Homestead (AMG 638168; Fig. 1). A northerly trending chain of lakes and claypans through the centre of MULLINE joins Lake Ballard to the north, on MOUNT MASON and BALLARD, to form part of the Yindarlgooda Palaeoriver (Hocking and Cockbain, 1990). Away from areas of greenstone, sand- and loam-covered plateaus with breakaways are underlain by lateritic duricrust over granitoid rock. There is extensive development of west-northwesterly trending sand dunes in the eastern part of RIVERINA.

MULLINE and RIVERINA lie mainly within the Austin Botanical District, or Murchison Region, of the Eremaean Province of Beard (1990). This region is characterized by extensive woodlands dominated by mulga (*Acacia aneura*) over a sparse, low shrub layer that may include acacia, cassia, and eucalypt species, with a ground layer of ephemeral herbs, and sparse perennial and annual grasses. Spinifex grass may grow in areas of extensive sandplain. The mulga scrub is very abundant in areas underlain by granitoid rocks, but a greater variety of vegetation is found in the greenstone belts. Eucalyptus trees replace mulga as the dominant tree type in the

* Capitalized names refer to standard 1:100 000 map sheets, unless otherwise indicated.

† Localities are specified by the Australian Map Grid (AMG) standard six-figure reference system whereby the first group of three figures (eastings) and the second group (northings) together uniquely define position, on this sheet, to within 100 m. AMG coordinates of localities mentioned in the text are listed in Appendix 1.

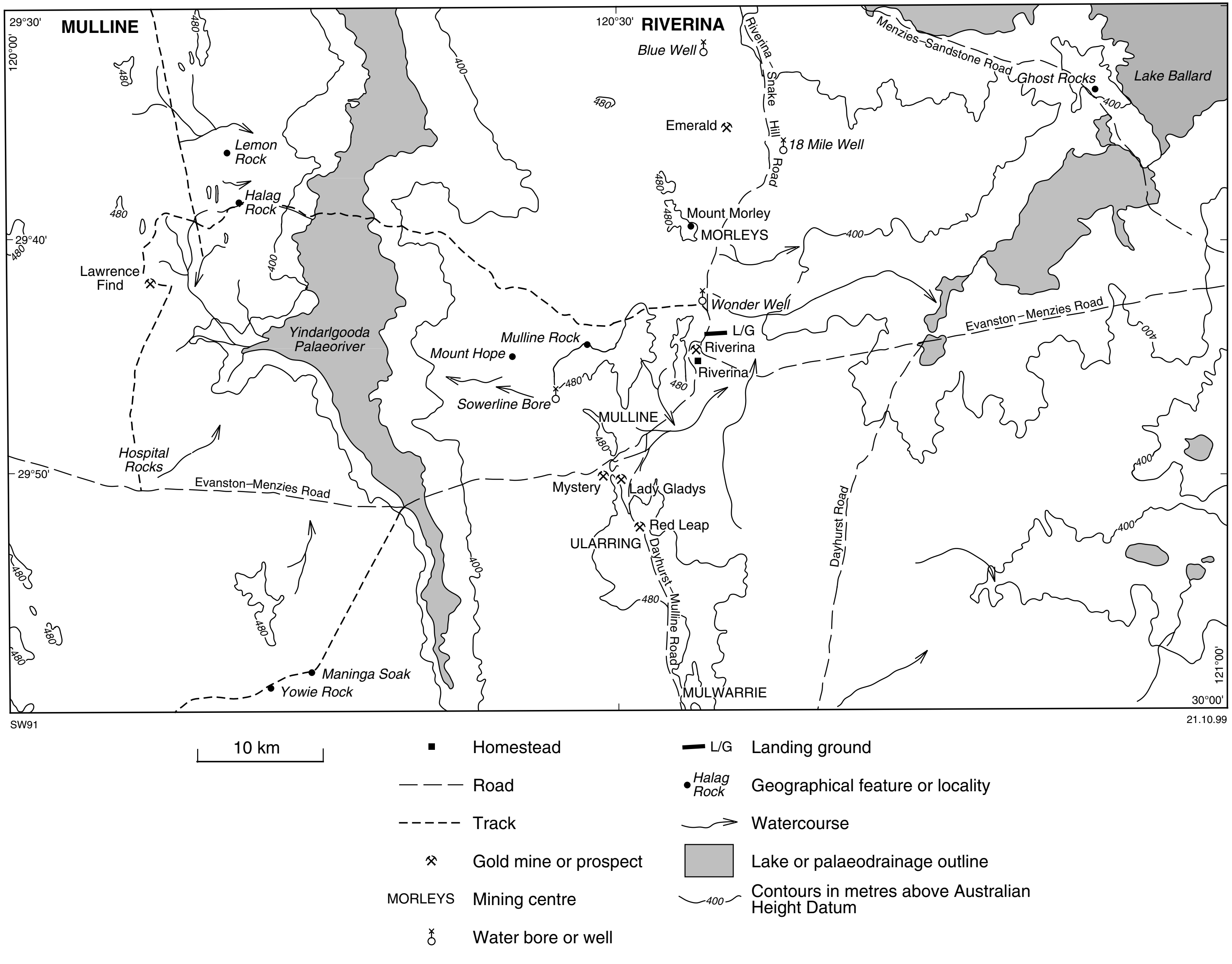

Figure 1. Mulline and Riverina — physiography and localities

southwest, which lies in the Coolgardie Botanical District of the Southwestern Interzone of Beard (1990).

Nomenclature

All Archaean rocks described in this report have been subjected to low- to medium-grade metamorphism. However, for ease of description, the prefix 'meta' is commonly omitted.

The term 'komatiite' here refers to ultramafic rocks with relict platy olivine-spinifex textures. Arndt and Nisbet (1982) used the term more broadly to describe ultrabasic extrusive rocks with more than 18% MgO. The terms 'komatiitic basalt' and 'high-Mg basalt' are used to characterize basaltic rocks with relict pyroxene-spinifex texture, or those that have been chemically analysed and shown to contain more than 10% MgO. These rocks typically contain between 10 and 18% MgO (Cas and Wright, 1987).

Precambrian geology

Greenstone sequences comprise less than 20% of the Archaean rocks on MULLINE and RIVERINA, the main part of the area being granitoid and granitoid gneiss terrain. There are three major areas of greenstones (Figs 2 and 3): the Mount Ida greenstone belt (Griffin, 1990a) along the boundary between the two sheets, between Mulwarrie in the south and the western end of Lake Ballard in the north; the Illaara greenstone belt of Griffin (1990b) in the northwestern part of MULLINE; and the Ghost Rocks segment of the Menzies – Broad Arrow greenstone belt in northeastern RIVERINA (Griffin, 1990a). Two, less well exposed greenstone sequences are the Maninga greenstone belt (Griffin, 1990b) in the central-southern part of MULLINE, and the Yerilgee greenstone belt (Griffin, 1990b) in the far southwest.

The MULLINE and RIVERINA sheets straddle the boundary between the Eastern Goldfields and Southern Cross Provinces of Gee et al. (1981). According to the scheme of Myers (1990) and Swager et al. (1995), in which the Yilgarn Craton has been subdivided into a number of tectono-stratigraphic terranes bounded by major shear zones, the eastern part of the area lies within the Kalgoorlie Terrane and the western part within the Barlee Terrane. The boundary between the terranes coincides with a large-scale, regional structure — the Ida Fault (Fig. 2).

Sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon geochronology indicates an age of deposition of 2.7 Ga for the Kalgoorlie Terrane (Swager et al., 1995; Swager, 1997; Nelson, 1997). Limited geochronological data from the Barlee Terrane indicate a longer period of greenstone deposition, with greenstone sequences dated from about 3.0 Ga (Wang et al., 1996; Nelson, 1999) to c. 2735 Ma (Pidgeon and Wilde, 1990). The only high-resolution geochronology on greenstones from MULLINE or RIVERINA is a SHRIMP U–Pb zircon age of 2691 ± 6 Ma (Nelson, 1995) on a foliated felsic rock, interpreted as a volcaniclastic metasedimentary rock, from within the Ghost Rocks sequence in northeastern RIVERINA.

Swager et al. (1995) proposed a broad, regional stratigraphic succession for the Kalgoorlie Terrane based on correlation of the main komatiite formation. Although stratigraphic sections have been described for individual greenstone belts in the Barlee Terrane (e.g. Dalstra, 1995), the overall stratigraphic history is only poorly understood (Griffin, 1990b).

Dalstra (1995) and Greenfield and Chen (1999) described deformation in the Marda–Diemals area in the Barlee Terrane to the west in which a north–south compressional event was followed by broadly east–west compression. Swager et al. (1995) and Swager (1997) described four main phases of deformation in the Kalgoorlie Terrane: D_1 thrust stacking and recumbent folding; D_2–D_3 transpression involving upright folding and transcurrent faulting; and a D_4 regional shortening episode.

Swager (1997) and Swager and Nelson (1997) presented evidence of local extensional tectonics for parts of the southern Eastern Goldfields Province, within the broader D_1–D_4 structural regime. These deformations, and earlier extensional events postulated by a few authors (e.g. Hammond and Nisbet, 1992; Williams and Whitaker, 1993) for areas to the north, have not been recognized in the study area.

There have been several phases of granitoid intrusion, with some plutons apparently post-dating the last movement on the Ida Fault. A sequence of foliated and gneissic granitoids lies immediately east of the Mount Ida greenstone belt in the northern part of RIVERINA. The contact between greenstones and gneissic granitoid is the Ballard Fault (Rattenbury, 1991), a zone of strong deformation with some tectonic interleaving. The Ballard Fault (Fig. 2) is the northern extension of the Zuleika Shear of Swager et al. (1995).

The granite–greenstone terrain has also been intruded by a number of mainly east-northeasterly trending mafic dykes (Fig. 3). They rarely outcrop, but are readily recognized as positive and negative features on aeromagnetic images (Fig. 4).

All Archaean rocks have been metamorphosed, mainly to upper greenschist to amphibolite facies. The presence of clinopyroxene and olivine in places suggests locally high grade, upper amphibolite-facies metamorphic conditions (Ahmat, 1986).

Archaean rock types

Metamorphosed ultramafic rocks (*Auk, Aup, Aur, Aut*)

Ultramafic rocks are most abundant in the eastern part of the Mount Ida greenstone belt (Fig. 3) on RIVERINA, but locally are found low in the Illaara greenstone belt sequence, and may form a significant component of the poorly exposed Maninga and Yerilgee greenstone belts

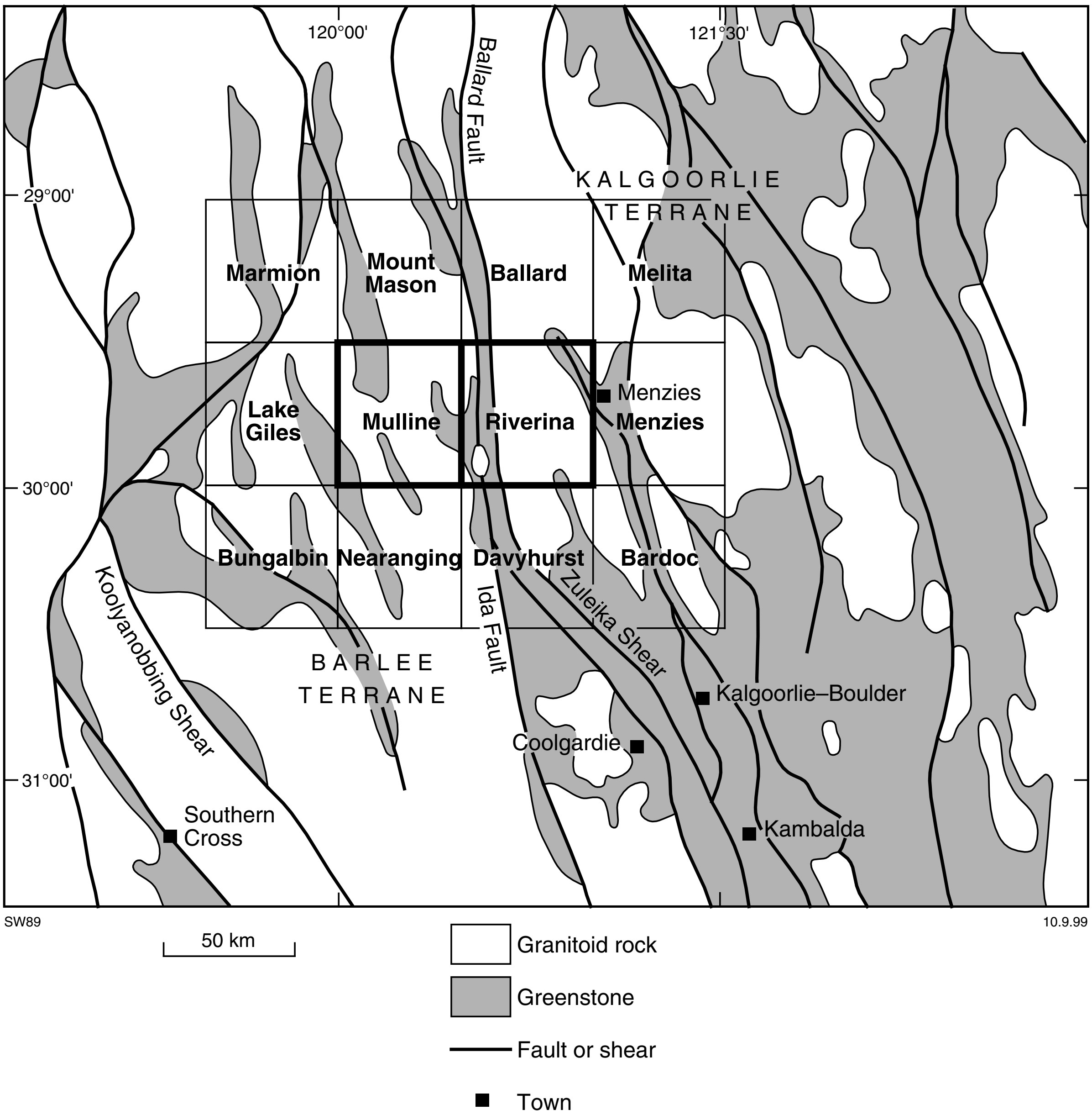

Figure 2. Regional geological setting of MULLINE and RIVERINA (adapted from Myers and Hocking, 1998)

in the southwestern part of MULLINE. Carbonate minerals are common weathering products of ultramafic rocks, and patches of calcrete are commonly found in areas of extensive ultramafic outcrop. Some of these rocks may also have undergone carbonate alteration, notably in the highly sheared area west of 18 Mile Well on RIVERINA.

Komatiite (*Auk*) includes all rocks that display relict platy olivine-spinifex texture. In areas of greenschist-facies metamorphism, komatiites contain tremolite–actinolite with magnetite(–chlorite–serpentine–plagioclase). Higher grade assemblages contain tremolite–actinolite and minor magnetite, and may contain olivine and serpentine. The preserved olivine-spinifex texture is typically represented by pseudomorphing of primary tabular or platy grains of olivine by tremolite–actinolite. Interstitial material may include very fine grained, felted tremolite–actinolite and magnetite, with or without chlorite and plagioclase. No komatiites have been identified on MULLINE, and those on RIVERINA are associated with the abundant high-Mg basalt and ultramafic rocks along the eastern side of the Mount Ida greenstone belt and in the Ghost Rocks area.

