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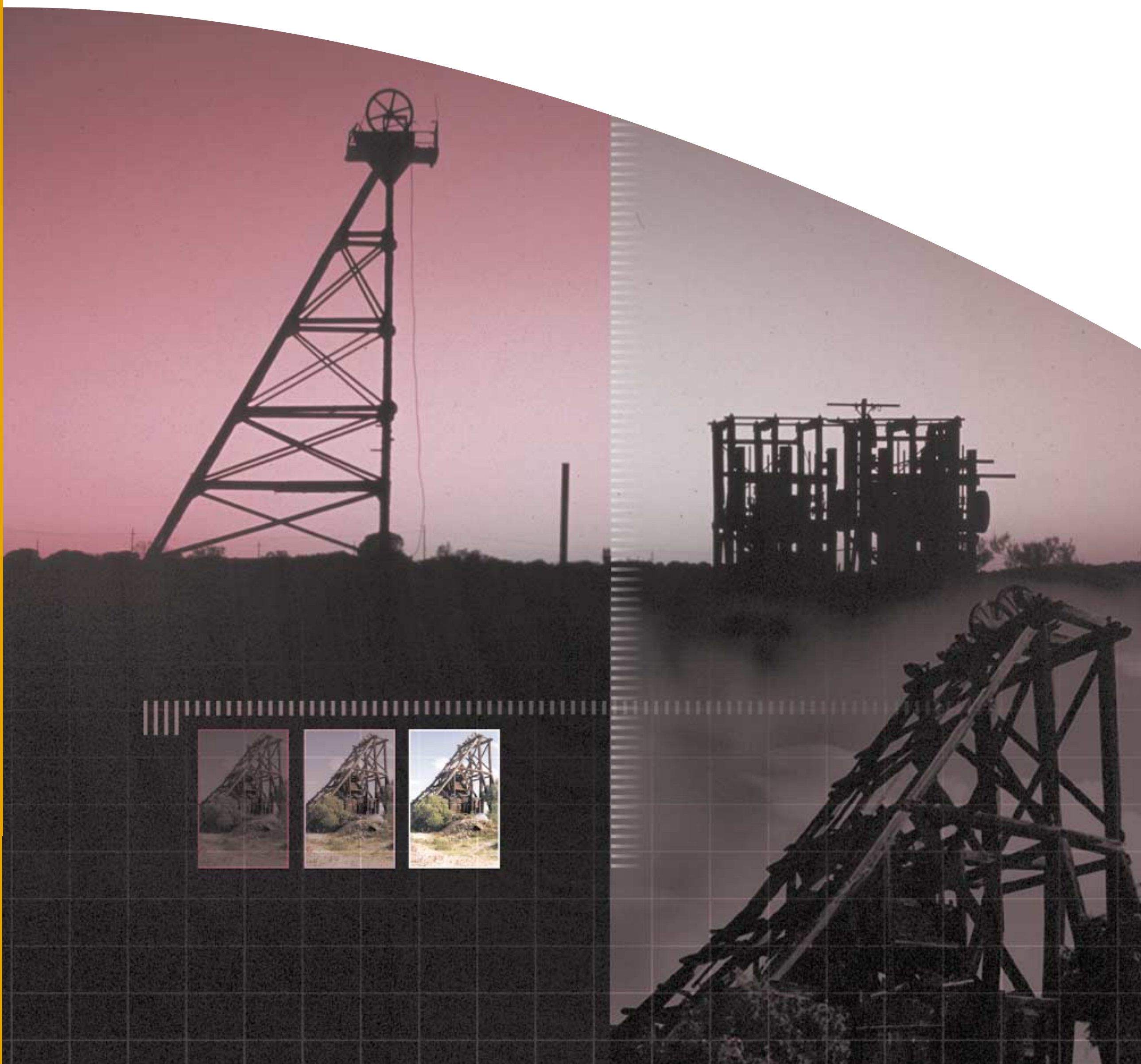
*S.F. Liu, D.C. Champion and K.F. Cassidy*



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*Geoscience Australia*
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S.F. Liu, D.C. Champion and K.F. Cassidy

**Geoscience Australia**

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# Contents

# Appendix



# Figures



# Tables

# Geology of the Sir Samuel 1:250 000 sheet area, Western Australia

**by S.F. Liu, D.C. Champion and K.F. Cassidy**

## Abstract

Archaean granite–greenstones in the SIR SAMUEL 1:250 000 sheet area can be divided into three north- to north-northwest-trending major greenstone belts separated by large areas of granitoid. From west to east, these are the Agnew–Wiluna, Yandal and Dingo Range greenstone belts. The western Agnew–Wiluna greenstone belt varies in width from 2 to 17 km, and can be divided into three domains namely the Yakabindie, Agnew and Mount Keith–Perseverance greenstone belts.

The Yakabindie greenstone belt comprises a layered sequence of the Kathleen Valley Gabbro overlain by the massive tholeiitic Mount Goode Basalt. The Agnew greenstone belt comprises a lower sequence of metamorphosed ultramafic, mafic, felsic volcanic, and sedimentary rocks, which is exposed in the Lawlers and Leinster Anticlines. The upper sequence, as exposed in the Mount White Syncline area, consists of metabasalt, metagabbro and metasedimentary rocks. Metamorphosed ultramafic, mafic, felsic volcanic and sedimentary rocks in the Perseverance area extend farther north to west of Mount Pasco. From Six Mile Well, ultramafic, sedimentary, and felsic volcanic/volcaniclastic rocks correlate with the greenstone sequences from Mount Keith to Wiluna. The Jones Creek Conglomerate represents a late clastic sequence and is restricted to a narrow, fault-bounded zone between the Yakabindie greenstone belt and granitoid in the west and the Mount Keith–Perseverance and Agnew greenstone belts to the east.

The southern Yandal greenstone belt consists of two major packages of greenstones, i.e. mafic and some ultramafic rocks in the Bronzewing–Mount McClure, Hartwell, Yandal Well and Darlot areas, and felsic rocks along the Ockerburry Fault Zone and Spring Well area. In the Dingo Range greenstone belt, the Dingo Range antiform is interpreted to be a refolded earlier fold of banded iron formation/chert, ultramafic and mafic rocks. Felsic volcanic/volcaniclastic rocks are present in the Mount Harold area. The Stirling Peaks area is largely undeformed metabasalt.

The western part of the sheet is largely granitoid, with an arcuate belt up to 18 km wide of highly deformed and gneissic granitoid west of the Waroonga Shear Zone. The southern Yandal greenstone belt is separated from the Agnew–Wiluna greenstone belt by a 20–40 km-wide interval of granitoid and gneiss, including the sigmoidal Koonoonooka monzogranite, and a highly deformed zone, up to 12 km wide, of interleaved granitoid and greenstone west of the Mount McClure Fault. A large area of variably deformed granitoid and gneiss separates the Yandal and Dingo Range belts. The granitoids are primarily monzogranite with minor granodiorite, syenogranite and quartz syenite, and can be divided petrographically and geochemically into two main groups, high–Ca (>60% of total granitoids) and low–Ca (>20–25%), and three minor groups, mafic (<5–10%), syenitic (<5%) and high–HFSE (high–field strength element, <5%).

Three major deformation events are recognised in the granite–greenstones in the SIR SAMUEL area. The first deformation, although poorly understood, produced bedding-parallel foliation including flattened pillow structures in basalt, and some tight to isoclinal folds. Major orogenic compression during $D_2$ produced the north-northwest greenstone belt trends and linear structures including faults, shear zones and folds. During $D_3$, deformation appears to have been largely concentrated along major shear zones. Some north- to north-northeast-trending structures were probably produced, or reoriented into their current positions, during $D_3$, which shaped the current structural architecture. Post-$D_3$ deformation is represented by normal faults, fractures, and sub-horizontal crenulations. A major phase of regional metamorphism was initiated during $D_2$ and peaked late during or after $D_2$. Granitoid intrusion occurred throughout the deformation and metamorphic history in the SIR SAMUEL area.

The SIR SAMUEL area contains significant gold and nickel mineralisation. Gold mineralisation is structurally controlled and associated with brittle-ductile shear zones and quartz veins. Mineralisation is hosted by a variety of lithologies, principally metamorphosed basalt and gabbro, metasedimentary rocks and locally in granitoids. Significant deposits include the Bronzewing and Darlot–Centenary gold deposits in the Yandal greenstone belt, and New Holland, Genesis and Bellevue deposits in Agnew–Wiluna greenstone belt. Nickel deposits include Perseverance and Rockys Reward at Leinster, and Mount Keith. Other mineralisation includes minor copper mineralisation in the Kathleen Valley area, and calcrete uranium prospects (e.g. Lake Maitland) and tin southwest of the Kathleen Valley town-site.

**KEYWORDS**: Archaean geology, greenstones, granitoids, Eastern Goldfields, Sir Samuel, Agnew–Wiluna, Yandal, Dingo Range, mineral resources, gold nickel.

# Introduction

The SIR SAMUEL[1] 1:250 000 map sheet area (SG51–13) is bounded by latitudes 27º00’S and 28º00’S and longitudes 120º00’E to 121º30’E (Fig. 1). The sheet is situated between LEONORA and WILUNA in the eastern Yilgarn Craton and bounds the western part of the Eastern Goldfields Province and the eastern part of the Southern Cross Province.

The first edition of the SIR SAMUEL 1:250 000 geological map (Bunting & Williams 1977) was prepared and published during the extensive nickel exploration in the 1970s but before the extensive gold exploration in the 1980s. Gold and nickel exploration and mining have resulted in a large amount of geological data, much of which is in the form of company reports in the WAMEX open-file system housed in the Geological Survey of Western Australia (GSWA).

Second generation mapping was carried out by geologists from the Geoscience Australia (GA; formerly Australian Geological Survey Organisation) and GSWA on the six 1:100 000 sheets in the SIR SAMUEL area between 1994 and 1997 as part of the joint National Geoscience Mapping Accord (NGMA) project. YEELIRRIE (Champion & Stewart 1998), MOUNT KEITH (Jagodzinski et al. 1997), and WANGGANNOO (Lyons et al. 1996) have been published by GA, and DEPOT SPRINGS (Wyche & Griffin 1998), SIR SAMUEL (Liu et al. 1996) and DARLOT (Wyche & Westaway 1996) by GSWA. Most adjacent 1:100 000 geological maps have also been released – WILUNA (Langford & Liu 1997), LAKE VIOLET (Stewart & Bastrakova 1997), SANDALWOOD (Blake & Whitaker 1996), TATE (Champion 1996), BANJAWARN (Farrell & Griffin 1997), WEEBO (Oversby et al. 1996a), WILDARA (Oversby et al. 1996b) and MUNJEROO (Duggan et al. 1996). The geological maps in the SIR SAMUEL area have recently been collated as geospatially referenced digital information in Phase 2 of the East Yilgarn Geoscience Database project by GSWA (Groenewald et al. 2001).

The mapping was carried out using 1:25 000 colour aerial photographs (taken in March 1994) for MOUNT KEITH, WANGGANNOO, SIR SAMUEL, and DARLOT, and 1:50 000 black and white aerial photographs (taken in May 1989) for YEELIRRIE and DEPOT SPRINGS. This work was assisted by Landsat Thematic Mapper imagery. The aerial photographs and Landsat images are available from the Department of Land Administration (DOLA) of Western Australia and the National Mapping Division of Geoscience Australia (formerly AUSLIG) in Canberra. Interpretation of 400 m line spacing aeromagnetic data, together with images of airborne g-ray spectrometric data and regional gravity data (available through GA and GSWA), and information from mining and exploration company reports (WAMEX), were used extensively during this work. Discussions with mining and exploration companies working in the SIR SAMUEL area by the mapping geologists also contributed to the understanding of the geology of the area. Topographic and cultural data are modified from the digital data supplied by DOLA and GA with information from the 1994 colour aerial photographs.