Peridotite (*Aup*) is relatively abundant in the eastern part of the Mount Ida greenstone belt. West of the Ida Fault, peridotite has only been mapped in the Maninga greenstone belt on MULLINE. The rocks are typically altered, and consist of very fine to fine grained, commonly matted tremolite–actinolite, with or without

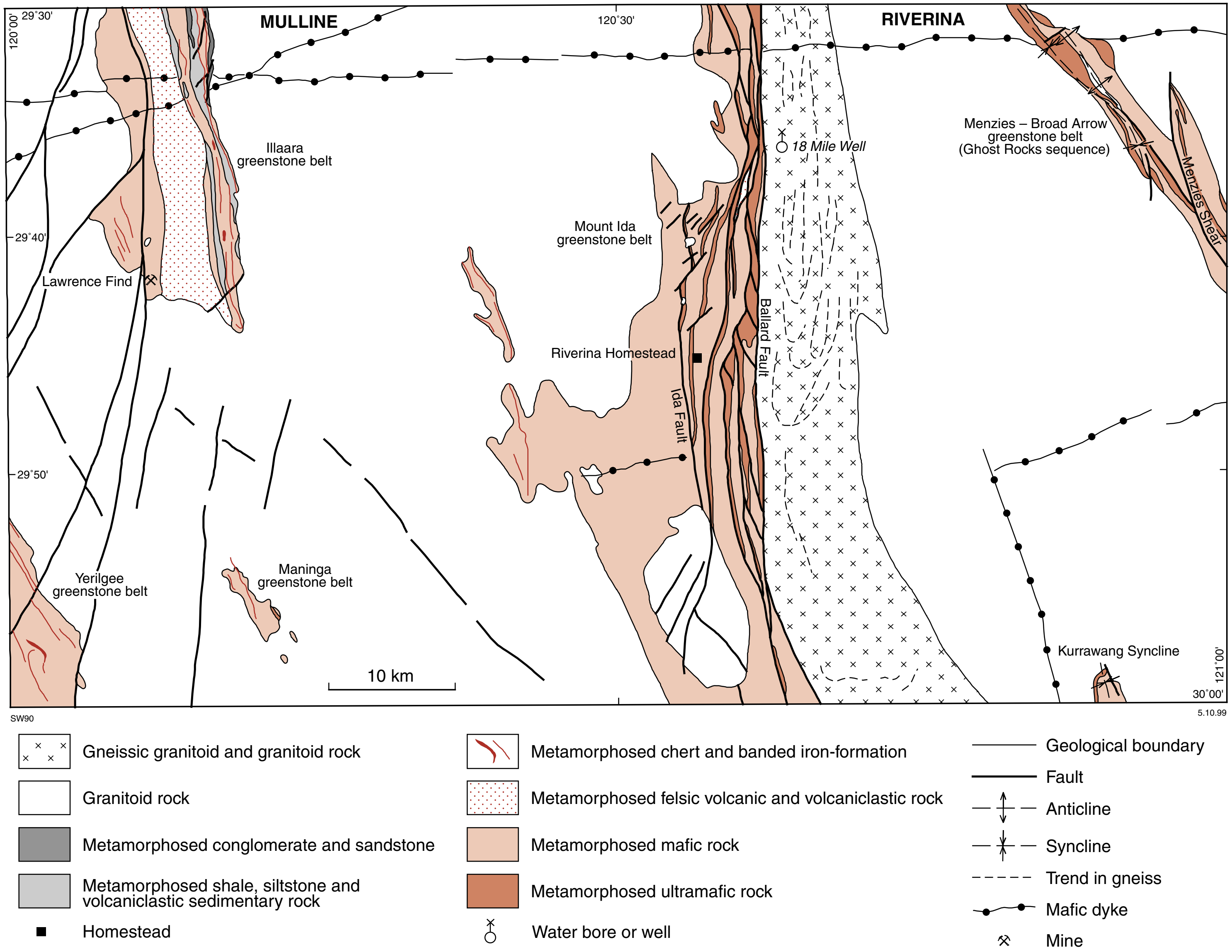

Figure 3. Interpreted geology of Mulline and Riverina

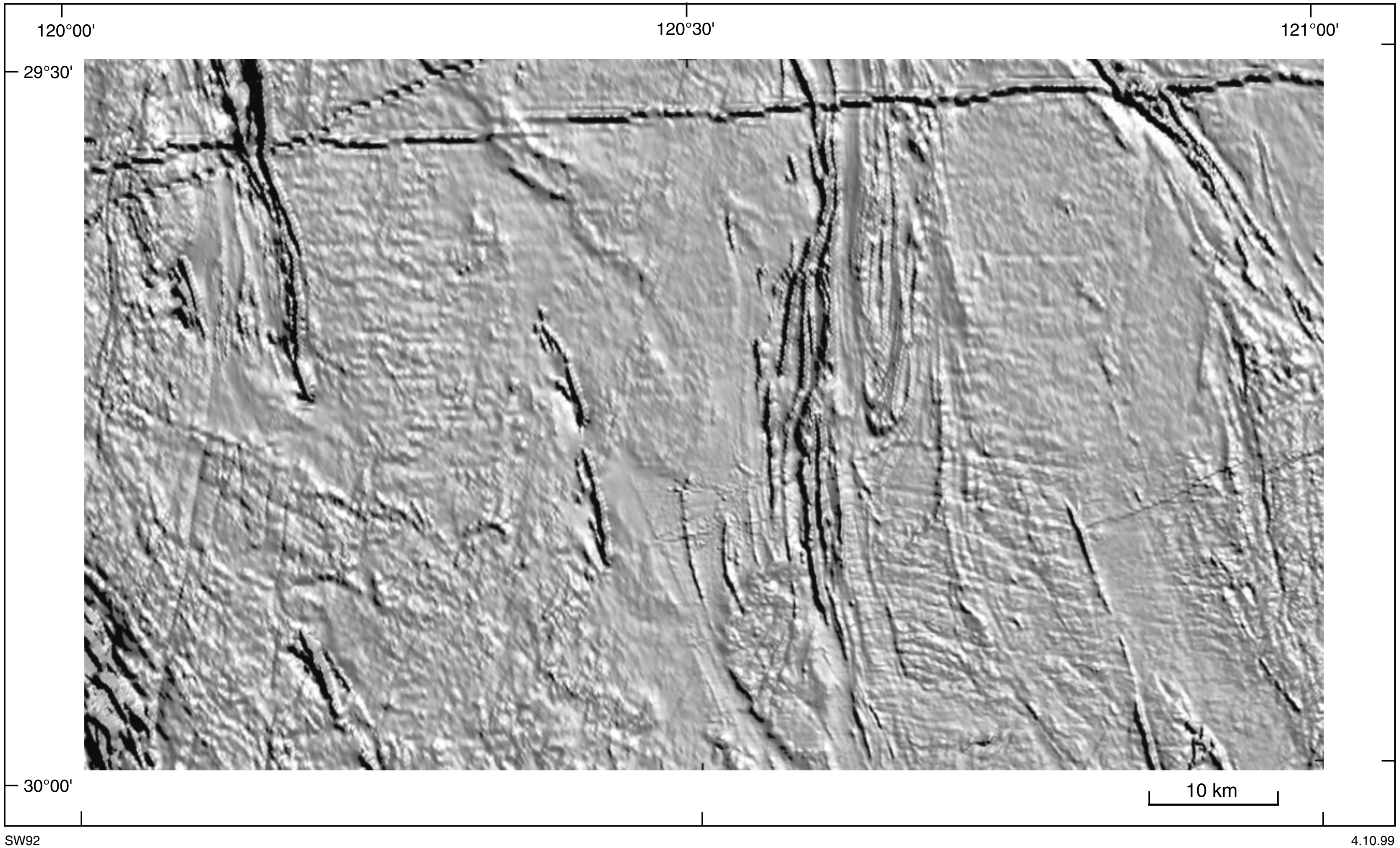

Figure 4. Aeromagnetic image of MULLINE and RIVERINA (reproduced with the permission of World Geoscience Corporation Ltd)

serpentine, olivine, chlorite, talc, carbonate, and magnetite. Medium- to coarse-grained, partly altered olivine is preserved in peridotite at several localities in the Mount Ida greenstone belt on RIVERINA (e.g. northwest of Mount Morley at AMG 635175). The olivine may be a product of metamorphism, but the relatively coarse grain size (up to about 1 mm) and lack of preferred crystal orientation suggest that it is a relict primary phase. Relict orthocumulate and mesocumulate textures are preserved locally by traces of very fine grained magnetite, and alteration patterns in serpentinite. Silica caprock with relict cumulate textures (*Czu*) is an alteration product of peridotite, and is common in the Ghost Rocks sequence and locally present along the eastern side of the Mount Ida greenstone belt.

Tremolite(–chlorite) schist (*Aur*) is the most wide ranging ultramafic rock type on MULLINE and RIVERINA. Outcrops are typically pale to dark green, and moderately to strongly deformed. Thin sections of the rock contain fine- to medium-grained tremolite–actinolite, with or without magnetite, chlorite, olivine, serpentine, talc, and plagioclase. Primary igneous textures are rarely preserved. The schists are commonly associated with, and probably derived from, komatiite or peridotite. However, some tremolite schist contains small amounts of plagioclase, and may be derived from high-Mg basalt.

Fine-grained talc–chlorite schist (*Aut*) outcrops locally on RIVERINA, and has been intersected in mineral exploration drillholes at the northern end of the Ghost Rocks sequence.

Metamorphosed fine-grained mafic rocks (*Ab, Abm, Abv, Ama*)

Variously deformed and recrystallized, fine-grained mafic rocks are abundant in all greenstone sequences on MULLINE and RIVERINA (Fig. 3). Both tholeiitic and high-Mg basalts are widely represented, although primary igneous textures are only locally preserved. Tholeiitic basalts are more abundant in the Barlee Terrane.

Metamorphosed, massive, fine- to medium-grained mafic rocks (*Ab*) are mainly tholeiitic basalts, but may include subordinate high-Mg basalt. They typically contain roughly equal amounts of calcic amphibole and plagioclase, with minor opaque minerals, and, locally, small amounts of epidote, chlorite, and sphene. Although metamorphosed and recrystallized, primary igneous textures, including intergranular texture and networks of elongate feldspar laths that suggest rapid cooling, are well preserved locally. Other igneous features, such as amygdales now filled with quartz, chlorite, and clay minerals, are also preserved locally. Strongly deformed pillow-lava structures, and pieces of the very fine grained 'rinds' of pillow structures, have been found in a number of places, such as the eastern slopes of Mount Morley (on RIVERINA) and the hills further east. Clear pillow structures are preserved at the bottom of the Lady Gladys opencut (AMG 586967) where they are deformed (flattened), with the direction of elongation shallowly easterly dipping (Fig. 5). Although deformed, interpillow relationships suggest that they are the right way up.

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Figure 5. Pillow-lava structures in the Lady Gladys opencut (AMG 586967). The structures have been deformed, and are flattened with a moderate east dip

Tholeiitic basalts in the Illaara and Mount Ida greenstone belts typically attained a higher metamorphic grade than those to the east in the Kalgoorlie region. Although specific mineral assemblages that accurately indicate metamorphic grade of mafic rocks are not readily recognizable, the association with medium- to high-grade metapelitic rocks in the Illaara greenstone belt on MULLINE, abundance of dark, recrystallized hornblende, and local presence of garnetiferous amphibolite (e.g. southeast of the Emerald gold mine on RIVERINA; AMG 680228) suggest a relatively high metamorphic grade (see **Metamorphism**).

Limited whole-rock geochemistry data indicate that most basalts in the Barlee Terrane lie within the tholeiitic range for SiO_2 (Appendix 2). However, some material has the composition of basaltic andesite (e.g. GSWA 112249; AMG 205152). Metamorphic recrystallization may have destroyed primary igneous textures making it difficult to distinguish areas of high-Mg basalt in places — for example, there is vague, coarse, relict spinifex texture in recrystallized mafic rocks on the eastern side of the extensive area of basalt, east of Lawrence Find on MULLINE.

The high-Mg or komatiitic basalt (*Abm*) is a fine-grained mafic rock with between 10 and 18% MgO (Cas and Wright, 1987). Although commonly associated with komatiite, there are many instances where it is found away from areas containing abundant komatiite. High-Mg or komatiitic basalt is a significant component of the greenstone successions on MULLINE and RIVERINA, but is only shown on the map face where it has been unequivocally identified by the presence of the characteristic pyroxene-spinifex texture. The rock is typically fine grained and contains tremolite–actinolite, with or without chlorite and plagioclase. The high-Mg basalt weathers to a dark-green colour, with a light-brown surface rind. The needle-like, pyroxene-spinifex texture is a relict texture, as primary mineralogy has been destroyed by metamorphism, and original pyroxenes replaced by tremolite–actinolite. The texture is commonly visible in hand specimens. High-Mg basalt is relatively abundant on the eastern side of the Mount Ida greenstone belt, but, although present, appears to be less significant in the Illaara greenstone belt. The rock may be a significant component of the poorly exposed Yerilgee greenstone belt.

Variolitic basalt (*Abv*) on RIVERINA is characterized by an abundance of distinctive, spherical to oblate, leucocratic patches, up to about 10 mm across. Oblate varioles are common in deformed basalt. The varioles are a more plagioclase-rich phase of the basalt, and may not be primary features. Variolitic basalts commonly, but not invariably, have compositions in the high-Mg basalt range.

Although all greenstones have been metamorphosed to greenschist or lower amphibolite facies, rocks have been mapped as amphibolite (*Ama*) only where they are found in extensive units of completely recrystallized rocks, in which plagioclase forms an interstitial crystal mosaic and no primary igneous texture is preserved. These rocks are typically strongly foliated. They form dark outcrops, and in thin section contain dark-green hornblende and, locally, patches of clinopyroxene (e.g. in the area north of Blue Well in the northwestern part of RIVERINA). Amphibolite is most commonly found adjacent to granitoid intrusions, but also forms thin lenses and bands within gneissic granitoid (*Agn*) on the eastern side of the Mount Ida greenstone belt on RIVERINA.

Metamorphosed medium- to coarse-grained mafic rocks (*Ao, Aog, Aogl*)

Metamorphosed, medium- to coarse-grained mafic rocks are an important component of all greenstone successions on RIVERINA and MULLINE. However, the discontinuous, rubbly nature of the outcrop over much of the map area makes it difficult to delineate areas of coarser grained rocks.

Undivided, medium- to coarse-grained mafic rocks (*Ao*) have no distinctive mineralogical or textural features. They are typically recrystallized to plagioclase and medium- to dark-green hornblende, with accessory magnetite and, locally, leucoxene after ilmenite. Relict subophitic to ophitic texture is preserved locally. They may have been mainly intrusive bodies, but some outcrops probably represent thicker parts of mafic flows.

Metamorphosed gabbro (*Aog*) is a coarse-grained mafic rock with relict igneous texture in which original pyroxene has been replaced by hornblende. Relict subophitic to ophitic textures are commonly preserved. Where mafic minerals comprise less than about 40% of the gabbro, it has been mapped as leucogabbro (*Aogl*). Differentiation trends in gabbro may suggest way-up directions (e.g. AMG 640997 on RIVERINA).

Metamorphosed intermediate rocks (*Ail, Aip, Aiv*)

Metamorphosed intermediate rocks have been noted in the Illaara greenstone belt on MULLINE and the Mount Ida greenstone belt on RIVERINA. They are typically deformed, recrystallized, and altered, with only vague, locally preserved, igneous textures.

Layered intermediate rocks (*Ail*) have been mapped in the Illaara greenstone belt. They are completely recrystallized and contain very fine to fine grained feldspar, including local K-feldspar, medium- to dark-green amphibole, and minor quartz. Layers of colourless clinopyroxene are present locally. Some rocks have undergone extensive epidote alteration, and contain abundant sphene. Layering in these rocks is probably a metamorphic foliation, and thin sections show a second foliation, defined by fine amphibole needles, that overprints the main layering at a high angle. Although the protolith of the intermediate layered rocks is no longer recognizable, their association with deformed and metamorphosed rocks of probable basic to intermediate composition that have igneous and volcaniclastic textures suggests that they are derived from igneous or volcaniclastic rocks of acid to intermediate composition.

Metamorphosed and feldspar-phyric intermediate porphyry (*Aip*) in the Illaara greenstone belt contains relict plagioclase phenocrysts up to 3 mm long in a fine-grained, recrystallized feldspathic groundmass, with abundant, very fine grained aggregates and scattered grains of biotite. Fine aggregates of quartz may be secondary. An analysis of intermediate porphyry (GSWA 112028; AMG 234161) falls within the andesite range for SiO_2 (Appendix 2). The porphyry is associated with intermediate volcanic and volcaniclastic rocks (*Aiv*), and may represent a lava or high-level intrusive.

Metamorphosed, intermediate porphyry in the Mount Ida greenstone belt (*Aip*) outcrops in two valleys east of Mount Morley, where it has a fine-grained, dominantly feldspathic groundmass with minor quartz. Some examples contain both plagioclase and minor K-feldspar. Plagioclase phenocrysts up to 3 mm in diameter, zoned in a few specimens, are partly saussuritized. The rock contains up to 25% mafic minerals, dominantly olive- to pale-green, pleochroic amphibole as fine, individual grains or clusters up to 3 mm across. Subordinate brown biotite is a product of metamorphism. Sphene and very fine grained zircon are common accessory minerals. In the first valley east of Mount Morley, the porphyry contains angular xenoliths of basalt and gabbro, and may be a high-level intrusive of dioritic composition.

Metamorphosed intermediate volcanic and volcaniclastic rocks (*Aiv*) have been mapped in the Illaara greenstone belt, where they include a range of poorly outcropping, fine-grained, weathered and deformed rocks, mainly similar in composition to the intermediate porphyry described above. Plagioclase is the most common feldspar, and some outcrops contain phenocrysts, up to 2 mm in diameter, of partly saussuritized plagioclase. More-felsic, quartz-rich rocks contain substantial K-feldspar. Medium- to light-green, pleochroic amphibole is the most abundant mafic mineral species, but biotite is present in some varieties, particularly the more felsic rock types. Epidote, chlorite, and sphene are common accessory minerals.

Metamorphosed foliated felsic rocks (*Afs*)

An extensive outcrop of strongly foliated felsic rock (*Afs*), 3.5 km southwest of 18 Mile Well (around AMG 683203) on RIVERINA, contains large (up to 4 mm), saussuritized plagioclase and recrystallized, rounded quartz porphyroclasts in a very fine grained, quartzofeldspathic groundmass. Plagioclase is the dominant feldspar, but K-feldspar is also present. Fine-grained muscovite, biotite, opaque iron oxides, and secondary chlorite are minor mineral species. The irregular texture of the rock and abundance of rounded quartz porphyroclasts suggest that the protolith may have been a volcaniclastic sedimentary rock or an extrusive (or high-level intrusive) quartz–feldspar porphyry. However, the uniform texture of the rock in outcrop and the mineralogy are also consistent with an interpretation of this rock as a mylonitized granodiorite. Low outcrops of strongly foliated felsic rock (*Afs*), 4 km northwest of 18 Mile Well (around AMG 679253), consist of fine-grained, weathered, micaceous quartzofeldspathic schist.

Strongly foliated felsic rock in the Ghost Rocks sequence of northeastern RIVERINA consists of coarse grains of quartz and feldspar with abundant muscovite, and minor biotite and chlorite, in a fine- to medium-grained, recrystallized, quartzofeldspathic groundmass. This rock contains bipyramidal quartz, is interpreted as a metamorphosed volcanic or volcaniclastic rock, and has a SHRIMP U–Pb zircon age of 2691 ± 6 Ma (Nelson, 1995).

Metamorphosed sedimentary rocks (*As, Asf, Ash, Aso, Asq, Ac, Aci*)

Metamorphosed sedimentary rocks are a relatively minor component of the greenstone successions on RIVERINA, but form a substantial part of the Illaara greenstone belt on MULLINE.

Undivided metasedimentary rocks (*As*) represent a composite unit of weathered, poorly exposed shales and siltstones, with thin intervals of fine-grained quartz wacke or semi-pelitic schist. In the Illaara greenstone belt, undivided sedimentary rocks have been deformed and metamorphosed so that quartz is recrystallized. Fine-grained, metamorphic muscovite and biotite define the metamorphic foliation.

Felsic metasedimentary rocks (*Asf*) are mainly pelitic, semi-pelitic, and quartzofeldspathic schists. They have been mapped only in the Illaara greenstone belt where they are most abundant in a northerly trending, mainly recessive unit near the eastern side of the belt. Here, they are poorly exposed and deeply weathered, but comprise a range of very fine to fine grained quartzose and quartzofeldspathic schists, with minor chlorite, biotite, and muscovite. Also present is weathered pelitic schist with large, equant voids, up to 4 mm across, possibly after garnet. Cordierite-bearing schists have been identified about 2 km west of Halag Rock (around AMG 260185). Very fine to fine grained quartzofeldspathic schist in the same area as the cordierite-bearing schist contains blades of orthoamphibole (?gedrite) that cut across and clearly post-date the foliation.

Metamorphosed shale and siltstone (*Ash*) are a significant component of the Illaara greenstone belt on MULLINE, but also found in thin, interflow sedimentary units in the Mount Ida greenstone belt on RIVERINA. They are commonly deformed, but thin bedding is preserved locally. These fine-grained metasedimentary rocks are quartzose or quartzofeldspathic, with locally abundant fine clay or opaque iron-oxide minerals. Grey, banded chert may be a minor constituent of some shale and siltstone units. Shale in the Illaara greenstone belt is locally pyritic (e.g. 9 km north-northwest of Lemon Rock, around AMG 241308).

Metamorphosed oligomictic conglomerate (*Aso*) is restricted to a single unit within the Illaara greenstone belt sequence in the northern part of MULLINE. The same unit extends north onto MOUNT MASON (Duggan, 1995), where it is much thicker. The conglomerate consists of pebbles, cobbles, and boulders (up to 60 cm across) of rounded to well-rounded quartzite in a poorly sorted, recrystallized quartz arenite matrix that contains very fine, interstitial muscovite and opaque oxide grains. The recrystallized quartzite that forms the clasts is poorly sorted, with original grain size ranging from less than 0.1 mm up to 2 mm. Although largely recrystallized, clasts were probably derived from a clean quartz sandstone as there is very little interstitial material, mainly very fine grained opaque oxides. Associated with the conglomerate is recrystallized, fine- to coarse-grained, poorly sorted ferruginous quartz arenite with common granules and pebbles of rounded quartz. All the sandstone and conglomerate is moderately to strongly deformed, and the quartzite clasts have been significantly stretched (Fig. 6).

Metamorphosed quartzite and quartz–muscovite schist (*Asq*) form a distinctive unit on the eastern side of the Illaara greenstone belt in the northern part of MULLINE. Like the oligomictic conglomerate described above (*Aso*), the unit of quartzite and quartz–muscovite schist thickens to the north on MOUNT MASON (Duggan, 1995). The limited number of younging indicators suggests that this unit may be the stratigraphically lowest exposed formation in the Illaara succession. These rocks are very strongly deformed and recrystallized, and original bedding features are difficult to discern (Fig. 7). The quartzite is ridge-forming, and appears to have been derived from very coarse to fine grained, poorly sorted, clean quartz sandstone, although some dark layers contain very fine grained tourmaline. The quartz–muscovite schist, which is abundant in the recessive units between quartzite ridges, formed from quartz sandstone with a clay-rich matrix. The muscovite is locally bright green (fuchsite), indicating a significant chrome content. SHRIMP U–Pb analyses by Froude et al. (1983) identified two substantial populations of detrital zircons, one between 3.7 and 3.6 Ga and the other between 3.4 and 3.3 Ga, in quartzite that is stratigraphically equivalent to the lowest quartzite in the Illaara greenstone belt, sampled along strike northwest of MULLINE.

Metamorphosed chert (*Ac*) and banded iron-formation (*Aci*) outcrop on MULLINE on the western side of the Mount Ida greenstone belt, west of the Ida Fault, and further west in the Illaara, Maninga, and Yerilgee greenstone belts. These siliceous metasedimentary rocks typically form the most prominent ridges. They contain quartz and various amounts of magnetite, limonite, and grunerite. They are typically strongly recrystallized, with primary fine laminations (0.1 – 0.5 mm) and coarser bedding units (1–3 mm) indicated by variations in grain size of recrystallized quartz, and variations in the amounts of the iron-rich minerals. Minor and intrafolial folds are common in some units, and there are many small-scale fractures and offsets. Bedding surfaces commonly preserve a lineation that may be either a fine stretching lineation or a very fine crenulation. The common presence of grunerite indicates widespread, relatively high grade (amphibolite-facies) metamorphism.

SW77 8.9.99

Figure 6. Deformed conglomerate in the Illaara greenstone belt with stretched pebbles, cobbles, and boulders of quartzite in a poorly sorted, sandy matrix (AMG 239318)

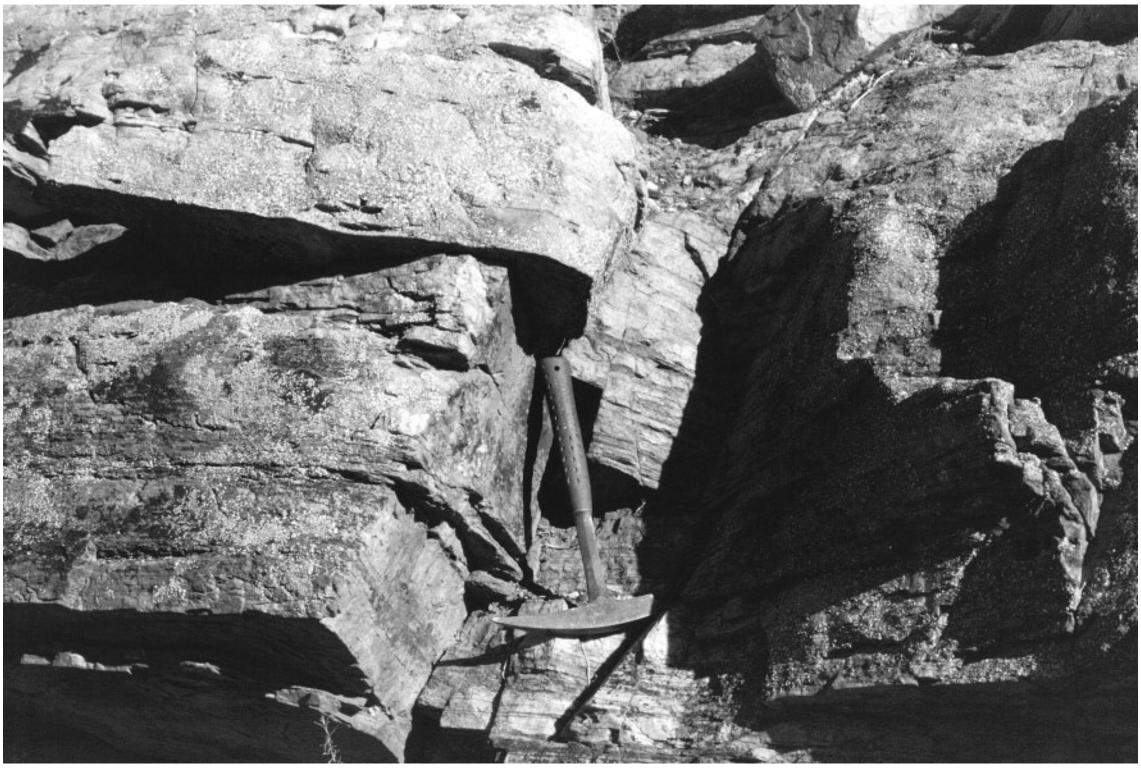


Figure 7. Bedded quartzite near the base of the Illaara greenstone belt sequence with strong bedding-parallel cleavage (AMG 250327)

Metamorphosed feldspar(–quartz) porphyry (*Apf*)

Metamorphosed feldspar(–quartz) porphyry (*Apf*) forms thin (<2 m) units within the greenstones, particularly within the tholeiitic basalts in the southern part of the Mount Ida greenstone belt on MULLINE and RIVERINA that extends south onto DAVYHURST (Wyche and Witt, 1994). The rocks are recrystallized with phenocrysts (mainly up to 2 mm, but locally up to 4 mm) of plagioclase(–quartz) in a very fine grained, quartz–feldspar(–biotite–muscovite–iron-oxide) groundmass. They are typically massive, but locally contain a pervasive foliation. Porphyry–greenstone contacts are commonly deformed. Although most commonly parallel to structural trends, some porphyry units appear to crosscut the regional fabric. They are probably dykes, and possibly related to the emplacement of the Ularring Monzogranite (*Agmu*).

Granitoid rocks (*Ag, Agl, Agm, Agmg, Agmj, Agml, Agmu, Agmy, Agn*)

Granitoid rocks, although not well exposed over much of the region, make up a large proportion of the Archaean rocks on MULLINE and RIVERINA. In the Eastern Goldfields Province, compositions range from syenite to tonalite, but the greatest volume of exposed granitoid rock is in the monzogranite–granodiorite range (Witt and Davy, 1997). Granitoid rocks west of the Ida Fault are dominated by monzogranite. In a petrographic study of regional variation of granitoid rocks in the southern part of the Eastern Goldfields Province, Libby (1978) suggested that there is a significant increase in the K-feldspar content in the western part of the KALGOORLIE and MENZIES 1:250 000 sheets.