## Previous investigations

The first edition of the SIR SAMUEL geological map and explanatory notes were by Bunting & Williams (1977, 1979). The second edition of the map (Liu 2000) was largely compiled from the new 1:100 000 maps, plus some additional fieldwork by the author for consistency checking and problem solving in 1997. A solid geology map of the SIR SAMUEL area (Liu et al. 2000a) is also based on the published 1:100 000 geological maps plus

[1] 1:250 000 map sheet names are printed in small capitals to avoid confusion with identical place names. Similarly 1:100 000 map sheet names are printed in large capitals.

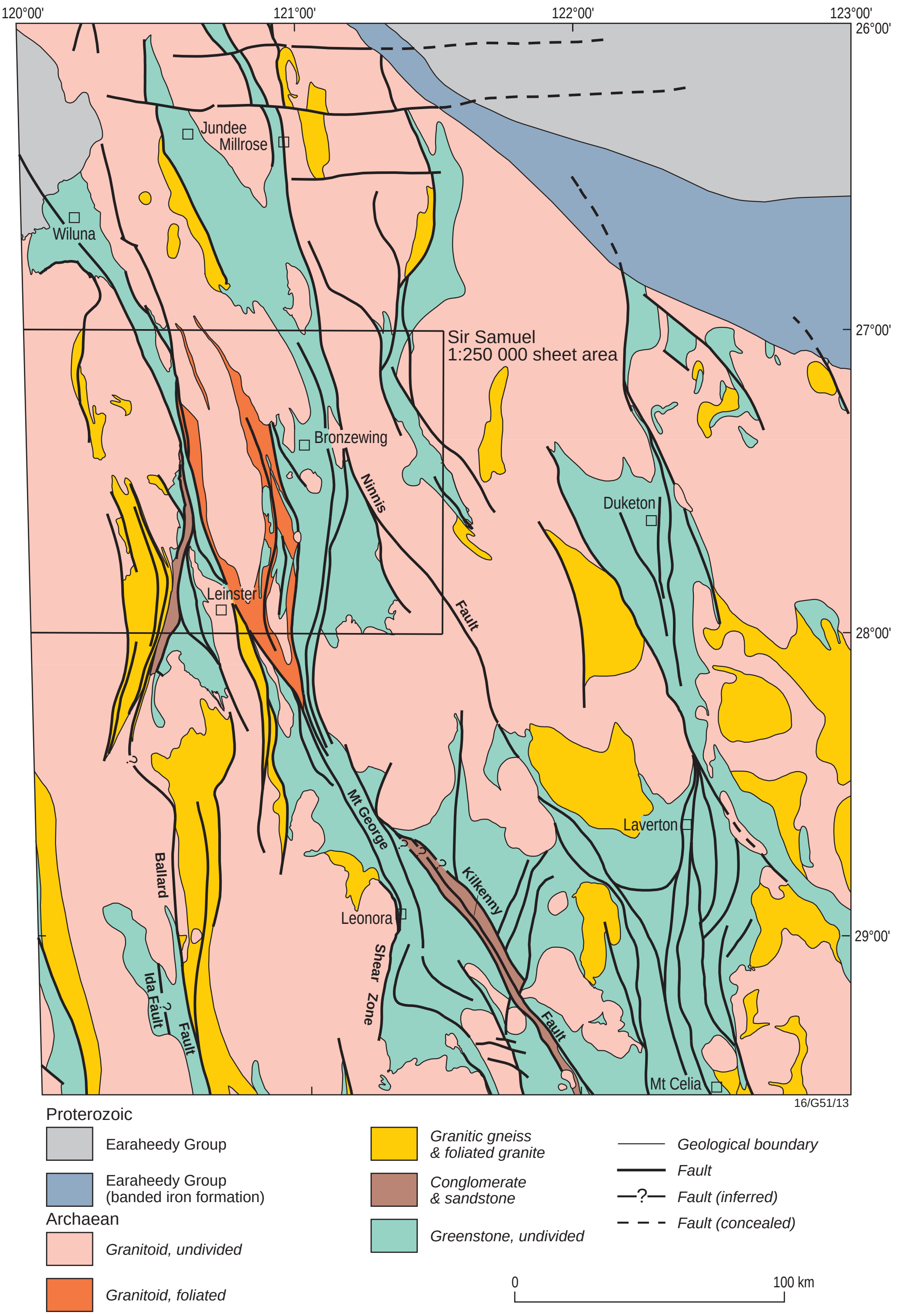



**Figure 1. Location of the Sir Samuel 1:250 000 sheet area in the north Eastern Goldfields**

interpretation of the 400 m line spacing aeromagnetic data acquired by GA under the NGMA program and additional geological information from exploration companies. The current Sir Samuel explanatory notes draw extensively on published explanatory notes for three 1:100 000 sheets, i.e. DARLOT (Westaway & Wyche 1998), MOUNT KEITH (Jagodzinski et al. 1999) and SIR SAMUEL (Liu et al. 1998). Additional information is derived from synthesis work by Liu & Chen (1998a & b), Chen et al. (1998, 2001) and the published literature.

Naldrett & Turner (1977) recognised two

greenstone sequences in the Mount Keith–Lawlers area, a lower sequence to the west dominated (over 90%) by mafic rocks and an upper sequence to the east, with approximately one-third mafic and two-thirds felsic rocks. These two sequences are separated by an unconformity and associated conglomerate. Dowling & Hill (1990) and Hill et al. (1990, 1995) described the physical features of komatiite flows at Mount Keith, and Dowling & Hill (1992) documented the Mount Keith nickel deposit. The volcanology of komatiite in the Agnew–Mount Keith area was studied in detail by Hill et al. (1995, 1996) as part of their study of the Norseman–Wiluna belt (see also Hill et al. 1996). Giles (1980, 1982) and Messenger (2000) have documented the Spring Well felsic volcanic complex. These reports include mapping, petrography and geochemistry. Recently Barley et al. (1998) studied the complex as part of their research on the felsic volcanic and sedimentary successions in the Eastern Goldfields. Discussion of the Yandal greenstone belt is presented in Messenger (2000) and Vearncombe et al. (2000).

Durney (1972) studied the conglomerate in the Jones Creek area in the Mount Keith–Perseverance greenstone belt, and recognised a major unconformity within the Archaean greenstones. Marston & Travis (1976), in a study of the Jones Creek Conglomerate, concluded that the structural complexity makes regional stratigraphic relationships, particularly Durney's (1972) suggestion that the Jones Creek Conglomerate separates two major mafic dominated greenstone sequences, difficult to justify. Results of geochronological dating of the Jones Creek Conglomerate and some other rocks in the SIR SAMUEL area are reported in Nelson (1997a, 1998, 2000) and Krapez et al. (2000).

Platt et al. (1978) presented the first detailed structural study in the north Eastern Goldfields for the Lawlers Anticline area, a small part of which is in the SIR SAMUEL area. Eisenlohr (1987, 1989, 1992) carried out a detailed mapping and structural study of the Kathleen Valley–Lawlers (Agnew) area with emphasis on the northern part. He recognised contrasting deformation styles between eastern and western greenstone sequences in the Mount Keith–Agnew area. A structural synthesis by Hammond & Nisbet (1992) for the Norseman–Wiluna belt covered the SIR SAMUEL area. Bongers (1994) studied in detail the structures of the Mount Keith nickel mine area. Overprinting evidence was presented to outline a structural history of four deformations in Liu & Griffin (1996) and Liu et al. (1998) for the Yakabindie–Leinster area. Jagodzinski et al. (1999) discussed structures in the MOUNT KEITH sheet area. Vearncombe et al. (2000) synthesises the regional, structural and exploration geology of the Yandal greenstone belt. Syntheses of structural work from the current NGMA mapping in the north Eastern Goldfields are presented in Farrell (1997), Liu & Chen (1998a & b), Chen et al. (1998, 2001) and Wyche & Farrell (2000). Late transpression is discussed in Chen et al. (1998, 2001).

Several recent studies of the nickel and gold deposits on SIR SAMUEL have been published. These include studies on the Mount Keith nickel deposit (Burt & Sheppy 1975, Hopf & Head 1998), the Perseverance and Rocky's Reward nickel deposits (Libby et al. 1997, 1998, De-Vitry et al. 1998), the Bellevue gold deposit (Brotherton & Wilson 1990), the Bronzewing gold deposit (Eshuys et al. 1995, Dugdale 1997, Phillips et al. 1998a), the Darlot–Centenary gold deposit (Bucknell 1997, Krcmarov et al. 2000), the Mount McClure gold deposits (Otterman & Miguel 1995, Harris 1998), and the New Holland and Genesis gold deposits (Inwood 1998).

## Physiography and access

The SIR SAMUEL area is about 700 km northeast of Perth, and about 400 km north of Kalgoorlie. The Meekatharra–Wiluna–Kalgoorlie road, which bypasses Leinster, is sealed from Wiluna to Kalgoorlie and being sealed from Wiluna to Meekatharra at the time of writing. The road from the Perseverance nickel mine, via Leinster, is sealed to the Meekatharra–Wiluna–Kalgoorlie road. The road from Leinster to north of Agnew is also sealed, where a gravel road links, via Sandstone, to the Great Northern Highway to Perth.

Gravel roads provide access to the Mount McClure and Bronzewing gold mining operations to the northeast, Darlot gold mine in the southeast and all homesteads (Fig. 2). The low relief and numerous station and exploration tracks enable good access by 4WD to all parts of greenstones in the SIR SAMUEL area.

Leinster is a major town in the south of the SIR SAMUEL area. It was established in 1989 to support the Perseverance (formerly Agnew) nickel mine, 11 km to the north. The townsite of Agnew, 1 km outside the sheet area in the south, is the centre for the New Holland and Genesis gold mines on SIR SAMUEL, and Emu and Redeemer gold mines, on LEONORA. Pastoral leases on SIR SAMUEL include Albion Downs, Depot Springs, Leinster Downs,

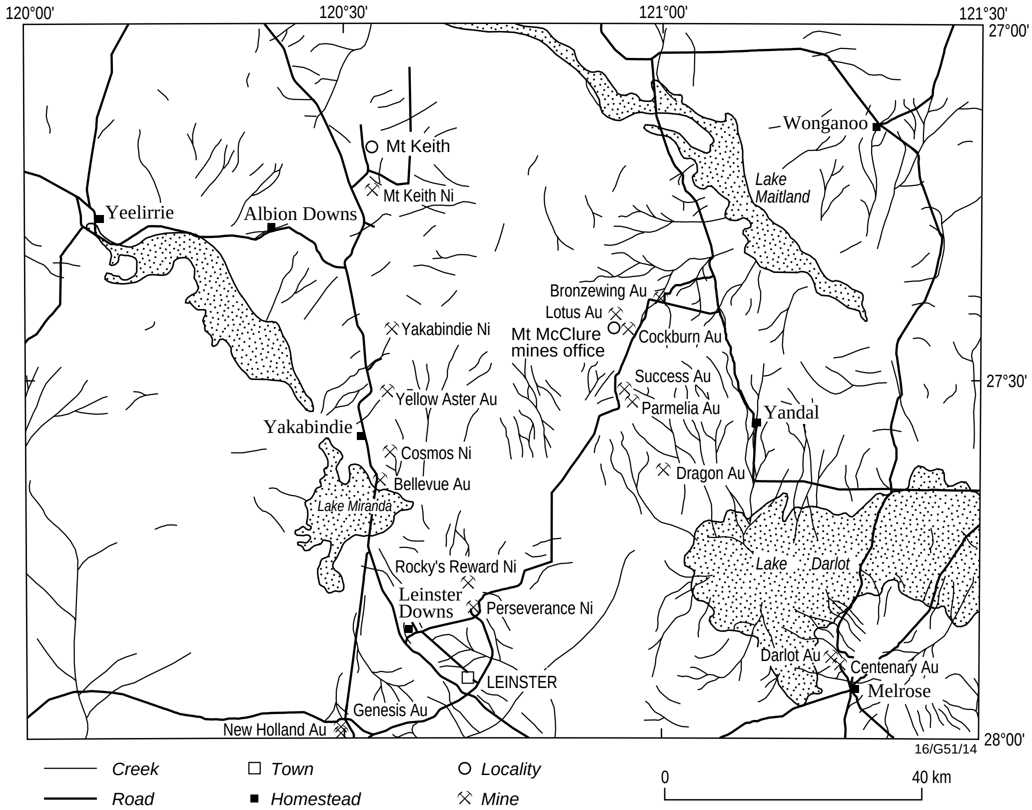



**Figure 2. Main cultural and physiographic features in the Sir Samuel 1:250 000 sheet area**

Melrose, Wonganoo, Yakabindie, Yandal and Yeelirrie (Fig. 2).

The Sir Samuel area has subdued topography ranging from flat to undulating (Fig. 2). The hills are 500–540 m above sea level and rise above the plains at 460–500 m above sea level. The hills correspond to areas of outcrop of greenstones that trend approximately north to north-northwest. They are separated by large areas of sandplain containing some low breakaways above outcrops of granitoid. The Agnew–Mount Keith–Perseverance and Yandal greenstone belts are cut by the east-trending Lake Miranda and Lake Darlot playa systems respectively. The area from a few km to 20 km north of Lake Miranda has the highest relief and the best exposure.

The hilly areas over greenstone generally have a dense cover of *Acacia* (mulga mainly) and *Cassia* shrubs. Both narrow and broad ephemeral drainage courses are characterised by dense vegetation that includes *Acacia*, *Eucalyptus*, and sandalwood. Bluebush, saltbush and samphire grow around the playa lake systems. Sandplains largely overlie areas of sheetwash and granitoid and are dominated by spinifex and *Acacia* woodland. The vegetation assemblages in the Eastern Goldfields have been described by Burbidge (1943) and Beard (1990).

The Sir Samuel area is in a semi-arid area. According to the Commonwealth Bureau of Meteorology (www.bom.gov.au), annual rainfall at Lawlers (just south of the map sheet area) is about 210 mm. This includes winter showers and significant rainfalls that result from tropical storms and cyclones in the summer. Temperatures regularly exceed 40ºC in the summer months from December to February (average daily maximum temperature 35ºC to 36ºC). There are occasional frosts in the winter months between June and August (average daily minimum temperature 6ºC to 7ºC).

# Archaean Geology

## Geological framework

The western part of Sir Samuel covers the boundary area between the Southern Cross and Eastern Goldfields provinces in the Yilgarn Craton, although the boundary in this region has not been well defined (see section on 'Greenstone Belts and Major Faults' for more discussion).

The Archaean geology in the Sir Samuel area can be divided into seven parts: four north-northwest-trending areas of granitoid that are separated by three north-northwest-trending greenstone belts (Figs 1, 3–4). The greenstone belt in the west is part of the Agnew–Wiluna greenstone belt that extends southwards to LEONORA and northwards to WILUNA. The central belt is part of the Yandal greenstone belt that extends northwards to WILUNA, and the belt in the east is part of the Dingo Range greenstone belt.

The Agnew–Wiluna greenstone belt was further divided into the Agnew, Coles Find, Mount Keith–Perseverance, and Wiluna greenstone belts by Griffin (1990), based on structural and greenstone outcrop continuity, for the convenience of discussion. The boundaries of these greenstone belts are not always well defined. The Yakabindie greenstone belt west of Miranda Fault was subdivided from the Agnew–Wiluna greenstone by Liu et al. (1998, Figs 3, 5). In the Wiluna area, the Erawalla Fault separates the Coles Find greenstone belt from the Wiluna belt (Griffin 1990, Liu et al. 1995). In this Record, greenstones in the Mount Keith–Perseverance area are discussed as one greenstone domain, which is faulted along the Sir Samuel Fault against the Agnew belt.

Large areas of granitoid and gneiss separate the greenstone belts (Figs 3–7). Although parts of the granite–greenstone contacts are intrusive, in most cases, the contacts are faulted or sheared. East of the Perseverance Fault and west of the Mount McClure Fault are strongly foliated granitoids that include some interleaved amphibolite. West of the Waroonga Shear Zone there is an arcuate north-trending zone, a few kilometres to 18 km wide, of strongly deformed granitic gneiss.

The granite–greenstone terrain experienced three major deformation events (Farrell 1997, Liu & Chen 1998b, Wyche & Farrell 2000, Chen et al. 2001). The nature of the first deformation event ($D_1$) is not well understood, but it produced bedding-parallel foliation ($S_1$) and some tight to isoclinal folds. The second event ($D_2$) was east-northeast–west-southwest-directed orogenic compression that resulted in the shaping of north-northwest-trending regional structures including shear zones, faults, folds and the linear distribution of greenstone belts. A prominent sub-vertical to steeply dipping foliation was produced in appropriate rock types. This event progressed into a third event ($D_3$) of transpression during which deformation was largely concentrated along major shear zones. Some north- to north-northeast-trending faults and shear zones are considered to have developed, or further developed, during this event. Post-$D_3$ deformation is difficult to correlate because of the lack of overprinting evidence, but includes east-, northeast- and northwest-trending faults and fractures, and sub-horizontal crenulations. Some east-trending fractures and faults are filled with Proterozoic mafic dykes that are not exposed but readily interpreted from aeromagnetic data.

Regional fault/shear zones and linear greenstone belts are prominent features in the SIR SAMUEL area as in the surrounding areas of the Eastern Goldfields. Some of these structures had a long-lived history, which may have lasted from greenstone formation to the last major tectonic event, $D_3$, that shaped the structural architecture of the area and the entire Eastern Goldfields. It should be noted that the term 'fault' is used in a general sense, partly because of historical reasons. Many regional faults are actually ductile shear zones 1 km or wider. For convenience of presentation, however, single lines of fault are shown on maps. In most cases, the fault lines mark only the most extensively deformed part of the shear zones or the boundaries between different rock types. Large areas of highly deformed rocks are marked by a symbol for 'highly deformed rocks' in the solid geology map (Liu et al. 2000a). In most cases, the historical usage of the terms 'fault' or 'shear zone' are followed. The context makes it clear what is meant in most cases.

Regional faults/shear zones broadly fall into three groups: (1) north-northwest- to northwest-trending faults including the Perseverance and Ninnis Faults; (2) approximately north- to north-northeast-trending faults including the Miranda, Emu and Mount McClure faults and the Ockerburry Fault Zone; and (3) the arcuate Waroonga Shear Zones (Fig. 3).

The prominent north-northwest-trending Perseverance and Ninnis Faults are parts of two major lineaments, the Keith–Kilkenny and Celia Lineaments, respectively. Both lineaments are apparently 'crustal-scale' structures, which probably predated, but were active during, the formation of greenstones in the region. At the early stages the Perseverance Fault may have linked with the Kilkenny Fault Zone along the north-northwest-trending Keith–Kilkenny lineament, but in the current structural configuration, the Perseverance Fault links with the Mount George Shear Zone north-northwest and south-southwest of Leonora (Fig. 1, Liu & Chen 1998b). Most regional faults/shear zones appear to be fairly steep or nearly vertical at surface.

Metamorphism in the area is generally low, mostly in the greenschist facies away from the

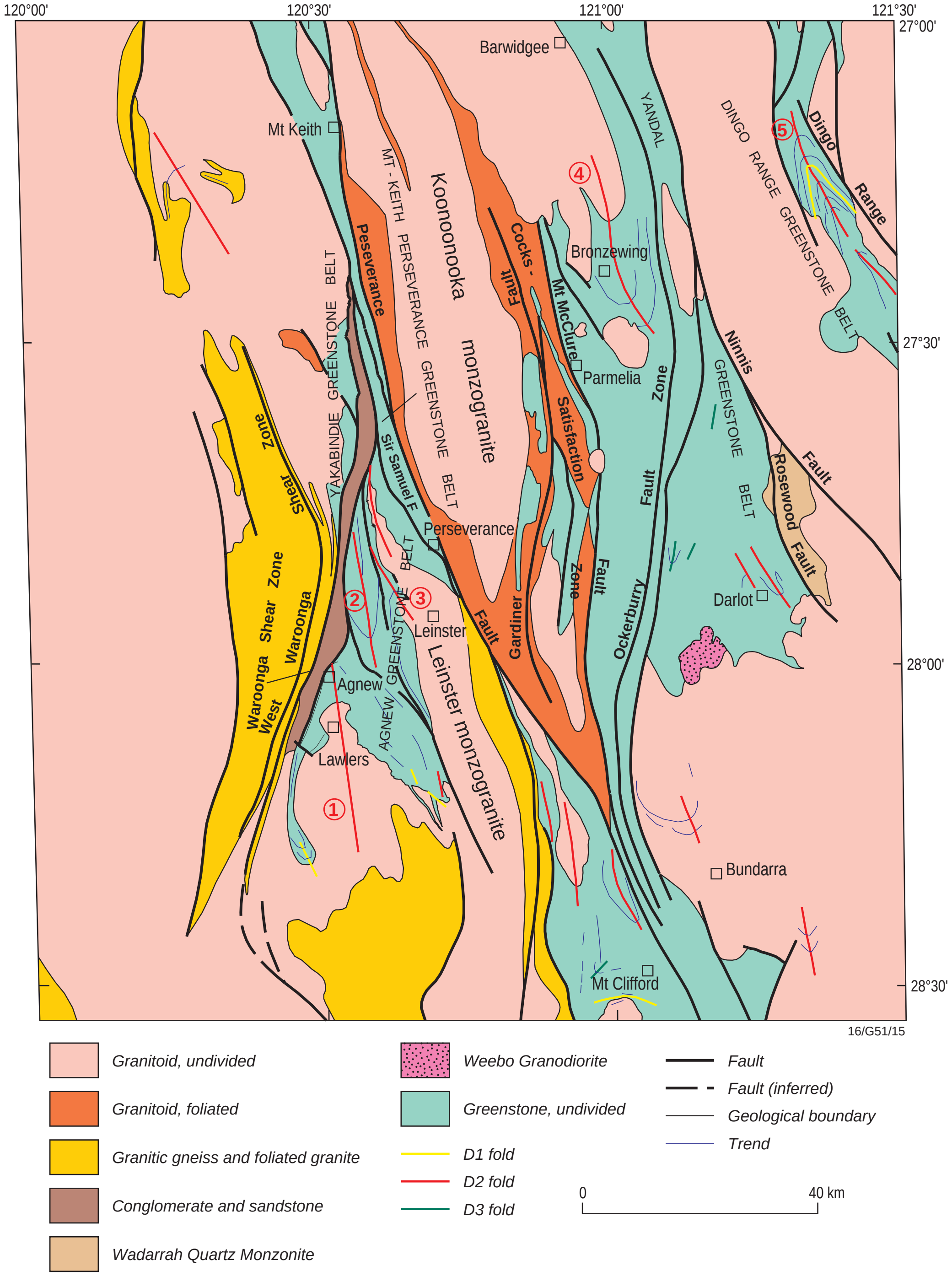



**Figure 3. Simplified geology of the Sir Samuel and northern part of the Leonora 1:250 000 sheet areas. Numbers refer to localities mentioned in the text: 1 – Lawlers Anticline, 2 – Mount White Syncline, 3 – Leinster Anticline, 4 – Bronzewing Anticline, 5 – Dingo Range antiform**

granite–greenstone contacts. Near the contacts, the greenstones are commonly metamorphosed to amphibolite facies (Binns et al. 1976).