Undivided granitoid rock (*Ag*) is either too deeply weathered for identification or no data were available to allow classification. Most undivided granitoid is probably syenogranitic to granodioritic in composition. West of the Ida Fault, most of the undivided granitoid is in the syenogranite to monzogranite range, with monzogranite dominant. Most granitoids contain minor biotite and muscovite, and accessory opaque oxides. Textures range from equigranular to coarsely porphyritic.

An undivided, probably late stage granitoid intrusion (*Agl*), about 1 km west of Wonder Well on RIVERINA, is fine-grained, even-grained, allotriomorphic-granular, biotite monzogranite. Biotite, commonly altered to green chlorite, is the only primary mafic component. Muscovite forms discrete flakes, and is also a common secondary mineral in partly saussuritized plagioclase. Although quartz is slightly strained, there is no clear metamorphic fabric.

Monzogranite (*Agm*) is the most abundantly out-cropping granitoid variety on MULLINE and RIVERINA, where it forms locally prominent bornhardts such as Mulline Rock and Hospital Rocks. The monzogranite is typically massive, fine to medium grained, and locally porphyritic. Rocks west of the Ida Fault have mainly granitic textures, suggesting that they have undergone less metamorphic recrystallization than those to the east. Monzogranites from the western areas, particularly the southern part of MULLINE, are also enriched in fluorite (Libby, 1978). Most samples contain brown biotite, locally altered to green chlorite. Muscovite, where present, is typically a minor, possibly secondary constituent. Apatite, zircon, sphene, and opaque oxides are common accessory minerals.

The Goongarrie Monzogranite (*Agmg*) outcrops in the southestern part of RIVERINA, but has its main exposure to the southeast. The type area is on BARDOC, where it is a sparsely porphyritic biotite monzogranite, with K-feldspar phenocrysts to 1.5 cm, and rare, small, biotite-rich enclaves (Witt, 1994). The unit occupies the core of a regional F_2 anticline and, on MENZIES, contains a widely spaced foliation with local, narrow shear zones, parallel to the regional fabric (Swager, 1994).

The Jorgenson Monzogranite (*Agmj*) occupies the northeastern corner of RIVERINA and extends east onto MENZIES. The unit was described by Swager (1994) as porphyritic monzogranite, with K-feldspar phenocrysts up to 4 cm long in a medium- to coarse-grained matrix, associated with subordinate, weakly porphyritic syenogranite. There is a very strong contact-parallel foliation, with steeply plunging mineral lineations adjacent to granite–greenstone contacts. The strongly foliated contact zone is marked in places by a locally garnetiferous felsic schist (Swager, 1994).

The Clark Well Monzogranite (*Agml*) intruded the Mount Ida greenstone belt about 1.2 km south of Mount Morley on RIVERINA. The unit is an allotriomorphic- to hypidiomorphic-granular, fine- to coarse-grained, weakly seriate biotite monzogranite, which is only weakly recrystallized and contains no metamorphic fabric. Dark-brown to olive-green biotite, partly replaced by chlorite, is the only mafic mineral present, and makes up about 4% of the rock. Muscovite, some of which is clearly secondary, is a minor (<1%) constituent. Plagioclase is vaguely zoned. The exposure represents the top of the intrusion, and a roof pendant of metabasalt is preserved on top of a small hill in the middle of the outcrop. There is no distinct metamorphic aureole, although basalts immediately adjacent to the intrusion are very dark and may have been hornfelsed. A second, smaller intrusion outcrops in a small valley about 300 m to the south.

The Clark Well Monzogranite intruded along, and adjacent to, a deformed recessive unit that corresponds to a prominent magnetic lineament, and contains a range of rock types, including peridotite, high-Mg basalt, tholeiitic basalt, gabbro, and shale. This feature coincides with the marked change from abundant ultramafic and magnesium-rich rocks to the east, to abundant tholeiitic rocks and banded iron-formation to the west, and is interpreted as the trace of the Ida Fault. As the monzogranite clearly post-dates all the significant tectonic fabric in the surrounding greenstones, the SHRIMP U–Pb zircon age of 2640 ± 8 Ma (Nelson, 1995) indicates that major movement on the fault had ceased by this time.

The Ularring Monzogranite (*Agmu*) is a large, ovoid intrusion within the Mount Ida greenstone belt in the southwestern part of RIVERINA. The surface and magnetic expression of the body is up to about 14 km from north to south, and about 6 km at its widest point. The unit is a fine- to coarse-grained, weakly seriate, allotriomorphic- to hypidiomorphic-granular biotite monzogranite. Brown to olive-green biotite, the only mafic component, is commonly altered to green chlorite. Muscovite is locally abundant in partly saussuritized plagioclase, but is also present as discrete grains that were probably a primary phase. Sphene and opaque iron-oxides are common accessory minerals. Quartz grains are slightly strained, but there is no clear metamorphic foliation.

The Ularring Monzogranite cuts across the Ida Fault, but is itself cut by several prominent north-northeasterly trending quartz veins that correspond to prominent lineaments on aeromagnetic images (Fig. 4). These features are faults, equivalent to the D_4 structures of Swager et al. (1995), with dextral displacements of up to about 500 m. Thus the Ularring Monzogranite post-dates the major movement on the Ida Fault, but pre-dates the north-northwesterly trending joints and faults that represent the last tectonic activity in the region, prior to the emplacement of the mainly east-northeasterly trending mafic and ultramafic dyke suite.

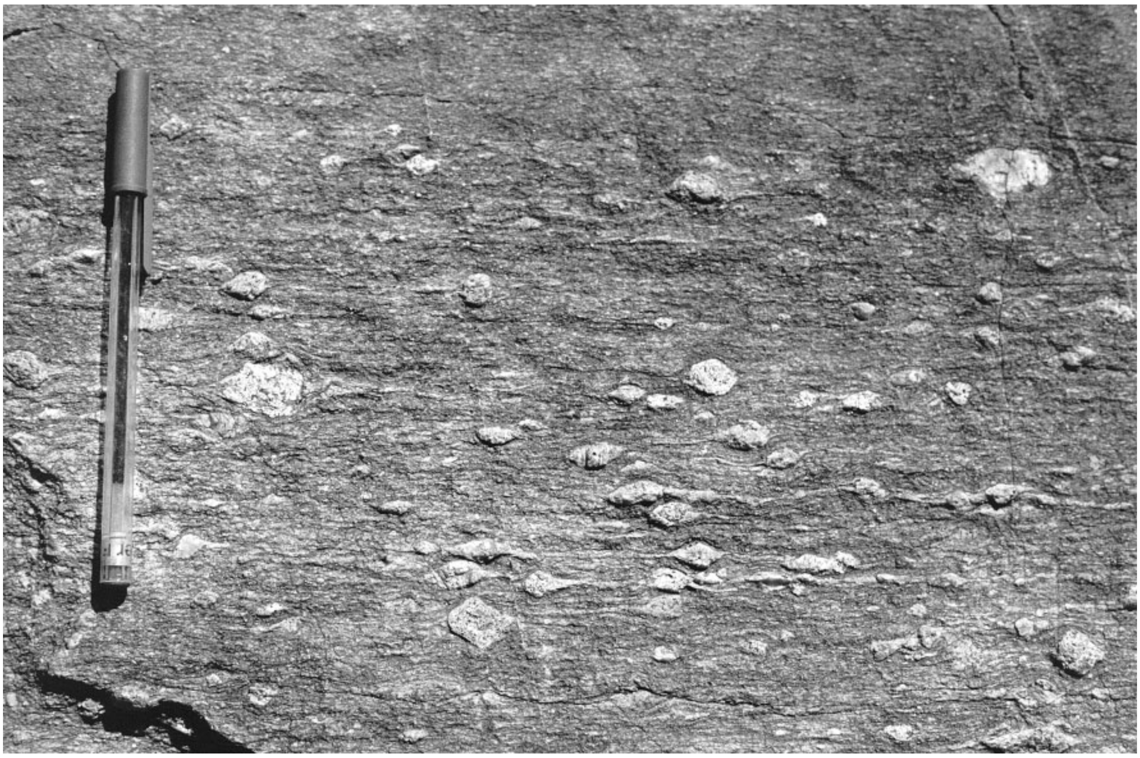
The Mystery Monzogranite (*Agmy*) is restricted to the western side of the Mount Ida greenstone belt, near the Mystery mine in southeastern MULLINE. The unit is a massive, fine- to medium-grained, allotriomorphic- to hypidiomorphic-granular, weakly seriate, biotite monzogranite. The rock has not been significantly recrystallized and, although quartz grains are slightly strained, there is no metamorphic foliation apart from a local, weak, contact-parallel foliation immediately adjacent to the contact. The Mystery Monzogranite is probably a late-stage intrusion like the Clark Well and Ularring Monzogranites.

Gneissic granitoid rock (*Agn*) occupies a broad zone along the eastern side of the Mount Ida greenstone belt. Although well exposed in only a few areas, aeromagnetic images indicate that the zone may be up to about 9 km wide on RIVERINA (Fig. 4).

Gneissic granitoid rocks include a range of types from strongly foliated granitoid to compositionally banded gneiss. They appear to be mainly granodioritic to monzogranitic in composition, but have undergone substantial cataclastic deformation and, therefore, primary mineral ratios are difficult to determine. The banded rocks are fine-grained, quartz–feldspar–biotite gneiss, with compositional banding on a scale of less than 1 cm to several tens of centimetres, defined by the relative abundance of biotite (Fig. 8). The more mafic bands contain minor epidote and sphene. Some bands contain coarse feldspar porphyroclasts up to 5 cm across (Fig. 9). Pressure shadows adjacent to feldspar porphyroclasts do not give an unequivocal sense of movement, suggesting that much of the applied stress was compressive. Epidote-rich amphibolite is locally exposed in lenses and thin bands in recessive areas between gneiss outcrops. Two SHRIMP U–Pb zircon determinations of c. 2680 Ma have been obtained for gneiss, considered equivalent to the RIVERINA gneissic granitoid, from WILBAH to the north.

SW80 8.9.99

Figure 8. Compositional banding in granitoid gneiss near 18 Mile Well (AMG 700240). Dark layers contain more abundant biotite



SW84 8.9.99

Figure 9. Feldspar porphyroclasts in gneissic granitoid near 18 Mile Well (AMG 700240

These ages are interpreted as crystallization ages of the granitoid precursor to the gneiss (Black, L. P., pers. comm., in Williams, 1993).

Large-scale, complex folding of the gneiss is evident on aeromagnetic images (Figs 3 and 4). At outcrop scale, tight folds with well-developed axial planar foliation can be seen where quartz and pegmatite veins have been folded with the gneiss (Fig. 10), and there is a shallowly plunging mineral lineation. The gneiss lies immediately east of the granite–greenstone contact, east of the easterly dipping Ida Fault (see **Structural geology**). The relatively young age of the gneiss, the fact that it is restricted to a zone along the eastern side of the Mount Ida greenstone belt, and its apparently complex history suggest that it records a substantial part of the complex history of the Ida Fault and associated structures.

Felsic veins and dykes (*q, g, p*)

Quartz (*q*) veins are abundant, commonly prominent features on MULLINE and RIVERINA. Small quartz veins are found adjacent to granite–greenstone contacts and, like most of the granitoid (*g*) and pegmatite (*p*) veins, are probably related to Archaean granitoid intrusion. However, many of the more prominent quartz veins are oriented parallel to major structural features and aeromagnetic lineaments, and some of these may be Proterozoic in age.

Quartz veins most commonly trend north-northeasterly, and are aligned with aeromagnetic lineaments. These veins are probably filling small-scale, brittle D_4 faults (see description of Ularring Monzogranite above, and **Structural geology**). A prominent, northerly trending quartz vein, about 3 km southwest of 18 Mile Well on RIVERINA, is probably related to late movement within the zone of strong deformation associated with the Ida and Ballard Faults. Another prominent quartz vein, on the western side of the Illaara greenstone belt on MULLINE, is contiguous with quartz veins to the south, and coincides with a major aeromagnetic lineament (Fig. 4). This quartz vein probably marks a very late stage fault.

In places, the structures that host quartz veins also contain pegmatite, most notably near Wonder Well on RIVERINA, where north-northeasterly and northwesterly trending quartz and pegmatite veins intruded ultramafic schist that hosts beryl (emerald) mineralization (Garstone, 1981). Pegmatite veins are typically very coarse grained, blocky, quartz–feldspar intergrowths. Coarse muscovite is common in the pegmatite in the Illaara greenstone belt. Pegmatite and quartz veins near Wonder Well are commonly flanked by fine-grained, phlogopite-bearing schist.

Mafic and ultramafic dykes (*Edy*)

Prominent aeromagnetic lineaments that cut across all other structural trends probably represent fractures filled by mafic and ultramafic dykes (Figs 3 and 4). While the typical orientation is east-northeasterly, some prominent dykes have substantially different trends. A major north-

SW87 8.9.99

Figure 10. Folded quartz vein in granitoid gneiss near 18 Mile Well (AMG 701239)

northwesterly trending dyke in southeastern RIVERINA, apparent as both an aeromagnetic and aerial photograph lineament, may be the northern extension of the Celebration Dyke (Wyche, 1998).

Fresh, medium-grained gabbro near the Mystery mine in southeastern MULLINE corresponds to a weak, easterly trending aeromagnetic feature, and is a rare example of an outcropping mafic dyke. This rock is mainly medium grained (up to 5 mm), with subhedral calcic plagioclase (labradorite), and subordinate, very pale yellow-green, subhedral clinopyroxene, minor serpentinized olivine, and opaque oxide minerals.

Hallberg (1987) suggested that the dykes were emplaced between about 2.4 and 2.0 Ga, when the northern and southern margins of the Yilgarn Craton were still tectonically active. A SHRIMP U–Pb zircon age of 2661 ± 3 Ma, on what appears to be a granophyric differentiate of a mafic dyke on BARDOC (Nelson, 1998), may represent the age of xenocrystic zircons assimilated from granitoid rocks intruded by the dyke.

Greenstone stratigraphy

Barlee Terrane

Greenstones west of the Ida Fault lie within the Barlee Terrane of Myers (1990). The Barlee Terrane includes much of what has been called the Southern Cross Province (Gee et al., 1981; Griffin, 1990b). Although no universal stratigraphy has been proposed for the Barlee Terrane, it has a widely developed lower greenstone sequence characterized by the presence of banded iron-formation and chert, and abundant tholeiitic basalt, with subordinate intermediate to felsic volcanic and volcaniclastic rocks, clastic sedimentary rocks, and komatiitic or high-Mg basalt and komatiite. An unconformably overlying sequence of clastic sedimentary rocks and felsic and intermediate volcanic rocks, mapped on the JACKSON (Chin and Smith, 1983) and BARLEE (Walker and Blight, 1983) 1:250 000 sheets, has not been recognized in the study area.

The Barlee Terrane stratigraphy is exposed in four greenstone belts. The most complete sequence is that exposed in the Illaara greenstone belt in northwestern MULLINE. Here, the lowermost stratigraphic unit is a quartzite (Figs 3 and 7) in which poorly preserved cross-beds consistently indicate younging to the west. This quartzite, which may be the lowest exposed formation of the Barlee Terrane succession, has been intruded by granitoid, and the contact tectonized. The quartzite is overlain by a sequence of chert, banded iron-formation, and clastic sedimentary rocks, with intercalated tholeiitic basalt and subordinate komatiitic basalt and komatiite. There is at least one gabbroic intrusion at this level. Banded iron-formation and chert become less common higher in the succession, and the sequence grades up into a very poorly exposed package of felsic to intermediate volcanic and volcaniclastic rocks. There is a thick, uniform sequence of tholeiitic basalt with thin interflow beds of chert, banded iron-formation, and shale west of a major northerly trending fault marked by a prominent quartz vein and cleaved, ferruginous chert and shale (Fig. 3).

There is some lateral variation in the lower part of the Illaara greenstone belt succession. The basal quartzite unit thins markedly from north to south, and disappears altogether about 3 km north-northwest of Lemon Rock (AMG 260245). The quartzite is strongly deformed along the granite contact, and it is not clear whether the thinning represents a facies variation or a tectonic discordance. A coarse, locally conglomeratic, clastic unit low in the sequence is about 300 m thick in the northern part of MULLINE, and considerably thicker further north on MOUNT MASON (Duggan, 1995). However, the very coarse grained component thins rapidly to the south, and grades into a unit of interbedded fine- to coarse-grained sandstone and shale.

The presence of abundant quartz-rich metasedimentary rocks low in the succession suggests that the greenstone sequence was deposited on a pre-existing sialic basement. The deposition of the greenstones on a pre-existing sialic basement is further indicated by the presence of two populations of old (>3.3 Ga) detrital zircons in the basal quartzite (Froude et al., 1983; see **Metamorphosed sedimentary rocks**).

The Maninga and Yerilgee greenstone belts in the southwestern part of MULLINE are less well exposed. The Maninga greenstone belt consists of a series of low hills, and scattered outcrops of a very deeply weathered sequence containing shale and banded iron-formation, tholeiitic basalts, and ultramafic rocks. No clear younging direction indicators have been found, and the belt has been extensively intruded by granitoids. Although it is not possible to establish a stratigraphic succession for this belt, the association of rock types suggests that it may be equivalent to the lower part of the Illaara greenstone belt succession.

The Yerilgee greenstone belt cuts across the southwestern corner of MULLINE, and extends southeast into the KALGOORLIE 1:250 000 sheet area (Wyche, 1998), and northwest into the BARLEE 1:250 000 sheet area (Walker and Blight, 1983). The belt contains a series of ridges formed over deeply weathered and lateritized banded iron-formation and chert. Associated shales are deeply weathered and poorly exposed. Mafic and ultramafic rocks are intercalated with the sedimentary rocks, but the lack of exposure makes it difficult to estimate the ratio of ultramafic to mafic components. No younging direction indicators have been found, and the absence of marker horizons means that it is not possible to demonstrate whether or not the major ridges represent different levels within the same sequence or repetitions of the same part of the sequence. Again, the association of rock types suggests that this belt may be equivalent to the lower part of the Illaara greenstone belt sequence.

The Barlee Terrane rocks immediately west of the Ida Fault, in the Mount Ida greenstone belt, comprise a thick, uniform pile of dominantly tholeiitic basalts with rare, thin interbeds of shale and chert. One prominent ridge of banded iron-formation in the west has been extensively intruded by granitoids. No younging indicators have been found. The sequence may be equivalent to the upper, tholeiitic part of the Illaara greenstone belt.

Kalgoorlie Terrane

Greenstones east of the Ida Fault lie within the Eastern Goldfields Province (Gee et al., 1981; Griffin, 1990a). Swager et al. (1995) described a stratigraphic sequence for a region extending between Menzies and Norseman that they called the Kalgoorlie Terrane. The stratigraphy of Swager et al. (1995) comprises a lower basalt unit, a komatiite unit, an upper basalt unit, and a felsic volcanic–volcaniclastic unit, locally unconformably overlain by a coarse clastic sedimentary unit. The advent of precise SHRIMP U–Pb zircon geochronology has allowed more detailed definition of the history of felsic volcanism, suggesting that it began in the relatively early stages of greenstone deposition, and that felsic, mafic, and ultramafic volcanism may have been at least partly contemporaneous (Nelson, 1997). Only that part of the lower sequence comprising the basalt and komatiite units is represented on MULLINE and RIVERINA. However, it is difficult to discern the upper and lower basalt units due to the absence of reliable younging indicators, a lack of continuous exposure, and structural complications.

Hill et al. (1990, 1995) correlated olivine cumulates near the Riverina Homestead and at Ghost Rocks with cumulates of the Kurrajong sequence north of the map area on BALLARD (Rattenbury, 1991), and those that flank the Goongarrie – Mount Pleasant Anticline on BARDOC (Witt, 1994) and extend west into the Siberia district on DAVYHURST (Wyche and Witt, 1994). This unit is known as the Walter Williams Formation, and it forms the lower part of the regional komatiite unit of Swager et al. (1995) in the Kalgoorlie Terrane. SHRIMP U–Pb zircon geochronological data from the Kalgoorlie and Kambalda areas suggest that the Walter Williams Formation was deposited between c. 2710 Ma (Nelson, 1997) and c. 2692 Ma (Claoué-Long et al., 1988). A SHRIMP U–Pb zircon age of 2691 ± 6 Ma (Nelson, 1995) for a foliated felsic rock, interpreted as volcaniclastic (Swager, 1994), that lies stratigraphically above the komatiite unit near Ghost Rocks is consistent with a correlation between the ultramafic rocks at Ghost Rocks and those at Kambalda.

Structural geology

MULLINE and RIVERINA occupy the northwestern part of the Kalgoorlie Terrane of Swager et al. (1995) and extend west, across the Ida Fault, into the eastern part of the Southern Cross Province of Griffin (1990b) or Barlee Terrane of Myers (1990). There have been limited regional-scale, structural studies of the Southern Cross Province (e.g. Eisenlohr et al., 1993), and its tectonic history is poorly understood. Swager (1997) summarized various models for the tectonic evolution of the Eastern Goldfields region, and presented a review of the deformation history based on regional mapping studies, interpretation of aeromagnetic data, and the results of deep-crustal seismic reflection surveys.

Barlee Terrane

Limited geochronological data from the Barlee Terrane (Pidgeon and Wilde, 1990; Dalstra, 1995; Wang et al., 1996; Nelson, 1999) indicate a much longer history of greenstone deposition than in the Kalgoorlie Terrane. Structural studies in the Marda–Diemals area, west of MULLINE, suggest a two-stage deformation scheme comprising an early north–south compressive regime at about 2.73 Ga, followed by a broadly east–west compressive regime (Dalstra, 1995; Greenfield and Chen, 1999).

On MULLINE, there is no unequivocal evidence of the early (north–south) compressive deformation (D_1) recognized to the west. As in other parts of the Southern Cross Province, banded iron-formation units commonly preserve small-scale, isoclinal minor folds and intrafolial folds that may be remnant effects of early, low-angle thrusting and recumbent folding. There is evidence of refolding of such structures in the Marda–Diemals area to the west (Dalstra, 1995; Greenfield and Chen, 1999), but no refolded folds have been observed on MULLINE. According to Greenfield and Chen (1999), late D_1 movement on regional-scale shear zones may have reactivated structures that date from the early development of the basin, and produced local extensional basins and loci of low strain that facilitated the intrusion of felsic igneous rocks. The timing of D_1 is poorly constrained, but structural and geochronological data from the Marda–Diemals area suggest that granitoid rocks were emplaced late during D_1, at about 2.73 Ga (Greenfield and Chen, 1999).

In the Marda–Diemals area, Greenfield and Chen (1999) attributed the most readily apparent macroscopic deformation to a long-lived, east–west compressive event (D_2). This deformation initially produced large-scale (with hinges tens of kilometres long), open to tight folds with typically steeply dipping axes. As the deformation progressed, regional-scale shear zones developed or were reactivated. The regional north- to north-northwesterly trending foliation developed during this compressional regime. On MULLINE, the only macroscale structures attributable to D_2 are the fold hinge at the southern end of the Illaara greenstone belt (AMG 283078) and probable folds suggested by aeromagnetic patterns in the Yerilgee greenstone belt in the southwest (Fig. 4). Interpretations showing regional-scale shear zones across MULLINE are based on patterns on craton-scale aeromagnetic images. For example, Myers and Hocking (1998) interpreted a major structure, the Perrinvale Fault, along the eastern side of the Illaara greenstone belt. While it is true that quartzites and mafic rocks west of the granite–greenstone contact are strongly deformed, deformation in the granitoids is apparent only immediately adjacent to the contact (Fig. 11). This suggests that if there is a major D_2 shear along this contact, much of the movement took place prior to intrusion of the granitoids.

North-northeasterly trending aeromagnetic lineaments (Fig. 4) and quartz veins, with less prominent south-easterly trending conjugates, cut both greenstone and granitoid rocks, and overprint all structures except the

Figure 11. Granitoid rock intruding banded iron-formation near Lemon Rock (AMG 269219). The granitoid is moderately deformed near the contact

fractures associated with mafic and ultramafic dykes. There are clear dextral offsets on a few of these features — for example, the north-northeasterly trending faults that cut the Ularring Monzogranite have dextral offsets of about 500 m on aeromagnetic images. A major north-northeasterly trending aeromagnetic lineament in the western part of MULLINE coincides with a fault that truncates the southeastern end of the Yerilgee greenstone belt, and disrupts bedding and structural trends in the western part of the Illaara greenstone belt (Fig. 3). This fault is filled locally by prominent quartz veins. Other north-northeasterly trending faults that cut the eastern part of the Illaara greenstone belt may have also formed during this deformation. These structures appear to post-date the emplacement and crystallization of most granitoid rocks. They correspond to the late-stage, brittle fractures of Greenfield and Chen (1999) in the Marda–Diemals area and D_4 structures in the Kalgoorlie Terrane (Swager et al., 1995). They probably represent the last stage of east–west shortening in the eastern part of the Yilgarn Craton.

Kalgoorlie Terrane

Swager (1997) briefly reviewed the plethora of structural models for the Eastern Goldfields Province, with emphasis on those relevant to the Kalgoorlie Terrane and greenstone terranes further east.

Most deformation schemes for the southern part of the Eastern Goldfields region, and particularly the Kalgoorlie Terrane, recognize an early deformation (D_1) that produced regional-scale recumbent folds and thrust duplexes (Archibald et al., 1978; Martyn, 1987; Swager and Griffin, 1990; Swager et al., 1995). There is no unequivocal evidence of this event on MULLINE or RIVERINA. However, the gneissic granitoid on RIVERINA records an apparently complex history that may be at least partly contemporaneous with D_1 elsewhere in the Kalgoorlie Terrane.

The gneissic granitoid appears to have been through at least two major deformation events, and was probably emplaced as a granitoid or suite of granitoids at about 2680 Ma (Black, L. P., pers. comm., in Williams, 1993). Deformation probably ceased by the time of intrusion of the undeformed Clark Well Monzogranite at c. 2640 Ma (Nelson, 1995). The first deformation produced distinct compositional layering (Fig. 8). This was followed by at least one folding episode. Although the layering is not clearly folded at outcrop scale, broad changes in foliation trends (e.g. AMG 722060) consistent with fold structures evident on aeromagnetic images (Fig. 4) indicate large-scale folding, probably during regional D_2–D_3 deformation. Aeromagnetic patterns in unexposed areas of gneissic granitoid east of Riverina Homestead, which look like 'mushroom-style' fold interference patterns, suggest a complex folding history. The granitoid gneiss is cut by numerous quartz and pegmatite veins. The presence of more than one generation of these veins is indicated by the fact that some have been folded (Fig. 10), whereas others crosscut all fabrics in the rock.

The distribution of mafic and ultramafic rocks, coupled with patterns on aeromagnetic images, suggests some repetition of units in the eastern part of the Mount Ida greenstone belt between the Ida and Ballard Faults. Although no distinctive marker horizons have been identified that would allow correlation of various mafic and ultramafic units, it is possible that some of the complex layering evident within the greenstone belt represents folding or thrusting within the D_1 regime. However, such structures could also be the products of folding and thrusting during D_2–D_3 compression.

Most preserved tectonic fabrics in the Kalgoorlie Terrane are attributed to a dominantly east–west, progressive compressional regime (D_2–D_3) that produced upright folds, and strike, thrust, and reverse-slip faults (Swager et al., 1995). This regime probably post-dated the deposition of the greenstones, and coincided with the major period of granitoid intrusion (Swager, 1997). Clear D_2 fold structures on RIVERINA include the syncline–anticline pair described by Swager (1994) in the Ghost Rocks greenstones and the northern end of the Kurrawang Syncline in the southeast (Fig. 3; Swager et al., 1995). Strong tectonic fabrics in the Mount Ida greenstone belt are probably due to D_2–D_3 deformation. Large-scale folding in the gneissic granitoid, evident in aeromagnetic images (Fig. 3), and small-scale folding (e.g. folding of veins in outcrop; Fig. 10) probably occurred during D_2–D_3 deformation. The shallowly plunging mineral lineation seen on foliation surfaces in gneissic granitoid may mainly be a compressional feature, as porphyroclasts in nearby outcrops do not give a clear sense of movement (Fig. 9).

The last stage of D_3 was probably compression or transpression, partitioned into large-scale shear zones within greenstone belts and along granite–greenstone contacts. Examples of such structures include the Menzies Shear (Swager, 1994), Ballard Fault, and Ida Fault (Fig. 3). The Ballard Fault is the northern extension of the Zuleika Shear (Wyche and Witt, 1994).

Movement on the Ida Fault was probably accommodated by complex movements within the broad zone of deformation that occupies much of the eastern part of the Mount Ida greenstone belt, between the Ida and Ballard Faults, and extends into the granitoids and gneisses to the east. The Ida Fault forms a clear, linear trace on regional-scale aeromagnetic images, and is marked in places by a pronounced lineament that is visible on both aerial photographs and satellite images. There is a distinct change in rock associations across the fault zone from typical mafic- and ultramafic-dominated sequences of the Kalgoorlie Terrane to the east, to a less magnesium-rich sequence containing banded iron-formation in the Barlee Terrane to the west. Deformation fabrics near the fault are typically easterly dipping, consistent with data obtained during the deep-crustal seismic traverse to the south (Goleby et al., 1993). A well-preserved example of such an easterly dipping fabric is the moderately easterly dipping elongation or flattening deformation of pillow lava structures in the Lady Gladys opencut on RIVERINA (Fig. 5). The intrusion of the undeformed Clark Well Monzogranite into the Ida Fault at 2640 ± 8 Ma (Nelson, 1995) indicates that major movement on the fault had ceased by this time.

There is some evidence of elevated metamorphic grade near the Ida Fault, and in greenstones west of the fault (Wyche and Witt, 1994; see **Metamorphism**). However, there has been no detailed documentation of changes in metamorphic grade across the fault, and it is not clear how much of this effect can be attributed to the abundant intrusion of the late granitoids into, and adjacent to, the fault.