The geochronology of the greenstone sequences in the Sir Samuel area is poorly constrained. A tonalitic sample from the Kathleen Valley Gabbro sequence, which is part of the Yakabindie greenstone belt (Fig. 3), has a Sensitive High Resolution Ion Microprobe (SHRIMP) U–Pb zircon age of 2736 ± 3 Ma (Black L.P., 2000, written comm.). This suggests that at least some of the greenstone sequences are older than the 2705–2675 Ma old greenstones that predominate in most of the Eastern Goldfields (Nelson 1997b, Krapez et al. 2000). A deformed felsic volcanic rock from the Rockys Reward mine near Leinster has a SHRIMP U–Pb zircon age of 2720 ± 14 Ma (Nelson, 1997b). Felsic volcanic rocks from the Spring Well Complex in the southern Yandal greenstone belt have ages of ca. 2700–2690 Ma (Nelson 1997b). Basement to the greenstones is not exposed in the Sir Samuel area. Granitic rocks are generally younger than the greenstones and have ages ranging from 2685 to 2640 Ma (Champion & Sheraton 1997, Nelson 1997a, Wyche & Farrell 2000, Geoscience Australia, unpublished data). A gneissic granite sample (strongly deformed granitoid) from west of the Mount McClure Fault was dated to be 2738 ± 6 Ma by Nelson (1997a) and represents an early phase of granitoid magmatism.

## Archaean rock units

### Metamorphosed ultramafic rocks

#### *(Au, Auc, Auk, Aul, Aup, Aur, Aus, Aut, Aux)*

Ultramafic rocks are a common component of the greenstone sequences on Sir Samuel, particularly in the Mount Keith–Perseverance and Agnew greenstone belts. They also occur in the Dingo Range greenstone belt and in the west part of the southern Yandal greenstone belt. In most cases they are deeply weathered and rarely crop out except where silicified. Better outcrop occurs around the Mount Keith nickel mine, 5–6 km south-southeast and just northwest of Six Mile Well, in the area east and north of McDonough Lookout, around Mount Sir Samuel, around the Perseverance Nickel mine (Fig. 5) and at Dingo Range (Fig. 3). They commonly correspond to prominent anomaly highs in images of aeromagnetic data (Fig. 4). In some areas of no outcrop but where ultramafic rocks are inferred from aeromagnetic data, their presence has been confirmed by shallow drilling, e.g. along the southwestern margin of the Yandal greenstone belt (Fig. 6). Exposed ultramafic rocks are commonly serpentinized, silicified and/or schistose, but the original igneous textures (cumulate textures and spinifex textures) are preserved in places. Where ultramafic rocks are inferred to underlie silica caprock, the map unit *Czu* has been used.

Undivided ultramafic rocks are mapped as *Au*, mostly in the area between Six Mile Well to Perseverance and about 1 km west of Mount Roberts. Metamorphosed komatiite (*Auk*) is recognised by the presence of platy olivine-spinifex textures in hand specimen. Only two units are mapped in the Sir Samuel area, one southwest of the Mount Keith nickel mine and the other about 7 km north-northwest of Six Mile Well. They are also found in association with other ultramafic rocks, e.g. peridotite around Six Mile Well. It forms small exposures in 'Spinifex Park', 2 km southwest of the Mount Keith nickel mine (Jagodzinski et al. 1999). Metamorphosed pyroxenite (*Aux*), occurring northeast of McDonough Lookout, has a medium- to fine-grained texture that is dominated in thin section by a mixture of tremolite and actinolite, and includes minor talc and chlorite.

Serpentinized peridotite, commonly with a distinctive olivine cumulate texture, is mapped as *Aup*, e.g. 4 km north of Mount Sir Samuel, 2.5 km south of Six Mile Well and 5 km west of Mount Keith in the Mount Keith–Perseverance belt, 5 km south of Mount Roberts in the Agnew belt, 3 km east-southeast of Mount McClure and 2.5 km northwest of Desperation Well in the Yandal belt. These rocks are commonly silicified. Relict cumulate olivine grains, up to 2 mm across, are pseudomorphed by radiating serpentine. Magnetite fills cracks in the olivine grains. The intercumulus material consists of serpentine, talc, carbonate, and in places, actinolite.

Ultramafic cumulates in the Mount Keith–Perseverance and Agnew greenstone belts have previously been interpreted as dyke-like intrusions (Burt & Sheppy 1976, Groves & Keays 1979, Groves & Hudson 1981, Marston et al. 1981), as subvolcanic sill-like feeder chambers for overlying spinifex-textured komatiites (Lesher & Groves 1986, Naldrett & Turner 1977), or as extrusive cumulate bodies formed in lava lakes (Donaldson et al. 1986). Hill et al. (1990) showed that these adcumulate bodies have gradational contacts with the overlying and/or underlying strata. It is considered that they accumulated in major flow channels, formed by thermal erosion of underlying rocks, during ultramafic eruptions (Hill et al. 1995).

A linear belt of talc-carbonate rock (*Auc*), 1.4 km long and ranging from 100 to 200 m wide, is located about 1 km south-southeast of Miranda Well. The rocks are yellow-brown and contain small red-brown spots (<3 mm) of hydrated iron oxides after magnetite (or carbonate). South of Miranda Well (AMG 661332), there is a low, rocky hill where the rocks above ground are strongly silicified and massive, whereas the rocks close to ground level are less silicified and have a strong foliation. Carbonates are commonly leached out, leaving small holes filled with hydrated iron oxides. Talc–carbonate rock (*Auc*) is also mapped northwest and south-southwest of Vivien Well.

Two units of chlorite schist (*Aul*) are mapped, one about 2 km northeast of Mount Keith and the other at the east edge of Dingo Range. The rock is grey or green, less commonly brown or yellow, fine- to medium-grained, and consists largely of chlorite with minor talc or quartz (Jagodzinski et al. 1999).

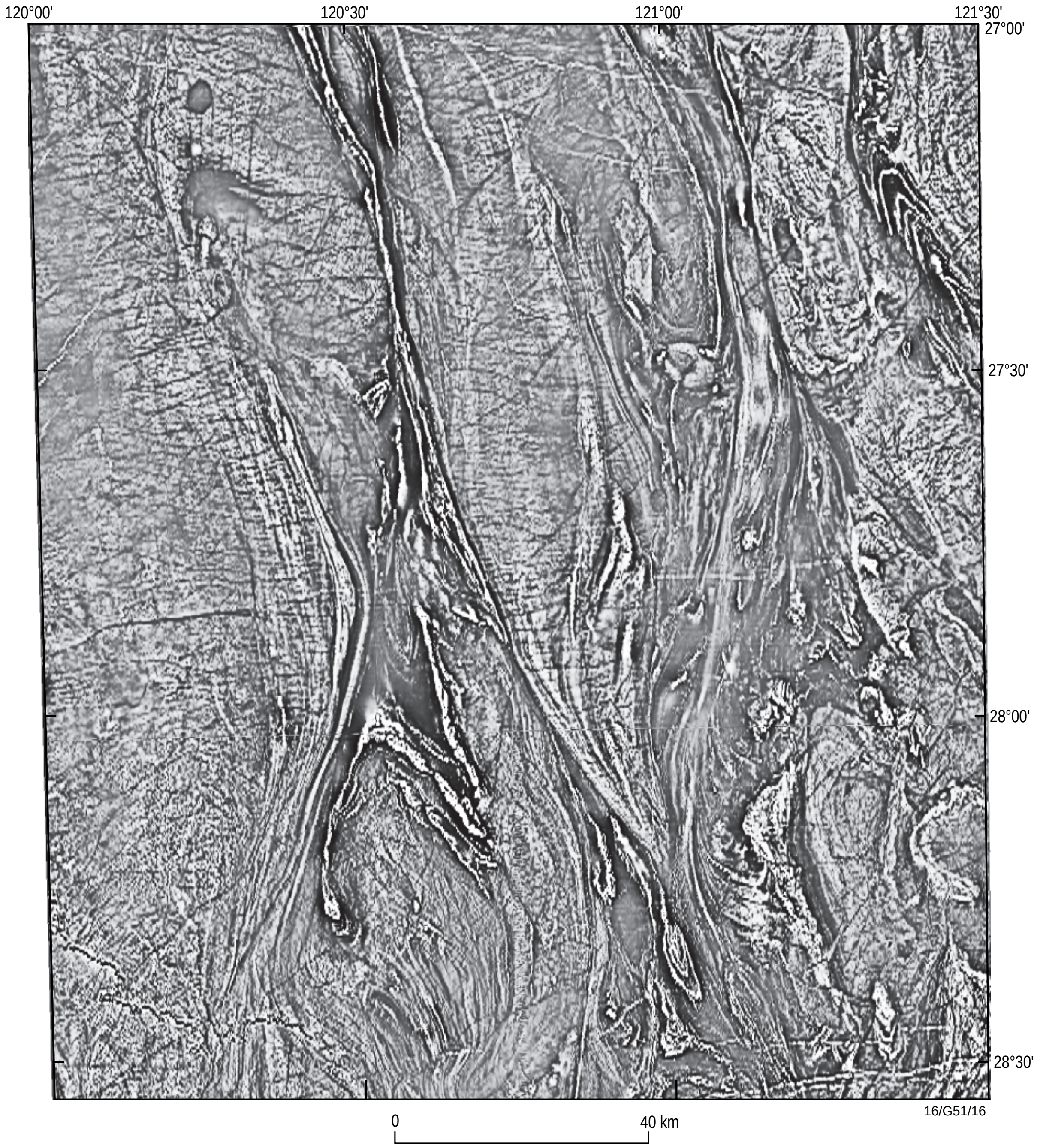


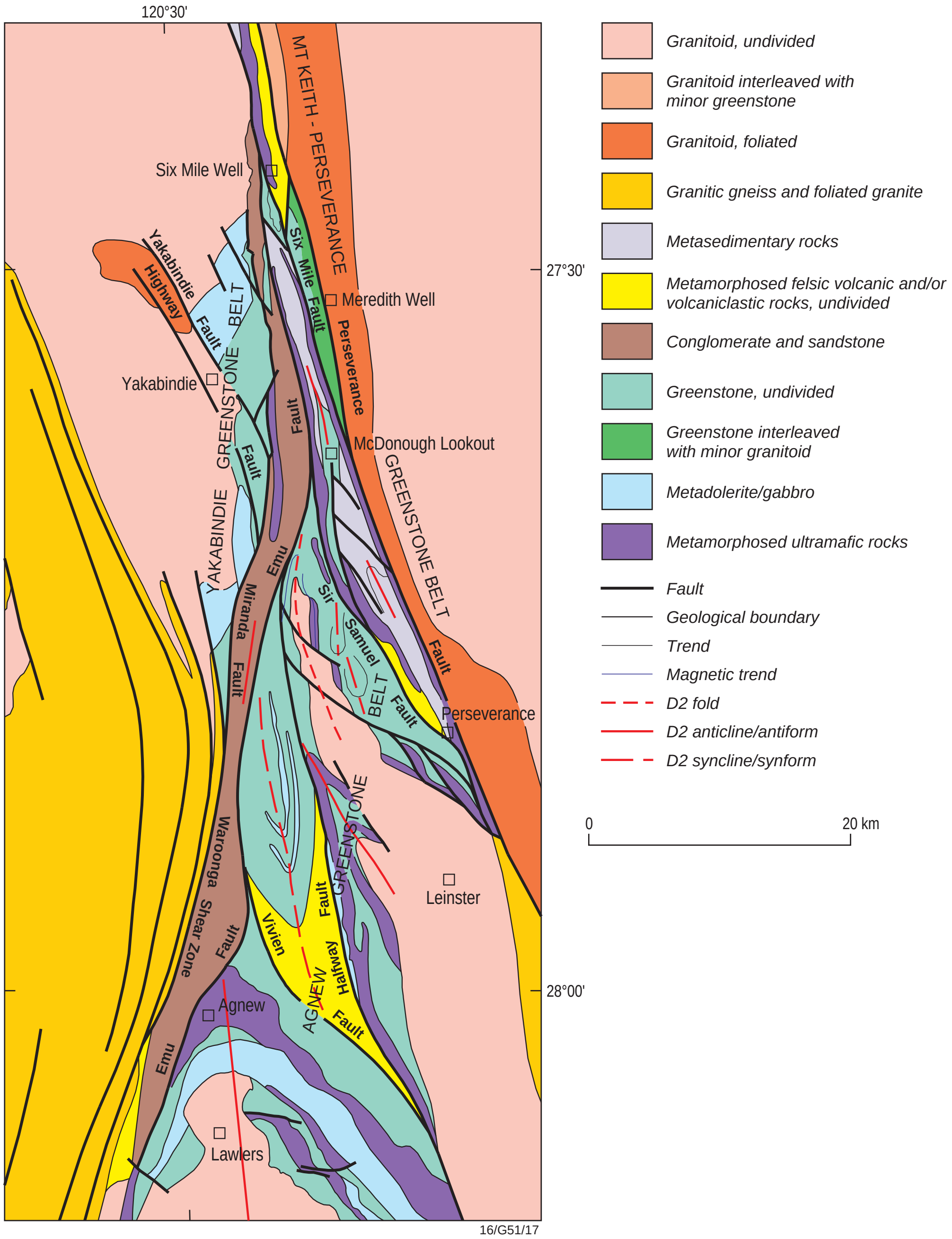

**Figure 4. Greyscale first vertical derivative of total magnetic intensity image of the Sir Samuel and northern part of the Leonora 1:250 000 sheet areas**

Tremolite–chlorite schist (*Aur*) crops out a few km south of Six Mile Well, 3 km north-northwest of Perseverance, 2 km west-southwest of Desperation Well, east of Mount McClure, and west of Boundary Well. It is commonly green, acicular or fibrous, and composed of fine tremolite needles (<1mm, but up to 8 mm) and varying amounts of chlorite, magnetite, talc and calcite. Like talc-schist (*Aut*), it represents zones of high strain through the greenstones, and is highly schistose (Jagodzinski et al. 1999).

Serpentinite (*Aus*) after dunite is present in rotary air-blast (RAB) drillholes 1–6 km north-northwest of Mount Keith mine and boulders are exposed in a ditch at AMG 546862 (Jagodzinski et al. 1999). Serpentinite is also mapped about 2 km southeast of Mount Grey Well and a few km northwest of Dingo Range.

Several units of talc schist (*Aut*) are mapped, mostly in the area south-southeast of Mount Roberts. Jagodzinski et al. (1999) described a unit 4 km north-northwest of Six Mile Well. The rock is commonly yellowish green, pale green, or white, but in places grey, buff, or brown, fine-grained, and

A)




composed largely of talc with lesser chlorite.

## Metamorphosed mafic extrusive rocks

### *(Ab, Abam, Abb, Abc, Abf, Abi, Abm, Abp, Abs)*

Basaltic rocks are a major component of the greenstones on Sir Samuel. They have been metamorphosed under greenschist to lower amphibolite facies conditions. They are mapped as undivided (*Ab*) where they are deeply weathered and mostly fine-grained, and where they cannot be assigned to a specific category described below.

Metabasalt (*Abb*) is widespread in the greenstone belts, e.g. it is well exposed south of Mount Sir Samuel, west of the Perseverance mine, in the Mount White area, and in the Stirling Peaks of the Dingo Range greenstone belt. In these areas, it generally occurs as thin flows associated with, and probably interbedded with, metasedimentary rocks and/or gabbro. It commonly forms low hills. Most of the metabasalt designated as *Abb* is fine-grained to aphyric and massive, and probably has a tholeiitic rather than a high–Mg composition (Naldrett & Turner 1977). The tholeiitic metabasalt that crops out as thick, massive flows over a large area, 3 km wide and 14 km long, east of Yakabindie is named the Mount Goode Basalt (*AbMG, AbMGp*, Liu et al. 1998).

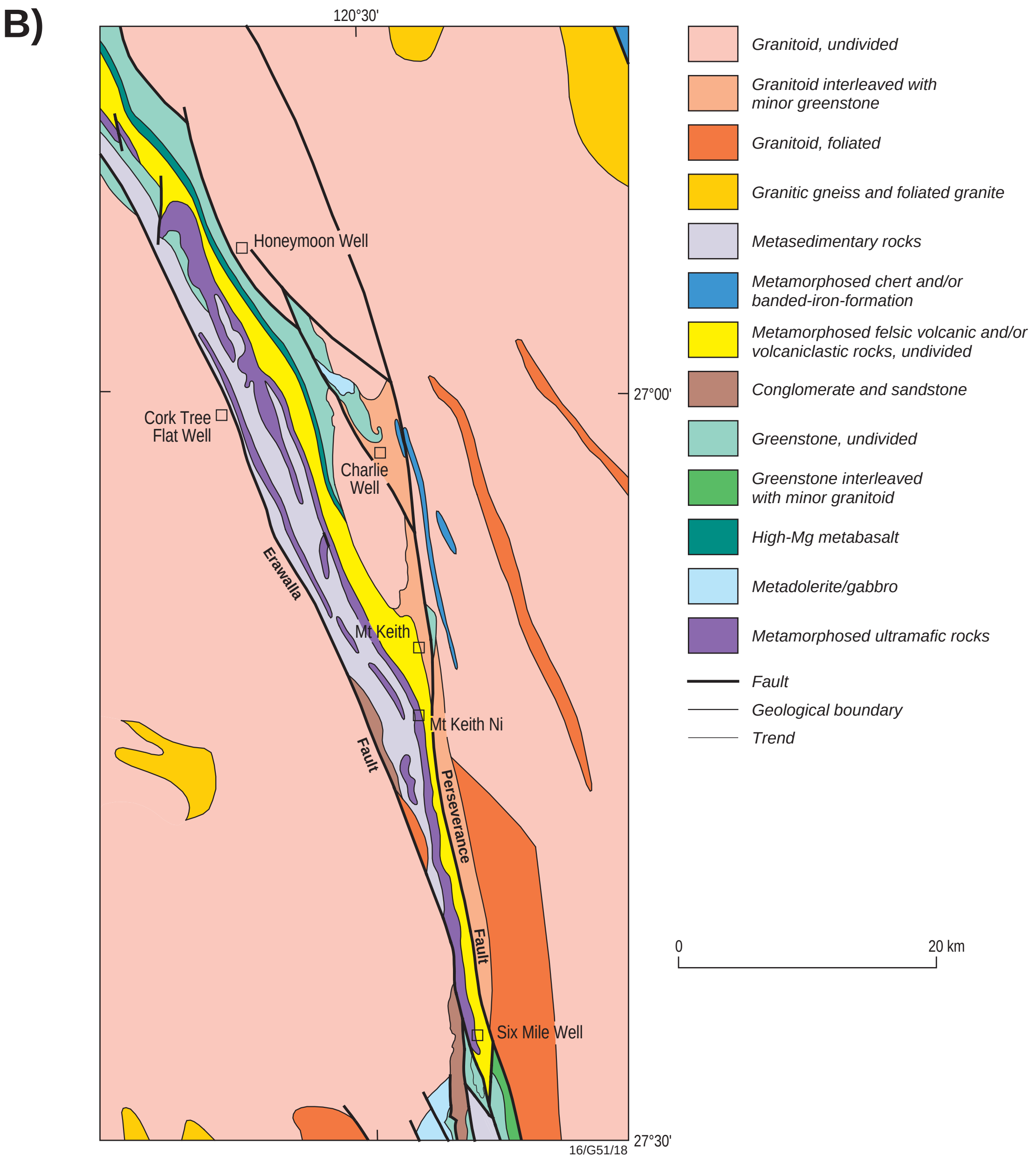



**Figure 5. A) Solid geology of the Six Mile Well – Lawlers area. Numbers refer to localities mentioned in the text: 1 – Lawlers Anticline, 2 – Mount White Syncline, 3 – Leinster Anticline; B) Solid geology of the Honeymoon Well – Six Mile Well area**

Metabasalt with plagioclase phenocrysts is a distinctive local variant (*Abp*) and is commonly referred to as 'cat rock' where phenocrysts are abundant. The plagioclase phenocrysts are locally up to 1.5 cm, and can constitute up to 15% of the metabasalt. This rock is commonly found in patches within metabasalt, but rarely can be mapped as a separate unit. On Sir Samuel it is only mapped about 7 km east of Barwidgee. The most distinctive outcrop of metamorphosed porphyritic basalt forms the southeastern part of the Mount Goode Basalt (*AbMGp*), and is discussed separately below.

Metamorphosed high–Mg basalt (*Abm*) is characterised by Mg-rich metamorphic minerals such as tremolite, secondary carbonate, and variolitic, and/or pyroxene spinifex textures (Liu et al. 1998). The variolitic texture consists of pale spheres, 2–10 mm in diameter, usually randomly distributed throughout the rock. Weathering can accentuate the texture, either preferentially eroding the spheres to create small depressions or the spheres may resist erosion to form scattered lumps on the surface. The pyroxene spinifex texture consists of randomly oriented needles, 5–15 mm long, of tremolite that have replaced primary pyroxene. High–Mg basalt (*Abm*) is shown in the Agnew and Mount Keith–Perseverance greenstone belts in the current map, although it was also mapped in the DARLOT 1:100 000 sheet area by Wyche & Westaway (1998). The largest units are mapped south of Six Mile Well, east of Yellow Aster, and south of Mount Roberts.

Intermediate volcanic and high-level intrusive rocks (*Abi*) are only mapped as part of the Spring greenstone belt. They are associated with more felsic rocks and range in composition from basaltic andesite to andesite (Westaway & Wyche 1998, Messenger 2000). The rocks are generally fine-grained, but locally porphyritic and glomero-porphyritic, with phenocrysts of plagioclase and/or clinopyroxene, in places up to 5 mm across.

Strongly carbonated mafic rock (*Abc*) is only mapped in a group of low hills about 4 km north-northeast of Yandal Well, around AMG 201395, in the southern Yandal greenstone belt (Westaway & Wyche 1998). The rocks are generally fine-grained, with pale-green metamorphic amphibole as the major constituent and contain abundant calcite, both as porphyroblasts up to about 1 mm, and as very fine-grained interstitial material. They are locally amygdaloidal with small quartz- and calcite-filled amygdales up to about 1 cm.

Strongly foliated fine-grained mafic rocks are mapped as *Abf*, or *Abs* where a schistosity is developed. The high degree of recrystallisation obscures evidence of the protolith for these rocks. *Abf* and *Abs* are most common in areas of shearing, such as the contacts with granitoids, and fault zones. *Abf* is mapped east of Mount McClure, west of Boundary Well, around Woorana Soak, and west of Mount Harold. *Abs* is mapped west of the New Holland gold mine in the SIR SAMUEL area.