The nature of the Ida Fault at depth has been interpreted from a deep-crustal seismic traverse that ran from the Barlee Terrane to the Kalgoorlie Terrane, on DUNNSVILLE, about 60 km south of the southern edge of RIVERINA (Goleby et al., 1993; Swager et al., 1997). In the seismic profile, the Ida Fault appears as a planar, shallowly (30°) easterly dipping reflector that can be traced to a depth of 25–30 km. The fault offsets a boundary between upper and lower crust, but not the crust–mantle boundary (Moho), which deepens gradually over a broad zone beneath the fault (Drummond et al., 1993; Goleby et al., 1993). Swager et al. (1997) interpreted the Ida Fault as a gently easterly dipping, extensional or normal fault with about 5 km displacement that developed late in the tectonic evolution of the region. They argued that features associated with the fault, such as the disposition of rock types nearby, a perceived change in metamorphic grade across it (higher to the west), and the markedly linear nature, suggest that it is a late-stage, normal fault that post-dated peak metamorphism and did not control basin formation and greenstone deposition.

On RIVERINA, however, the complex deformation history recorded in the Mount Ida greenstone belt and adjacent gneissic granitoids implies a history that may have been long and complicated, involving major movement reversals. The apparent normal movement on the Ida Fault, suggested by the seismic data, may have been preserved after tectonic inversion of an early extensional event, perhaps the basin-forming event, during D_2–D_3 compression. If the movement was extensional, then it may represent relatively small scale, late-stage orogenic collapse on a structure with a long and complex history (Swager, 1997).

The final compressive stage (D_4) is manifest as major north-northeasterly trending aeromagnetic lineaments that correspond to faults with small, dextral offsets, and are commonly filled by prominent quartz and, locally, pegmatite veins. East-southeasterly trending conjugate structures are less pronounced on aeromagnetic images (Fig. 4). These are regional-scale features that post-date the last movement on the Ida Fault. The Ularring Monzogranite, a late monzogranite intrusion that intruded the Ida Fault, is cut by a series of the north-northeasterly trending faults, with dextral offsets of about 500 m on aeromagnetic images. North of Riverina Homestead, in the Morleys mining centre on RIVERINA, a series of late, north-northeasterly trending faults have produced a clear dextral offset across the northerly trending zone of deformation between the Ida and Ballard Faults (Figs 3 and 4).

The last Precambrian structural event evident on MULLINE and RIVERINA was the emplacement of mainly east-northeasterly trending, mafic and ultramafic dykes along fractures, possibly between about 2.4 and 2.0 Ga (Hallberg, 1987).

Metamorphism

Binns et al. (1976), in a regional overview of metamorphic grade in the eastern Yilgarn Craton, indicated that the area occupied by MULLINE and RIVERINA lies within a zone of medium- to high-grade metamorphism, with metamorphic assemblages in the low- to high-amphibolite facies. The metamorphic assemblages are typically higher grade than those to the east in the Kalgoorlie area (Binns et al., 1976; Ridley, 1993), and are similar to medium- to high-grade assemblages to the west in the Marda–Diemals area (Ahmat, 1986; Dalstra, 1995).

The best-preserved metamorphic assemblages are found in the Illaara and Mount Ida greenstone belts. According to the classification scheme of Binns et al. (1976) for the east Yilgarn region, which was modified by Ahmat (1986), most greenstones in this region are metamorphosed to middle- to high-amphibolite facies.

Metamorphic grade in rocks of the Illaara greenstone belt is indicated by the presence of grunerite in banded iron-formation (*Aci*); biotite, andalusite, cordierite, and orthoamphibole (?gedrite) in metapelites (*Asf*); clinopyroxene and biotite in the layered intermediate rocks (*Ail*); and dark hornblende and tremolite–actinolite in tholeiitic and high-Mg mafic rocks (*Ab*, *Abm*). These assemblages are consistent with the high-temperature, low-pressure amphibolite facies of Ahmat (1986), and suggest that rocks in the Illaara greenstone belt attained a higher metamorphic grade than suggested by Ahmat (1986, fig. 5). The common development of randomly oriented porphyroblasts and granoblastic polygonal textures suggests that peak metamorphism outlasted the main compressive deformation event. This accords with observations elsewhere in the Southern Cross Province (Ahmat, 1986; Ridley et al., 1997). Widespread chloritization and local epidote and talc–carbonate alteration indicate a late-stage, regional, retrograde alteration event.

Metamorphic grade in the Mount Ida greenstone belt is less well constrained due to a lack of suitable assemblages in a sequence dominated by mafic and ultramafic rocks. However, amphibolite-facies metamorphism is suggested by the presence of possibly metamorphic olivine in some ultramafic rocks (e.g. west of Mount Morley); the abundant presence of dark hornblende in mafic rocks; and the local presence of garnetiferous mafic rocks (e.g. southeast of the Emerald gold mine at AMG 680228 and west of Mount Morley on RIVERINA). The highest grade metamorphosed mafic rocks, of upper amphibolite facies, are most abundant adjacent to granite–greenstone contacts. Some of these rocks (e.g. north of Blue Well on RIVERINA) contain clinopyroxene. This high-grade metamorphism may be more directly attributable to effects of granitoid intrusion than the typically lower grade metamorphism in the central parts of greenstone belts (Ridley, 1993). As in the Illaara greenstone belt, widespread, late-stage, retrograde alteration in this belt is indicated by common chloritization, serpentinization of ?metamorphic olivine, and epidote and talc–carbonate alteration.

Cainozoic geology

Ollier et al. (1988) and Chan et al. (1992) discussed the regolith and landscape evolution in the Kalgoorlie region.

During the regional regolith mapping and geochemical sampling program undertaken by GSWA over the MENZIES 1:250 000 sheet area in 1994 (Kojan and Faulkner, 1994), 1072 samples, or approximately one sample per 16 km^2, were collected and analysed for 48 components. A regolith-materials map was produced as part of this program, based on field observations and interpretation of satellite imagery and aerial photographs. On the map, regolith units were interpreted as relict, erosional, or depositional, in order to facilitate interpretation of trends and patterns in the geochemical data. A regolith-landforms map over the MENZIES 1:250 000 sheet area (Craig and Churchward, 1995) is one of a series of these maps produced by the Australian Geological Survey Organisation (AGSO).

No Palaeozoic or Mesozoic rocks have been identified on MULLINE or RIVERINA. However, an outcrop of silcretized coarse, sandy sediment (*?Ts*) west of Blue Well (around AMG 626302 on RIVERINA) may be a Tertiary deposit, equivalent to those found in palaeodrainage channels. The Lake Ballard and associated drainage systems in northeastern RIVERINA and the broad, northerly flowing drainage basin in central MULLINE form part of the Yindarlgooda Palaeoriver (Hocking and Cockbain, 1990) within the Roe Palaeodrainage system. Commander et al. (1992) described early Tertiary sediments from the Roe Palaeodrainage in the Kalgoorlie area to the south, where palaeochannels are up to 60 m deep.

All rocks have been affected by in situ weathering, particularly silicification, ferruginization, and calcification. Cainozoic units have been distinguished mainly by photo-interpretation.

Playa lake deposits (*Czts*) are characterized by evaporites interbedded with clay and sand. Dunes adjacent to playas (*Cztd*) are eolian deposits of sand, silt, and gypsum derived from the lake beds when dry.

Colluvium (*Czc*) consists of gravel, sand, and silt, including locally abundant white vein-quartz scree, which has been deposited as sheetwash or talus at the base of slopes. Quartzofeldspathic sand (*Czg*), which has formed in situ over areas of granitoid rock, is widespread in the western part of the sheet area. Sandplain deposits (*Czs*) consist of sheets and dunes of yellow, non-calcareous sand. There has been some debate as to how much of the sand formed in situ (Ollier et al., 1988), but the numerous dunes in the eastern part of RIVERINA suggest that it contains a significant proportion of reworked material. Sandplains commonly form thin veneers over laterite.

Laterite and its reworked products (*Czl*) are widespread and obscure the granite–greenstone geology in much of the region. Laterite forms a hard, ferruginous duricrust, which is locally reworked to gravel. The duricrust can range in thickness from a few centimetres up to about 10 m. Complete weathering profiles can be over 100 m thick (Ollier et al., 1988). Silica caprock (*Czu*) forms a hard, light- to medium-brown crust over ultramafic rocks on RIVERINA, particularly cumulates, commonly preserving primary igneous textures.

Areas of calcrete (*Czk*) in the central and northern parts of RIVERINA are probably groundwater calcrete (Hocking and Cockbain, 1990) formed within the ancient palaeodrainage regime. Quaternary alluvium (*Qa*), consisting of clay, silt, sand, and gravel, occupies active stream channels.

Economic geology

Although the region has a long history of mineral production, mainly of gold, there were no major, producing mines on MULLINE or RIVERINA when these notes were compiled in 1999.

Gold

Gibson (1904) described gold deposits between the Riverina and Mulwarrie mining areas (in the western and southwestern parts of RIVERINA respectively), and presented tables of gold returns from leases in the Mulline and Ularring districts (in the western part of RIVERINA) to the end of 1902. More detailed descriptions of the deposits, including a map of the Mulline district, are contained in Feldtmann (1915). Further brief descriptions of deposits at Ularring, Mulline, and Riverina were presented by Feldtmann (1916). Most mining activity in this area had ceased by about the time of the First World War, but various leases have been worked subsequently. Gold production data from up until about 1950 (Department of Mines Western Australia, 1954) also contains production data from the Morleys mining district on RIVERINA, which was active between about 1938 and 1941, and from the western part of the Menzies district, including Ghost Rocks. There is no recorded production from Lawrence Find on MULLINE.

Witt (1993a) presented detailed descriptions of all gold deposits in the Menzies mining area, mainly east of RIVERINA. The only deposit on RIVERINA included in his descriptions is St Albans (in the eastern part), where gold is hosted by northeasterly trending, moderately dipping quartz veins in amphibolite and ultramafic schist. General descriptions of styles of, and controls on, gold mineralization in the Menzies–Kambalda region are presented by Witt (1993b). There are no recent, published descriptions of gold mineralization in other parts of MULLINE and RIVERINA. According to Gibson (1904) and Feldtmann (1915, 1916), gold mineralization at the Riverina mine is hosted by quartz veins within a steeply dipping, northerly trending shear zone in metabasalt. The Riverina mine, which has operated intermittently between 1897 and 1989, has been the most productive deposit within the study area, with production of about 1573 kg of gold from 99 500 t of ore treated (Wilkinson, 1994, p. 125). All other deposits in the Mount Ida greenstone belt are hosted by quartz veins in various orientations, mainly in mafic rocks.

Lintern and Butt (1991, 1997) studied dispersion of gold in regolith in the Mulline district, and suggested a potentially economic laterite-hosted resource. However, a recent attempt to mine gold from laterite in the area using the heap-leach process did not prove economic (Gonnella, 1997, p. 160).

Copper

Feldtmann (1915) reported the presence of malachite and azurite in a mine dump at the Mulline mining centre in southwestern RIVERINA, and in a quartz vein a few kilometres to the east. Malachite and azurite are also found in vein quartz on dumps beside a small shaft about 1 km southwest of Wonder Well (AMG 644103).

Nickel

An extensive nickel–copper exploration program by CRA Exploration Pty Ltd in the late 1960s and early 1970s failed to find any economic mineralization. However, the reports produced as a result of this exploration contain detailed geological maps over much the northern part of the Mount Ida greenstone belt (e.g. Tuite, 1970).

Beryl

Beryl, including gem-quality emeralds, is associated with a series of northeasterly trending pegmatite veins within the northerly trending tremolite schist unit just east of Wonder Well on RIVERINA. The ultramafic schist is markedly altered near the pegmatite veins, where it may contain phlogopite, biotite, and talc (Garstone, 1981).

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Appendix 1

Gazetteer of localities

Locality	*Map sheet*	*Easting*	*Northing*
18 Mile Well	RIVERINA	271000	6722800
Blue Well	RIVERINA	264600	6730300
Emerald mine	RIVERINA	266400	6724300
Ghost Rocks	RIVERINA	295500	6728300
Halag Rock	MULLINE	227900	6718100
Hospital Rocks	MULLINE	221500	6695500
Lady Gladys opencut	RIVERINA	258600	6696700
Lawrence Find	MULLINE	221100	6711500
Lemon Rock	MULLINE	226900	6721900
Morleys mining centre	RIVERINA	265000	6715500
Mount Morley	RIVERINA	263800	6716800
Mulline mining centre	RIVERINA	260000	6700500
Mulline Rock	MULLINE	256500	6706900
Mulwarrie mining centre	RIVERINA	264000	6679200
Mystery mine	MULLINE	257200	6796900
Red Leap mine	RIVERINA	260400	6792900
Riverina Homestead	RIVERINA	264500	6706000
Riverina mine	RIVERINA	264300	6707000
Sowerline Bore	MULLINE	253500	6703000
St Albans mine	RIVERINA	205800	6716900
Ularring mining centre	RIVERINA	259500	6792500
Wonder Well	RIVERINA	264800	6710800

Appendix 2

Whole-rock geochemical data for RIVERINA and MULLINE

GSWA sample	112028	112241	112242	112243	112244	112245
Rock type	Andesite	Ultramafic	Basalt	Basalt	Basalt	High-Mg basalt
Locality	Lawrence Find	Mount Morley	Mount Morley	Wonder Well	Ularring (east)	Riverina
Map sheet	MULLINE	RIVERINA	RIVERINA	RIVERINA	RIVERINA	RIVERINA
Greenstone belt	Illaara	Mount Ida	Mount Ida	Mount Ida	Mount Ida	Mount Ida
Easting	223400	263400	262000	265200	269000	266500
Northing	6716100	6717200	6718100	6710600	6793800	6705500
			Percentage			
SiO_2	58.2	41.6	51.2	50.7	50.5	48.4
TiO_2	0.79	0.28	0.93	0.51	0.59	0.48
Al_2O_3	16.7	5.7	13.9	12.5	15.1	12.6
Fe_2O_3	2.07	5.28	2.02	1.2	1.81	1.51
FeO	4.77	6.49	9.29	9.15	8.23	8.03
MnO	0.11	0.2	0.25	0.27	0.21	0.23
MgO	4.42	27.8	7.02	9.08	7.64	12.4
CaO	6.89	4.18	10.8	13.1	11.7	12.5
Na_2O	4.7	0.05	2.3	1.45	2.03	1.41
K_2O	0.12	<0.05	0.5	0.08	0.11	0.09
P_2O_5	0.22	<0.05	0.08	<0.05	<0.05	<0.05
LOI	1.24	6.67	0.77	0.74	1.07	1.29
Total	**100.23**	**98.25**	**99.06**	**98.78**	**98.99**	**98.94**
			Parts per million			
As	–	–	–	–	–	–
Ba	220	<11	–	113	69	25
Cr	153	3 849	346	1 183	416	1 255
Cs	–	–	–	–	–	–
Cu	49	19	76	16	11	9
Ga	17	7	15	14	14	11
Hf	–	–	–	–	–	–
Nb	–	–	–	–	–	–
Ni	118	1 138	145	334	107	420
Pb	14	–	–	5	–	–
Rb	51	–	181	–	–	–
Sc	21	19	37	34	37	31
Sr	387	19	125	146	93	93
Ta	–	–	–	–	–	–
Th	7	–	3	–	2	–
U	–	–	–	–	–	–
V	167	115	279	228	239	202
Y	21	6	31	14	189	11
Zn	72	114	100	111	80	64
Zr	196	20	100	57	52	41
La	32	<5	9	<5	38	<5
Ce	67	<6	14	<6	29	<6