Amphibolite (*Abam*) crops out close to, or in contact with, granitic rocks, e.g. west of Meredith Well and along the western margin of the Yandal greenstone belt. Amphibolitic metabasalt is characterised by destruction of primary igneous textures and by a strong penetrative foliation (and commonly lineation). The foliation is commonly weakly crenulated at granitoid margins. It is most common at greenstone margins and in mafic inclusions in the adjacent granitic rocks. Amphibolite is recrystallised, and slightly coarser-grained and darker than the metabasalt (*Abb*). Felsic porphyry dykes, which are usually strongly foliated and quartz veined, commonly intrude amphibolite close to granitoid contacts (Jagodzinski et al. 1999).

### Mount Goode Basalt (AbMG, AbMGp)

The **Mount Goode Basalt** was formally named by Liu et al. (1998) for the extensive suite of basalt north of Lake Miranda and west of the Miranda Fault. Typical Mount Goode Basalt (*AbMG*) is massive, fine-grained tholeiitic metabasalt and forms the lower part of the Basalt. The upper part of the Mount Goode Basalt (*AbMGp*) is commonly porphyritic with plagioclase phenocrysts comprising up to 15%, and occasionally 30%, of the rock (Liu et al. 1998: fig. 6). Pillow lava structures are preserved locally. Pillow basalt, with plagioclase phenocrysts up to 20 cm in diameter, is well exposed at the southeastern end of an island in Lake Miranda (AMG 594376) about 3 km south of the Bellevue Gold Mine (Liu et al. 1998: figs 6–7).

### Interleaved greenstone and granitoid (Abg)

Interleaved layers of moderately to steeply dipping, foliated greenstone and granitoid (*Abg*) form banded units up to 1.5 km wide west of the north sector of the Mount McClure Fault, which marks the west boundary of the southern Yandal greenstone belt. Individual lenses of greenstone or granitoid vary in width from less than 1 m to about 50 m and form north-northwest-trending low narrow ridges. This unit, as a whole, has a distinctive striped pattern on aerial photographs and satellite and aeromagnetic images (Liu et al. 1998, Jagodzinski et al. 1999). It is also mapped north of Charlie Well near the northern edge of the map sheet in the Mount Keith–Perseverance greenstone belt.

Most greenstones in the interleaved granite–greenstone Cocks–Satisfaction Zone attained amphibolite facies metamorphic assemblages, in contrast to greenschist facies assemblages in the adjacent greenstone sequence to the east. The amphibolite is fine-grained and displays a strong foliation defined by alignment of elongate quartz, plagioclase, and hornblende grains. They locally display thin gneissic banding formed by segregation of mafic and felsic minerals (e.g. AMG 910614, AMG 904632). Despite the high metamorphic grade, some greenstones in the interleaved zone retain their primary textures in places. All rock types in *Abg*, and especially the granitoids, exhibit a strong sub-horizontal mineral lineation trending 340º (Jagodzinski et al. 1999). In granitoid, the lineation is defined by recrystallised quartz and aggregates of recrystallised biotite, commonly 1–2 mm wide and up to 4 cm long. West of Mount McClure, this lineation has a shallow plunge to the southeast.

The interleaved units designated as *Abg* west of the Gardiner Fault (Fig. 3) are interpreted from images aeromagnetic data.

## Metamorphosed mafic intrusive rocks

### *(Ao, Aod, Aog, AoKV, AoKVa, AoKVg, AoKVx)*

Medium- to coarse-grained mafic rock with a known or implied intrusive origin is a common rock type and mapped in all greenstone belts in the SIR SAMUEL area. Undivided metamorphosed mafic intrusive rocks (*Ao*) crop out in the Lawlers Anticline, Leinster Anticline, east of Mount McClure Fault and in the area between Stirling Peaks and Dingo Range. These gabbroic rocks are commonly deeply weathered and the interpretation of an intrusive origin is based primarily on a medium to coarse grain size.

Fine- to medium-grained, mafic intrusive rocks are mapped as *Aod*, for example, north of Charles Well, Mount Keith, in the Leinster Anticline, and north of Kens Bore. They commonly occur as concordant layers in basalt (Jagodzinski et al. 1999). They are massive and largely resistant to deformation. In high strain zones, the surrounding finer grained basalts tend to be strongly foliated, whereas the dolerite is only weakly foliated. The rocks mapped as *Aod* are smaller in grain size than those mapped as *Aog*, although the distinction is not well defined. Good exposures of *Aod* occur in hills 3 km north of the Agnew–Leinster road between Vivien Well and Old Brilliant Well. Here mafic rocks with both ophitic and granular textures are interlayered with metabasalt. Metadolerite also crops out as a small, north-northwest-trending dyke, less than 3 m wide and 20 m long, that intruded the Kathleen Valley Gabbro about 600 m north of an abandoned open pit (AMG 585529). Pyroxene is completely replaced by metamorphic amphibole but the rock retains an ophitic texture. Its strongly recrystallised nature suggests that it is late Archaean, rather than a Proterozoic dyke. Jagodzinski et al. (1999) consider that some intrusive dolerites can be distinguished from extrusive dolerites (medium-grained interiors of basalt flows) by its slightly coarser grain, darker colour, and occurrence as resistant ridges in the field.

Metagabbro (*Aog*) occurs as medium- to coarse-grained mafic rocks within the greenstone sequences in the Agnew, Mount Keith–Perseverance and Yandal belts. They are particularly well exposed in the Kathleen Valley Gabbro, where they are part of an extensive layered mafic sequence. Where relationships can be observed, they are generally concordant with surrounding units, suggesting that they are sill-like bodies.

Other than in the Kathleen Valley Gabbro, Westaway & Wyche (1998) also note crystal differentiation for a metagabbro outcrop 3 km west of Paul Well (AMG 032414). This unit is about 120 m thick and its composition varies, from west to east, from pyroxenitic gabbro at the base, through a series of thin units of leucogabbro, pyroxene-phyric gabbro and microgabbro up into coarse, quartz-bearing gabbro and microgabbro (Westaway & Wyche 1998). These authors also report gabbro bodies that show compositional and grainsize layering south-southeast of Boundary Well (AMG 073245) and north of Mica Mica Waterhole (AMG 177209). Similar zoned gabbro bodies occur on the southeastern extension of the Dingo Range greenstone belt in the DUKETON area.

Metagabbros are mapped as part of folds in the area south of Six Mile Well, Yandal Well and in the Mount White Syncline. In the Mount White Syncline they occur as sills between fine-grained metasediments and metabasalts. South of Six Mile Well, a metagabbro (*Aog*) sill is part of folded mafic and ultramafic rocks (Jagodzinski et al. 1999).

### *Kathleen Valley Gabbro (AoKV, AoKVa, AoKVg, AoKVx)*

The **Kathleen Valley Gabbro** crops out in a low hilly area in the area south of Jones Creek. Previously known as Kathleen Valley gabbro (Bunting & Williams 1979), and Kathleen Valley Gabbro and Granophyre (Cooper et al. 1978), the formal name 'Kathleen Valley Gabbro' was first used in Gee et al. (1981). Kathleen Valley Gabbro was also used in Liu et al. (1996, 1998), where it was described in detail.

The Kathleen Valley Gabbro is a differentiated layered mafic intrusion consisting mainly of gabbro, but ranging in composition to anorthosite and (amphibolitized) pyroxenite end members. The suite also includes tonalite and quartz gabbro. The rocks are metamorphosed to greenschist facies, with original clinopyroxene altered to blue-green acicular to fibrous amphibole. Original igneous textures and zoned plagioclase are preserved. The gabbro forms a fault-bounded block in the Yakabindie greenstone belt, and is in fault contact with metabasalt, and locally with the Jones Creek Conglomerate, to the east. It is overlain by the Mount Goode Basalt.

Primary igneous layering in the Kathleen Valley Gabbro dips steeply northwest. The compositional layering indicates that the gabbro youngs to the southeast, and is overturned. The strike of the metagabbros changes from northeast to north-

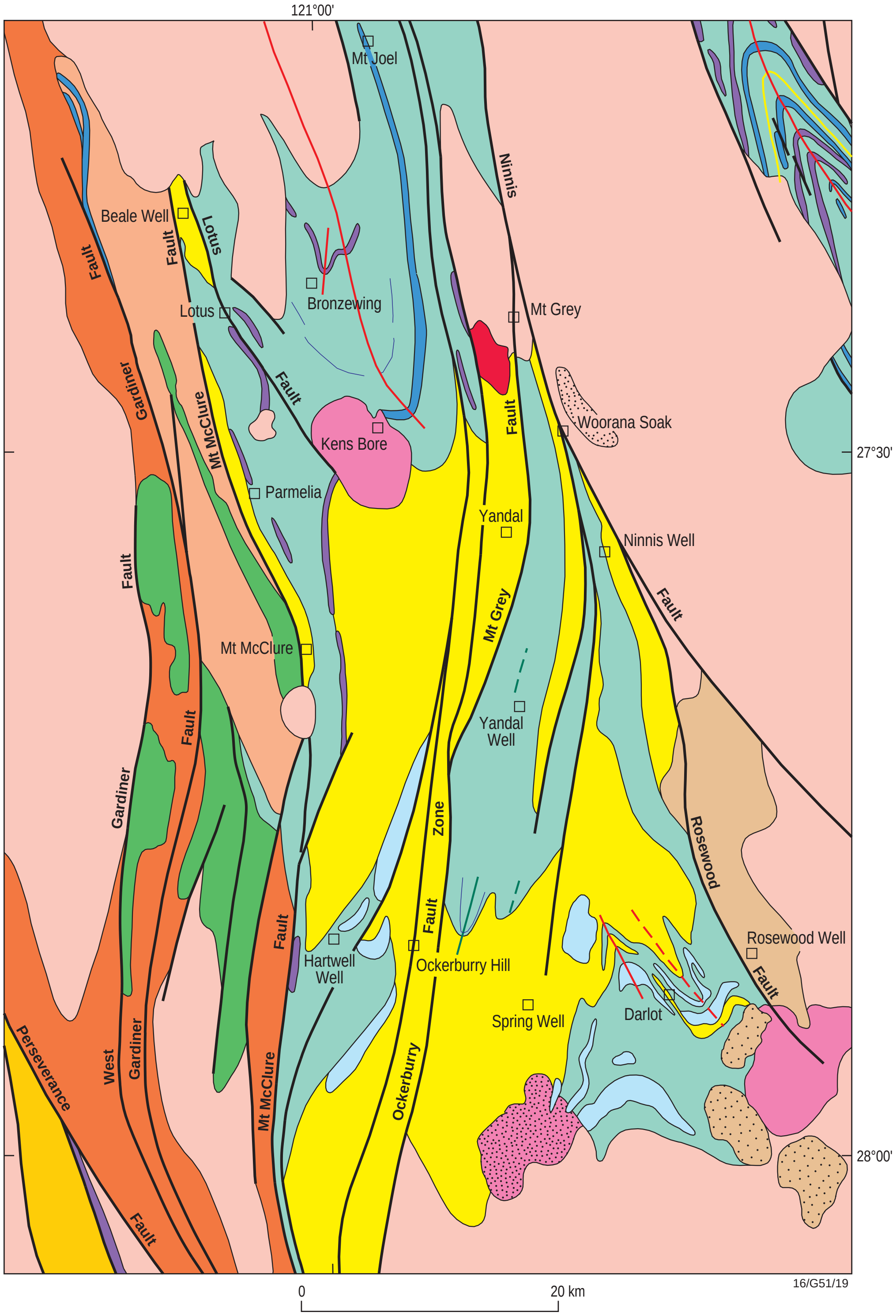



**Figure 6. Solid geology of the southern Yandal greenstone belt. See Figure 7 for legend**

northwest towards the Yakabindie shear zone to the west.