Appendix 2 (continued)

GSWA sample	*112246*	*112247*	*112248*	*112249*	*112250*	*112251*
Rock type	*Basalt*	*Basalt*	*High–Mg basalt*	*Andesite*	*Basalt*	*Basalt*
Locality	*Mount Morley*	*Red Leap mine*	*Halag Rock*	*Lawrence Find*	*Lawrence Find*	*Lawrence Find*
Map sheet	RIVERINA	RIVERINA	MULLINE	MULLINE	MULLINE	MULLINE
Greenstone belt	*Mount Ida*	*Mount Ida*	*Illaara*	*Illaara*	*Illaara*	*Illaara*
Easting	264400	260200	226900	220500	220200	218900
Northing	6715900	6793000	6716200	6712200	6726500	67730700
			Percentage			
SiO_2	52.7	49	51.9	55.1	53	52.9
TiO_2	1.01	1.43	0.25	0.73	1.75	1.79
Al_2O_3	16.3	13.8	11.7	14.9	14.2	14.6
Fe_2O_3	2.45	2.44	0.96	1.48	2.14	2.8
FeO	8.06	10.5	5.81	5.79	9.11	8.82
MnO	0.24	0.24	0.16	0.16	0.27	0.33
MgO	3.61	7.68	13.4	7.43	5.37	4.58
CaO	13.5	9.99	13.9	12.8	10.6	10.7
Na_2O	1.1	1.69	0.84	1.05	2.45	2.35
K_2O	0.37	1.44	0.05	0.06	0.16	0.2
P_2O_5	0.08	0.13	<0.05	0.06	0.3	0.31
LOI	0.3	1.12	1.42	0.85	0.47	0.57
Total	**99.72**	**99.46**	**100.39**	**100.41**	**99.82**	**99.95**
			Parts per million			
As	–	–	–	4	18	–
Ba	43	121	25	51	58	110
Cr	215	237	559	292	91	92
Cs	–	–	–	–	–	–
Cu	12	54	16	54	132	64
Ga	17	17	8	14	20	19
Hf	–	–	–	–	–	–
Nb	–	–	–	–	–	7
Ni	159	89	243	121	87	107
Pb	–	6	6	–	4	–
Rb	99	175	2	3	–	–
Sc	40	38	42	38	35	36
Sr	144	86	59	76	138	129
Ta	–	–	–	–	–	–
Th	–	2	–	–	–	2
U	–	–	–	–	–	–
V	299	341	163	270	375	387
Y	23	33	6	16	39	39
Zn	65	124	53	67	124	102
Zr	79	105	18	50	146	145
La	<5	7	<5	<5	10	<5
Ce	6	9	<6	<6	17	11

Appendix 2 (continued)

GSWA sample	*112252*	*112253*	*112254*	*112255*	*112256*	*112257*
Rock type	*Basalt*	*Basalt*	*Basalt*	*Basalt*	*Basalt*	*Basalt*
Locality	*Lemon Rock*	*Lemon Rock*	*Sowerline Bore*	*Riverina*	*Riverina mine*	*Blue Well*
Map sheet	MULLINE	MULLINE	MULLINE	RIVERINA	RIVERINA	RIVERINA
Greenstone belt	*Illaara*	*Illaara*	*Mount Ida*	*Mount Ida*	*Mount Ida*	*Mount Ida*
Easting	*223500*	*223800*	*253800*	*263100*	*264300*	*266900*
Northing	*6729300*	*6729900*	*6701300*	*6706200*	*6706800*	*6730700*
			Percentage			
SiO_2	46.7	51.6	52.8	52.1	51.6	51.6
TiO_2	1.09	0.62	1.74	1.01	0.73	0.74
Al_2O_3	13.4	14.4	14.7	16.1	14.9	14.9
Fe_2O_3	3.62	2	2.72	2.16	1.68	1.7
FeO	15.2	6.89	7.83	9.69	9.27	7.74
MnO	0.77	0.17	0.22	0.33	0.27	0.22
MgO	5.02	8.3	4.89	3.69	6.49	7.47
CaO	10.4	12.6	9.6	11.9	12.3	11.6
Na_2O	1.55	1.88	3.73	1.84	1.62	2.51
K_22O	0.28	0.09	0.18	0.15	0.15	0.12
P_2O_5	0.09	<0.05	0.28	0.08	0.05	0.05
LOI	0.8	1.04	0.63	0.35	1.11	0.76
Total	**98.92**	**99.59**	**99.32**	**99.4**	**100.17**	**99.41**
			Parts per million			
As	79	4	–	–	31	–
Ba	46	32	104	70	29	69
Cr	161	436	344	210	377	379
Cs	–	–	–	–	–	–
Cu	9	81	80	103	78	126
Ga	17	12	15	18	16	15
Hf	–	–	–	–	–	–
Nb	–	–	–	–	–	–
Ni	116	143	121	160	122	118
Pb	4	–	–	–	25	–
Rb	–	–	2	22	5	–
Sc	37	39	38	37	42	42
Sr	73	140	130	111	111	107
Ta	–	–	–	–	–	–
Th	–	–	–	–	–	–
U	–	–	–	–	–	–
V	336	263	360	290	269	265
Y	26	46	22	20	16	16
Zn	170	77	98	111	201	94
Zr	76	56	84	77	57	58
La	<5	<5	6	<5	<5	5
Ce	<6	<6	7	<6	<6	<6

NOTES: All analyses were carried out at the Chemistry Centre of Western Australia.
Major- and trace-element analyses were by X-ray fluorescence (XRF). The technique is discussed in Morris et al. (1991).
Localities are specified by the Australian Map Grid (AMG) standard six-figure reference system whereby the first group of three figures (eastings) and the second group (northings) together uniquely define position, on this sheet, to within 100 m.

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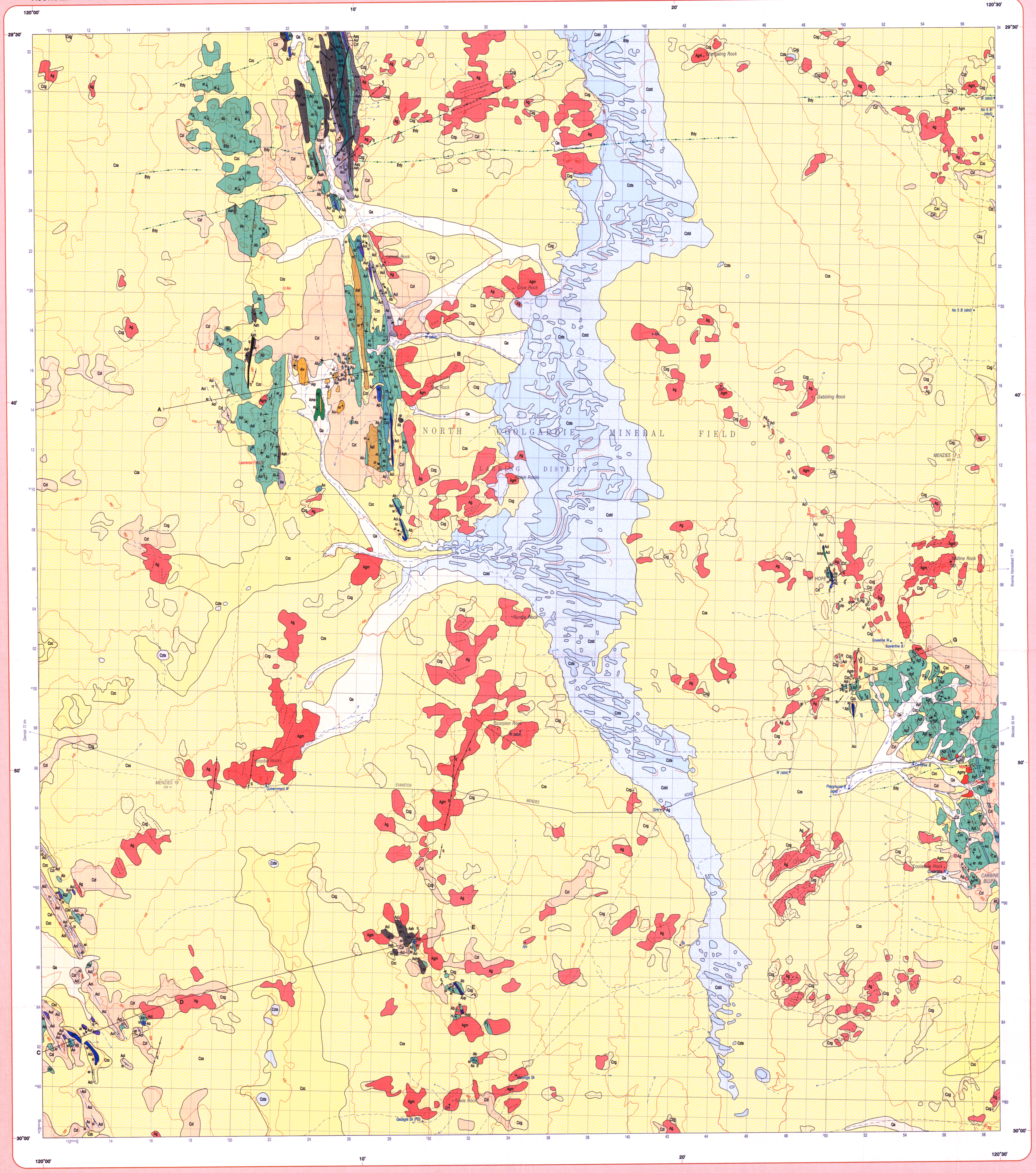
MULLINE

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA



PHANEROZOIC — CAINOZOIC — QUATERNARY

Qa — Alluvium — clay, silt, sand, and gravel; in channels

Czts — Evaporite interbedded with clay, silt, and sand in playas
Cztd — Sand, silt, and gypsum in stabilized dunes adjacent to playas

Czc — Colluvium — gravel, sand, and soil as sheetwash and talus
Czg — Quartzo-feldspathic sand and saprolite over granitoid rock; includes minor laterite
Czs — Sandplain — yellow sand with limonitic pisoliths near base
Czl — Laterite and lateritic gravel

PROTEROZOIC

Ėdy — Mafic and ultramafic dykes; interpreted from aeromagnetic data where dashed

ARCHAEAN

q, g, p — Veins and dykes: q — quartz, g — granitoid, p — pegmatite

Ag — Granitoid rock, undivided; syenogranite to granodiorite
Agm — Monzogranite, undivided
Agmy — **MYSTERY MONZOGRANITE:** fine, even-grained; with biotite; late tectonic

Apf — Feldspar(-quartz) porphyry

As — Sedimentary rock, undivided; includes sandstone, siltstone, shale, and chert; may have a volcaniclastic component
Ash — Shale and slate, locally silicified
Aso — Oligomictic conglomerate with quartzite clasts, quartzose sandstone, and minor shale
Asq — Medium-grained quartzite and quartz-muscovite schist
Asf — Sedimentary rock derived from felsic volcanic rocks; includes tuffaceous sedimentary rock; with local andalusite and/or garnet
Ac — Banded chert, locally ferruginous
Aci — Banded iron-formation

Aiv — Intermediate volcanic and volcaniclastic rock
Aip — Intermediate porphyry, feldspar-phyric
Ail — Layered intermediate rock

Ao — Mafic intrusive rock, undivided; medium- to coarse-grained
Aog — Gabbro

Ab — Basalt; mainly tholeiitic with local subordinate komatiitic basalt; includes doleritic layers and lenses
Abm — Komatiitic basalt; relict pyroxene spinifex texture
Ama — Mafic amphibolite

Aup — Peridotite, serpentinized and silicified
Aur — Tremolite(-chlorite-talc) schist; includes deformed komatiitic basalt

Metamorphosed at greenschist to amphibolite facies

Geological boundary
- accurate
- interpreted from aeromagnetic data

Fault
- accurate

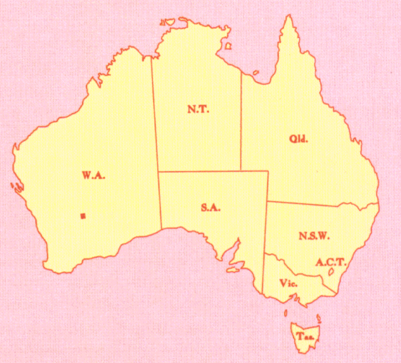
Bedding, showing strike and dip
- inclined — 60
- vertical

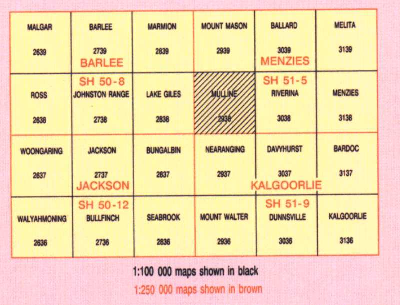
Dominant metamorphic foliation, showing strike and dip
- inclined — 55
- vertical

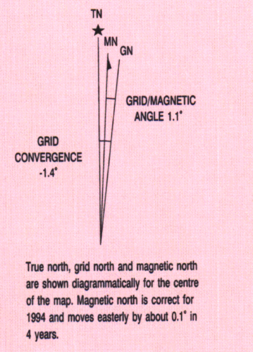
Mineral lineation, showing direction of plunge
- plunging — 25
- on foliation plane — 80, 50
- on bedding plane — 25, 20

Airphoto lineament
- structural trend
- foliation trend in greenstone
- fracture pattern in granitoid rock

Formed road
Track
Fence, generally with track
Yard — Yd
Horizontal control, major
Sand dune
Breakaway
Contour line, 20 metre interval — 320
Watercourse, ephemeral
Bore, well; with windpump — B, W
Rockhole, gnamma hole — RH, GH
Soak — Sk
Dam — D
Abandoned — (abd)
Position doubtful — (PD)
Mine (gold) — Mystery
Mineral exploration drillhole, showing subsurface data — Ab