Sinistral strike-slip movement along north-northwest-striking faults disrupts the intrusion around Kathleen, forming fault blocks with significant displacement. Deformation within the intrusion is confined to narrow shear zones. Smaller normal faults slightly offset compositional layering west of these larger shears in the main part of the gabbro sequences. Undeformed granitic pegmatite dykes trending dominantly northwest (parallel to the shear zones and normal faults) intrude the gabbros and crosscut a north-trending foliation within them. The components of the intrusion are described below, from stratigraphically lowest to

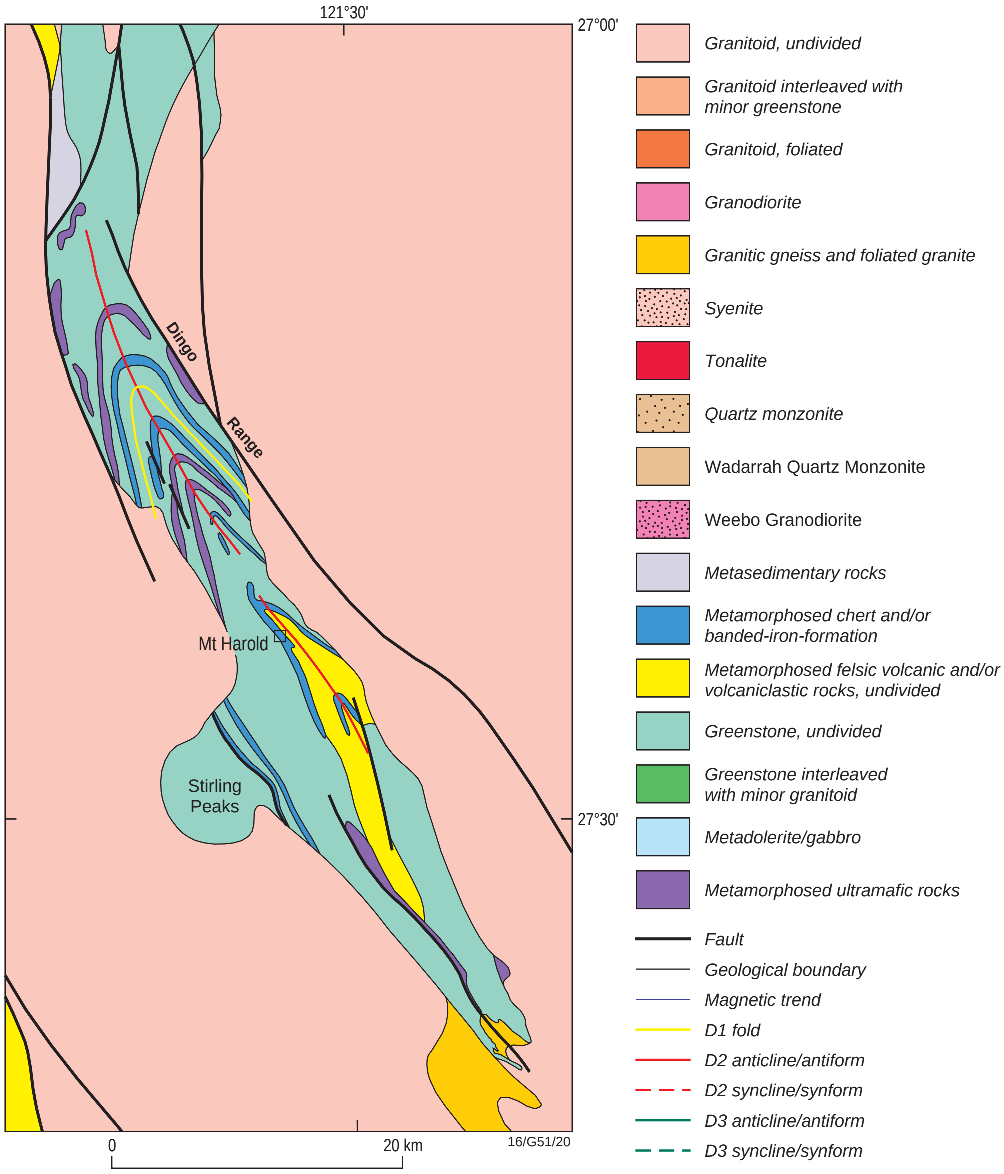



**Figure 7. Solid geology of the southern Dingo Range greenstone belt**

highest.

The exposed lowest, and northernmost, unit of the Kathleen Valley Gabbro is a layered gabbro (*AoKV*), at least 1100 m thick, with 2–10 m compositional rhythmic layering clearly visible on aerial photographs, and centimetre-scale layering in hand specimen (Jagodzinski et al. 1999: fig. 4). The layering is due to varying proportions of amphibole and plagioclase. Some anorthosite and pyroxenite layers are also present.

Overlying the layered gabbro unit (*AoKV*) is a unit, up to 1700 m thick, of metamorphosed, generally coarse-grained, anorthositic gabbro and anorthosite (*AoKVa*). Plagioclase varies from 60% to >95% in anorthosite (Jagodzinski et al. 1999: fig. 5), and occurs as both phenocryst and groundmass phases. Plagioclase phenocrysts, mostly less than 2 cm but up to 5–10 cm across, are commonly milky, and rounded to tabular (euhedral). Although generally pervasive, they typically only constitute a few percent of the total rock.

Some plagioclase-rich metagabbro has a poikilitic texture with euhedral plagioclase crystals within large (up to 15 cm) pyroxene (now amphibole) oikocrysts (e.g. AMG 580557). Amphibole has pseudomorphed the original pyroxene during metamorphism, occurring as replacing single oikocryst or multiple crystals with the same orientation.

Medium-grained metagabbro (AoKV), up to 1500 m thick, overlies anorthositic metagabbro (AoKVa), west of a north-northwest-trending shear zone west of Kathleen. Three layers can be recognised on aerial photographs in this unit, with the central layer being slightly darker due to a higher amphibole content.

Metamorphosed pyroxenitic gabbro (*AoKVx*) occurs in a layer about 100 m wide south of the medium-grained metagabbro unit (*AoKV*). It has a smooth pattern on aerial photographs. The rocks are dark, almost black, and fine- to medium-grained, with most grains ranging in size from 0.5 to 2 mm. The rocks contain more than 80% amphibole (derived from pyroxene), 10% plagioclase and less than 3% quartz. In thin section, the amphibole is blue-green and is probably actinolite or actinolitic hornblende.

Immediately south of the metamorphosed pyroxenitic gabbro (*AoKVx*) is a unit of quartz gabbro and tonalite (*AoKVg*) which constitutes one of the uppermost units of the Kathleen Valley Gabbro (Liu et al. 1996). The metamorphosed quartz gabbro and tonalite are best exposed in a 500 m wide zone 1 km north of an open pit east of the old Wiluna–Leinster road (AMG 583533). A tonalite sample from this unit has a SHRIMP U–Pb zircon age of 2736 ± 3 Ma (GA sample 97965402, Black L.P., 2000, written comm.). This age is younger than an earlier published conventional U–Pb zircon age of 2795 ± 38 Ma by Cooper & Dong (1983). Farther to the south there is a 200 m wide zone of metamorphosed quartz-bearing gabbro, and a 100 m zone of coarse-grained metagabbro.

## Metamorphosed felsic volcanic and volcaniclastic rocks
### *(Af, Afpf, Afs, Aft, Afv, Afx)*

Metamorphosed felsic volcanic and volcaniclastic rocks are a common rock type in the Agnew, Mount Keith–Perseverance, Yandal and Dingo Range greenstone belts. With exceptions in the Spring Well felsic volcanic complex, in which rocks are generally fresh and little deformed, most felsic volcanic/volcaniclastic outcrops are foliated and deeply weathered. It is thus often difficult to determine the protolith. These outcrops generally contain relict small euhedral or embayed quartz phenocrysts, which probably imply a volcanic or volcaniclastic origin in many cases. Undivided felsic volcanic and/or volcaniclastic rocks are mapped as *Af*. Porphyritic rocks are mapped as *Afpf*, e.g. in the Spring Well felsic volcanic complex. Where the foliation and recrystallisation in these poorly exposed felsic rocks is intense and a schistosity is developed, the outcrop is labelled *Afs* (felsic schist). It is commonly found along major fault or shear zones, e.g. Mount McClure Fault, Ockerburry Fault Zone. The schistosity is defined by white mica, and oriented feldspar and quartz. Quartz–feldspar schist of uncertain protolith is described below with the low-grade metamorphic rocks (*Al* section).

Felsic tuff (*Aft*) is a widespread rock type, but most outcrops are small; only two units are large enough to be shown in the current map, i.e. in the area east of Yellow Aster (Liu et al. 1998). They are relatively fresh, massive, felsic lithic tuff. The clasts are poorly sorted, dominated by crystal-rich felsic volcanic/volcaniclastic rocks, some of which also have fragmental texture (Liu et al. 1998: fig. 9). Clasts of fine-grained mafic schist and metasedimentary rocks are a minor component.

Rocks mapped as *Afv* (felsic volcanic and/or volcaniclastic rocks) indicates that a volcanic and volcaniclastic origin is clear. Rocks mapped in the undivided unit *Af* may include some weathered sedimentary rocks, which are difficult to distinguish from felsic volcanic and volcaniclastic rocks. *Afv* units are mapped southeast of Vivien Well in the Agnew greenstone belt, between Ninnis Well and Yandal Well, and around Spring Well in the Yandal greenstone belt. Descriptions of examples can be found in Westaway & Wyche (1998) and Liu et al. (1998).

Felsic volcanic breccia (*Afx*) is mapped in the Spring Well felsic volcanic complex, as well as one unit southeast of Yandal Well. Felsic volcanic breccias are generally poorly sorted and matrix-supported, with a range of volcanic clast types (Westaway & Wyche 1998: fig. 8). Outcrops generally show no internal stratification or bedding, although there is an overall grainsize reduction and locally bedding that is consistent with a westward younging of the complex.

### *Spring Well felsic volcanic complex*

The Spring Well felsic volcanic complex was studied in detail by Giles (1980, 1982). It consists of felsic volcanic and volcaniclastic rocks and high level intrusive rocks, in the area up to 10 or more km around Spring Well. Compositions vary from rhyolite to basaltic andesite. Mapped units on SIR SAMUEL include metamorphosed felsic volcanic/volcaniclastic rocks (*Afv*), rhyolitic and rhyodacitic tuff and/or breccias (*Afx*), felsic porphyry (*Afpf*), and andesitic metabasalt (*Abi*). For more details, the reader is referred to Wyche and Westaway (1996), Giles (1980, 1982), Barley et al. (1998) and Messenger (2000).

The rocks have some systematic variation in relation to the distance away from the volcanic centre (Giles 1980, 1982, Westaway & Wyche 1998). Away from the volcanic centre, rocks have a more limited range of volcanic textures with finer grained pyroclastic and volcaniclastic sedimentary rocks dominating. Westaway & Wyche (1998) consider that the lateral lithological and compositional changes, high proportion of pyroclastic rocks, and large volume of volcanic breccias near the volcanic centre suggest that the Spring Well complex represent a continental stratavolcano.

Barley et al. (1998) mapped four distinct facies associations. The lowermost association (Unit 1) is dominated by massive andesite and basaltic andesite lavas and sills, with subordinate epiclastic sandstones and conglomerates. Unit 2 records the deposition of proximal autoclastic and debris-flow breccia associated with shallow subaqueous to subaerial andesite to dacite lava flows, probably in a shoreline setting. Unit 3 comprises thick lobate dacite and rhyolite lava flows with associated autobreccia, possible welded ignimbrite, and polymictic conglomerates with fluvially reworked clasts. This unit reflects a transition into distinctly more felsic phase of volcanism, erosion, and fluvial deposition. The uppermost unit (4) comprises thick andesite conglomerates and breccias. All units were intruded by bifurcating microdioritic sills.