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

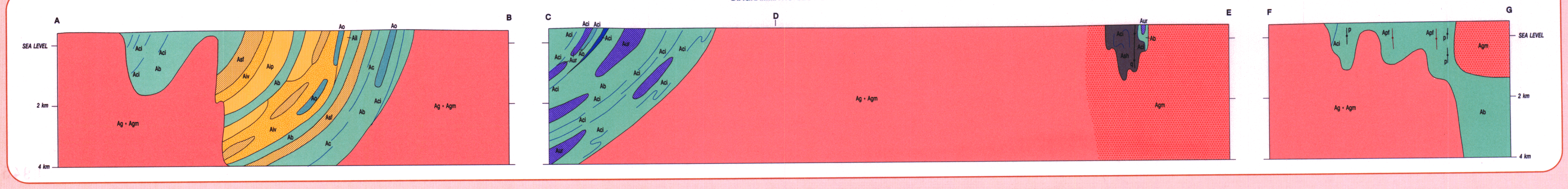
SCALE 1:100 000

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

TRANSVERSE MERCATOR PROJECTION

Grid lines indicate 1000 metre interval of the Australian Map Grid Zone 51

DIAGRAMMATIC SECTIONS



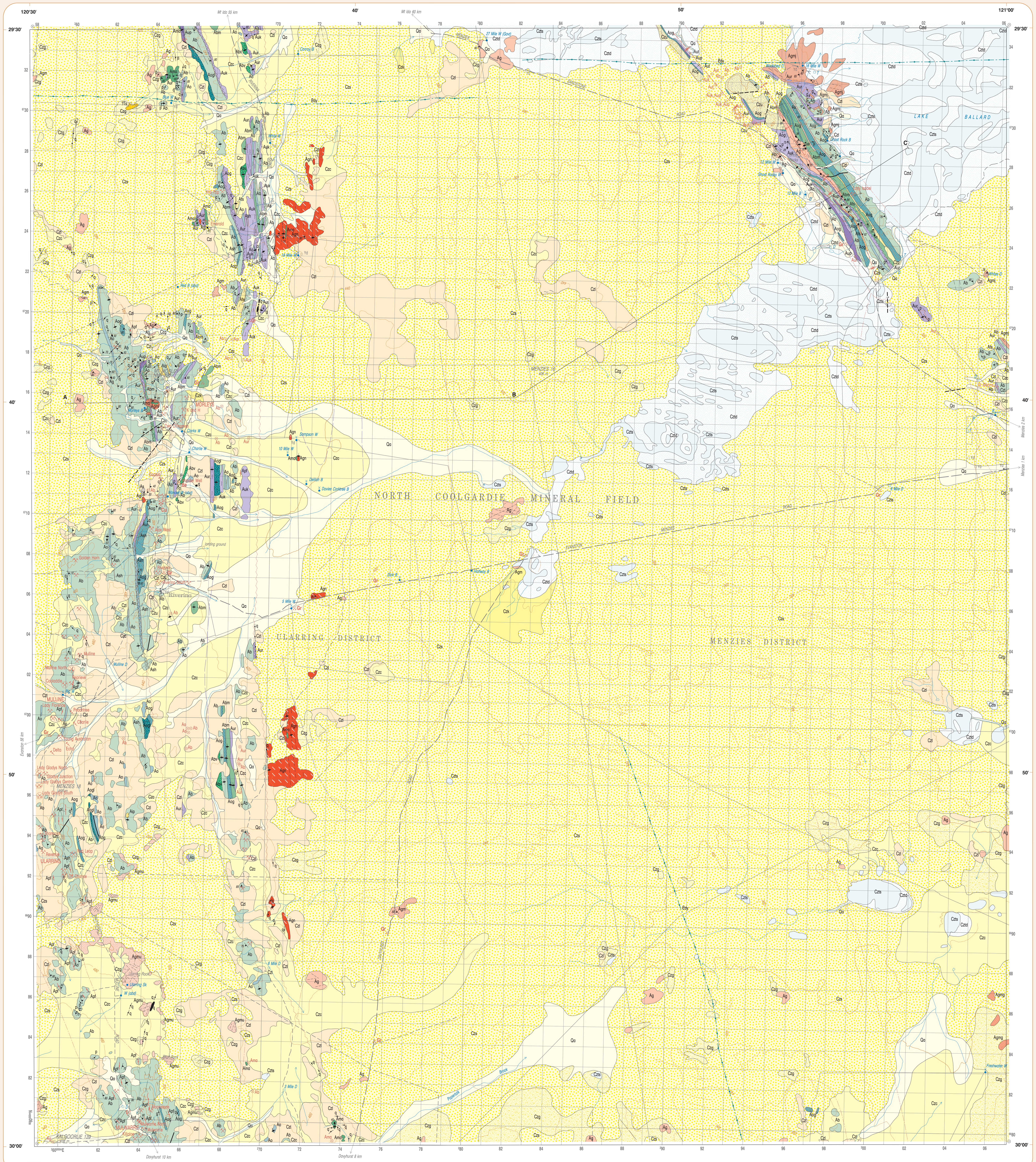
Geology by: S. Wyche, 1991, 1993
Edited by: B. Ramsey, G. Loan
Cartography by: C. Bartlett
Compiled and produced using computer-assisted graphic applications, and available in digital form
Topographic base supplied by the Department of Land Administration and modified from geological field survey
Published by and available from the Geological Survey of Western Australia, Department of Minerals and Energy, 100 Plain Street, East Perth, W.A., 6004
Printed by Allwest Print, Western Australia

MULLINE

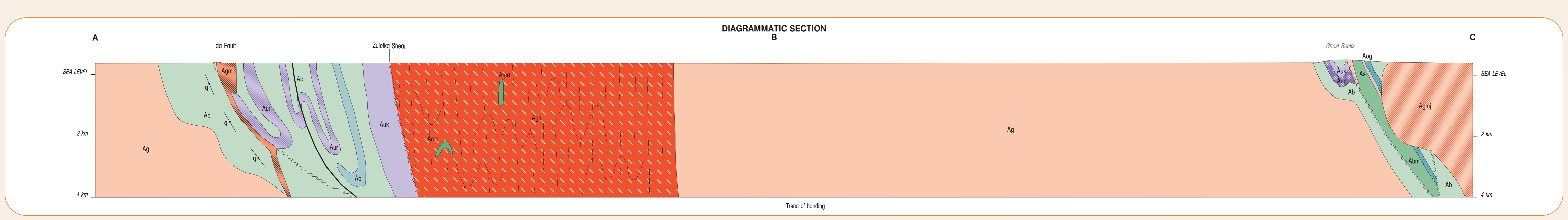
SHEET 2938 FIRST EDITION 1995

RIVERINA

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA



DIAGRAMMATIC SECTION



PHANEROZOIC — CAINOZOIC — QUATERNARY

Qa — Alluvium — clay, silt, sand, and gravel; in channels

Czts — Evaporite interbedded with clay, silt, and sand in playas
Cztd — Sand, silt, and gypsum in stabilized dunes adjacent to playas

Czc — Colluvium — gravel, sand, and soil as sheetwash and talus
Czg — Quartzo-feldspathic sand over granitoid rock
Czs — Sandplain—sand and silty sand; commonly as veneer on palaeosurface
Czl — Laterite and silcrete
Czk — Calcrete
Czu — Ferruginous silica caprock over ultramafic rocks

TERTIARY

?Ts — Sandstone and silcrete — coarse, angular, poorly sorted quartz sand in a clay-rich matrix; partly silicified

PROTEROZOIC

Ƥdy — Mafic and ultramafic dykes, interpreted from aeromagnetic data

ARCHAEAN

Veins and dykes: q — quartz, g — granitoid, p — pegmatite

Ag — Granitoid rock, undivided; syenogranite to granodiorite
Agm — Monzogranite, undivided
Agl — Granitoid rock, mainly monzogranite; massive with discordant margins
Agmu — **ULARRING MONZOGRANITE:** even-grained
Agml — **CLARK WELL MONZOGRANITE:** seriate
Agmg — **GOONGARRIE MONZOGRANITE:** with biotite; prominent K-feldspar megacrysts: local foliation defined by aligned K-feldspar and biotite
Agmj — **JORGENSON MONZOGRANITE:** strongly deformed contact
Agn — Gneissic granitoid rock; pervasively foliated; includes thin bands of amphibolite

Metamorphosed at greenschist to amphibolite facies

Apf — Feldspar(-quartz) porphyry

As — Sedimentary rock, undivided; sandstone, siltstone, shale, and chert; includes a volcaniclastic component
Ash — Shale and chert, banded in places; typically as interflow sedimentary rocks
Afs — Strongly foliated quartzo-feldspathic rock; felsic volcanic or volcaniclastic derivation

Aip — Feldspar-phyric intermediate intrusive rock

Ao — Mafic intrusive rock, undivided; dolerite and gabbro
Aog — Gabbro
Aogl — Leucocratic gabbro

Ab — Basalt, mainly tholeiitic; includes doleritic layers and lenses
Abm — Komatiitic basalt or high-Mg basalt; minor variolitic basalt
Abv — Variolitic basalt; mainly high-Mg basalt
Ama — Amphibolite

Auk — Komatiite; olivine spinifex textures
Aup — Peridotite; includes local tremolite(-chlorite) schist
Aut — Talc-chlorite schist
Aur — Tremolite(-chlorite) schist; includes deformed high-Mg basalt

Geological boundary
- accurate
- interpreted, partly based on aeromagnetic data

Fault
- accurate
- inferred and concealed

Shear zone
- accurate
- interpreted, partly based on aeromagnetic data

Fold
- local deformation event
  - D_2, anticline
  - D_2, anticline, inferred and concealed
  - D_2, syncline
  - D_2, syncline, inferred and concealed

Igneous layering, showing strike and dip
- inclined

Way-up indicator
- igneous layering or differentiation

Dominant metamorphic foliation, showing strike and dip
- inclined
- vertical

Strongly foliated rock

Cleavage, widely spaced, showing strike and dip
- vertical

Lineation, showing direction of plunge
- plunging
- on foliation plane, inclined
- on foliation plane, vertical

Airphoto lineament
- structural trend
- foliation trend
- fracture pattern in granitoid rock

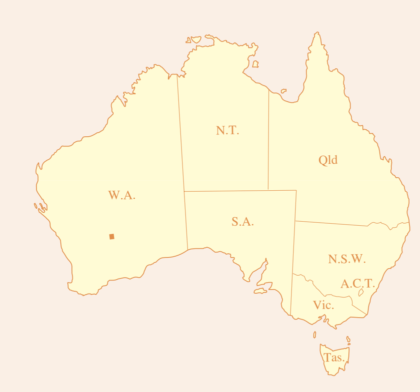
Aeromagnetic lineament

Formed road
Track
Fence, generally with track
Homestead — Riverina
Building, ruins
Yard — Yd
Horizontal control, major

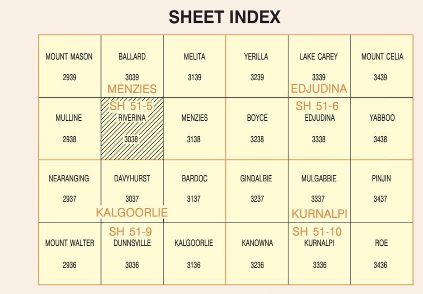
Breakaway
Sand dune
Contour line, 20 metre interval — 440

Watercourse, ephemeral
Pipeline — P
Bore, Well — B, W
Windpump
Dam — D
Tank — T
Soak — Sk

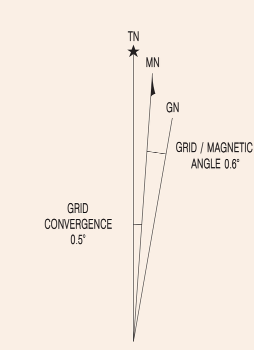
Mineral field district boundary
Mining centre — MULLINE
Major mine (gold, unless otherwise indicated) — Riverina
Mine
Major opencut
Opencut
Prospect
Quarry
Mineral exploration drillhole or costean, showing subsurface data — Ab
Mineral occurrence
- Beryl — Be
- Copper — Cu
- Gravel — Gr



SHEET INDEX



1:100 000 maps shown in black
1:250 000 maps shown in brown



True north, grid north and magnetic north are shown diagrammatically for the centre of the map. Magnetic north is correct for 1996 and moves easterly by about 0.1° in 4 years.

DEPARTMENT OF MINERALS AND ENERGY
K. R. PERRY, DIRECTOR GENERAL

GOVERNMENT OF WESTERN AUSTRALIA
HON. GEORGE CASH, J.P., M.L.C.
MINISTER FOR MINES

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
PIETRO GUJ, DIRECTOR

SCALE 1:100 000

1000 Metres 0 1 2 3 4 5 6 7 8 9 10 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 51

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

Reference points to align maps based on the previous datum, AGD84, have been placed near the map corners

Geology by C. P. Swager 1988 and S. Wyche 1990-91

Edited by L. Taylor, C. Strong, and G. Loan

Cartography by C. Brien, D. Ladbrook, and B. Williams

Topography from the Department of Land Administration Sheet SH51-5-3038, with modifications from geological field survey

Published by, and available from, the Geological Survey of Western Australia, Department of Minerals and Energy, 100 Plain Street, East Perth, WA, 6004

This map is also available in digital form

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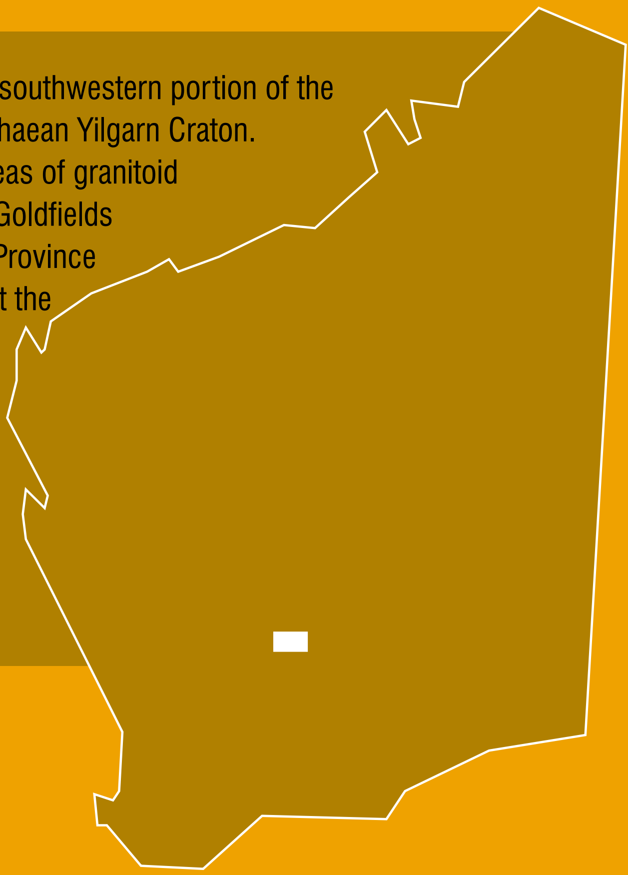
RIVERINA

SHEET 3038 FIRST EDITION 1996

Version 1.1 — October 2005

The MULLINE and RIVERINA 1:100 000 sheets cover the southwestern portion of the MENZIES 1:250 000 sheet in the eastern part of the Archaean Yilgarn Craton. MULLINE and RIVERINA contain large, poorly exposed areas of granitoid rocks, and greenstone sequences of both the Eastern Goldfields Province (Kalgoorlie Terrane) and the Southern Cross Province (Barlee Terrane). These Explanatory Notes complement the 1:100 000 maps, and describe the Precambrian rock types, and the metamorphic and structural history of the granite–greenstone terrain. The relationships between the Kalgoorlie Terrane, Barlee Terrane, and the structure that separates them, the Ida Fault, are also discussed. The Notes also contain descriptions of the Cainozoic regolith cover and mineralization.



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

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