Facies associations vary markedly in thickness along strike (Barley et al. 1998). The coarse andesite breccia units thicken from 150m north of Spring Well to more than 600m, south of Spring Well. Thick rhyolite and dacite lava flows and monomict breccias pinch out over short distances (hundreds of metres or less) along strike, and either represent fault contacts or indicate that lava flows were dome-like in geometry with associated thick aprons of autoclastic debris.

The Spring Well complex contrasts with other intermediate calc-alkaline volcanic complexes in the Eastern Goldfields (e.g. Edjudina, Melita, Teutonic Bore, and the Black Flag Group of the Kalgoorlie area) in its high proportion of volcaniclastic breccias, conglomerates, and sandstones (Barley et al. 1998). The inferred origin for these volcaniclastic facies ranges from autoclastic and fluvial for the coarse andesite and dacite breccias, to alluvial fan or debris-flow deposits with fluvially derived material for the conglomerates.

A SHRIMP U–Pb zircon age of 2690 ± 6 Ma has been obtained on a sample of crystal-rich porphyritic rhyolite from about 1 km southwest of Spring Well (AMG 183124, GSWA sample 118953; Nelson 1997a). The rhyolite is interpreted as a rheomorphic ignimbrite, and the age, therefore, represents that of explosive rhyolite volcanism at the Spring Well complex (Barley et al. 1998).

### Metasedimentary rocks

### *(As, Asc, Ascf, Ascq, Ash, Ashd, AsJC, AsJCa, AsJCb, Asq, Ass, Ac, Aci, Acis)*

Metasedimentary rocks are a minor but widespread rock type on Sir Samuel. They are mapped in all but the Yakabindie greenstone belt and are particularly common in the Mount Keith–Perseverance and Agnew greenstone belts. Most rocks are poorly exposed and deeply weathered. Undivided units are mapped as *As*, and occur mostly in the McDonough Lookout to Perseverance area and in the Mount White Syncline. Fine-grained metasedimentary rocks, mostly phyllite, are mapped as *Ash*. Many, particularly the finer grained varieties, have a well-developed foliation and some outcrops are silicified. The protolith for most of these rocks is assumed to be fine-grained sandstone, siltstone, and mudstone, but may include felsic volcanic rocks, particularly in finely interbedded sequences. Although not well exposed, for example, metasedimentary rocks are mapped in the Mount White Syncline based on clear trend patterns on aerial photographs. These rocks and gabbroic units define the macroscopic fold.

Metamorphosed pelitic, shaly, or phyllitic sedimentary rocks (*Ash*) occur mainly as thin beds within metamorphosed mafic, ultramafic and felsic volcanic rocks. The fine-grained metasedimentary rocks, where well exposed, can provide evidence of multiple deformation, e.g. 3 km north-northeast of McDonough Lookout at AMG 647450, as the pelitic rocks contain an early cleavage that has been crenulated. They include minor quartz-mica schist and locally contain andalusite and cordierite porphyroblasts. One unit of phyllite with abundant andalusite porphyroblasts (*Ashd)* occurs as a north-northwest-trending unit about 3.5 km northeast of Mount Goode. The best exposures can be seen in a small creek at AMG 628503 where the rocks contain scattered andalusite porphyroblasts (1–3 mm) constituting 15–20% of the rock.

Metamorphosed sandstones (*Ass*) are mostly mapped between Letter Box Well and Cork Tree Flat Well east of the Erawalla Fault near the north edge of map sheet. Another unit is mapped in the area north of McDonough Lookout. One quartzite unit crops out about 2 km northeast of Mount Keith as a discontinuous ridge 2 km long (Jagodzinski et al. 1999). The rock is blue-grey, fine-grained, recrystallised, foliated and lineated.

Conglomerate occurs in several parts on SIR SAMUEL, with the most prominent being the Jones Creek Conglomerate (*AsJC, AsJCa, AsJCb*) and its equivalent, Scotty Creek conglomerate. One unit of undivided conglomerate (*Asc*) was mapped about 3 km north-northeast of Yellow Aster.

Oligmictic conglomeratic (*Ascf*) of dominantly felsic volcanic clasts is mapped 4 km south of Ninnis Well (Westaway & Wyche 1998). It is associated with felsic volcaniclastic rocks, is poorly sorted and made up of mostly felsic volcanic clasts, some of which are vesicular, in a quartzofeldspathic matrix. The size of the clasts increases towards the eastern side of the outcrop, with some up to 15 cm in diameter. The conglomerate is deformed, with flattened clasts aligned with the regional foliation.

Pebbly cherty conglomerate with dominantly quartz or chert clasts (*Ascq*) occurs in the northeast of Mount Harold in the Dingo Range greenstone belt (AMG 476693, Fig. 8). Clasts vary from 1 mm to 3 cm in width and 5 mm to 20 cm in length and are mostly chert or banded chert. They are similar to rock types forming the ridges nearby, which are considered to be source rocks for the pebbly conglomerate. All clasts are strongly deformed. Length/width ratios vary from 3 to 7 and commonly greater than 5. $S_2$ foliation as defined by the flattening of pebbles was measured as 331º/68ºSW. Long axes of pebbles plunges 52º towards 297º, which is considered to be sub-parallel to the axis of the macroscopic antiform at Mount Harold.

Metamorphosed fine-grained, siliceous and/or ferruginous metasedimentary rocks (*Ac, Aci, Acis*) are mapped in many locations, particularly in the McDonough Lookout–Yellow Aster area, east and northeast of Mount Keith, north of Charles Well, Dingo Range, Mount Harold, and east of Stirling Peaks.

Metamorphosed siliceous metasedimentary rocks (*Ac*) are prominent in the area between McDonough Lookout and the Perseverance nickel mine, and in the Yandal greenstone belt along the eastern margin of the sheet area where they are well exposed as discontinuous ridges that run parallel to the north-northwest regional trend. The rocks are fine to very fine-grained and quartz-rich, with most quartz recrystallised during metamorphism. They are typically grey-and-white banded, locally pyritic and, at the surface, locally very ferruginous. These rocks are often referred to as ‘chert’, but a chemical sedimentary origin is not always clear. In the Mount Harold area, chert defines the macroscopic fold.

Banded iron-formation (BIF) (*Aci*), that weathers to prominent, narrow, ironstone ridges, crops out northeast of Charlie Well, east of Mount Keith, and between the Rocky’s Reward and the Perseverance open pits. Metamorphosed fine-grained siliceous and iron-rich sedimentary rocks are rarely more than a few metres thick, are highly magnetised, and are commonly associated with shale and quartz-mica schist. They can be good marker horizons preserving complex fold structures.

### *Jones Creek Conglomerate (AsJC, AsJCa, AsJCb) AsJCb)*

Metamorphosed conglomerate, the Jones Creek Conglomerate (Durney 1972), is a significant component of the Six Mile Well–Lawlers area (Figs 3, 5). Metamorphosed conglomerates 3–4 km west-northwest of Vivien have been informally called the Scotty Creek conglomerate, but are considered to be part of the same formation as that in the Jones Creek area. Much of the Jones Creek Conglomerate is a conglomerate with granitic clasts and matrix (*AsJC*) with interbedded arkose (*AsJCa*). In the east part of the unit there is conglomerate with mafic matrix (*AsJCb*). Durney (1972), Marston & Travis (1976), Liu (1997), Liu et al. (1998) and Jagodzinski et al. (1999) give detailed descriptions of the conglomerates.

#### *Conglomerate with granitic matrix (*AsJC*) and arkose (*AsJCa*)*

A 1000 m thick cross section of the unit crops out west of Jones Creek. Here the conglomerate unconformably overlies monzogranite to the west (Liu 1997: fig. 24). The sandstone beds are thinner over the granite ridge, suggesting a sedimentary contact between the granitoid and the sandstones. North of the granite ridge at this outcrop, a foliation (cleavage) cuts through the boundary between the sandstone and the granitoid. The unconformity, graded beds and cross-beds in arkose to the east of the contact, consistently indicates younging to the east. South of Jones Creek, however, the unconformity is deformed, sheared or faulted.

Towards the base of the conglomeratic sequence in the area north of the Jones Creek, there are three channel-like embayments in the underlying monzogranite. Clasts are large, up to 3 m across, angular, and tightly packed. The very immature nature of most of the clasts within the lower part

**Figure 8. Photograph of deformed chert-pebble conglomerate, 1 km northeast of Mount Harold (AMG 476693, hammer is 26 cm in length)**

of the conglomerate indicates that they were locally derived. Below the conglomerate there is a transitional zone of fragmented monzogranite passing through to unbroken monzogranite. It is thus difficult to precisely locate the unconformity in most cases. Away from the contact, the conglomerate is better sorted, with predominantly well-rounded, 8–20 cm cobbles of mainly massive medium- to coarse-grained monzogranite (*AsJC*), although the granitoid clasts range from 1 cm to 1 m in some beds (Jagodzinski et al. 1999). A minor amount of other clast types, e.g. foliated granitoid, felsic porphyry, and rare mafic rocks, are also present, particularly in places away from the unconformity. Metamorphosed arkose (*AsJCa*) is interbedded with the conglomerate. The meta-arkose and matrix of the conglomerate consist of quartz, plagioclase, microcline, biotite, and muscovite. They have been recrystallised and contain a fabric defined by the preferred alignment of mica, quartz, and feldspars (Marston & Travis 1976, Nelson 1997a). In the conglomerate, boundaries between clasts and matrix are generally sharp, but locally gradational due to partial recrystallisation (Jagodzinski et al. 1999).

Felsic conglomerate is also well exposed along the SIR SAMUEL–MOUNT KEITH 1:100 000 map sheet boundary. In the area west and immediately east of the old road to Wiluna, the conglomerate contains clasts of dominantly medium- to coarse-grained massive granitoid rock, with subordinate felsic porphyry and mafic rock. Clasts range in size up to 40 cm, but most are smaller than 20 cm. They are rounded to sub-rounded and closely packed. The conglomerate has been partially recrystallised and boundaries between clasts and matrix are generally sharp, but locally gradational. A few fractures less than 1 cm wide in massive outcrop are the only evidence of deformation within the conglomerate, but contacts with the adjacent rock units are strongly sheared. Arkosic beds within the formation, about 300 m east of the old road to Wiluna around AMG 597558 in the north, strike north-northwest and dip steeply to the west.

Unlike the felsic conglomerate described above, clasts in conglomerate in drill core from 2 km south of Yellow Aster are mostly felsic porphyry with only minor granitoid, mafic and sedimentary rock. Some of these conglomerates contain gold.

### *Conglomerate with mafic matrix (*AsJCb*)*

The mafic conglomerate component comprises rounded felsic clasts in a mafic matrix, which is often strongly deformed in the form of chlorite-rich schist (Durney 1972, Jagodzinski et al. 1997, Liu et al. 1996). Conglomerate with mafic matrix (*AsJCb*) is mapped from west of Six Mile Well to southeast of Kathleen over a distance of more than 10 km. It is also mapped in the Scotty Creek conglomerate in the Agnew area. They occur in close proximity to greenstones in the east, i.e. the Mt Keith–Perseverance greenstone belt in the north and the Agnew greenstone belt in the south, and the greenstones possibly sourced the mafic matrix.

Compared with conglomerate with granitic matrix, clasts in the conglomerate with mafic matrix are more variable, ranging from medium-grained granitoid, granitic porphyry, aplite, and vein quartz. Thus, these conglomerates are polymictic. In contrast to the relatively undeformed felsic conglomerate, the matrix of the mafic conglomerate typically is strongly foliated parallel to the regional north-northwest trend (Jagodzinski et al. 1999). The best exposure of conglomerate with mafic matrix are found along a creek at AMG 596636 (GA site 97965429). The matrix is largely chlorite schist with a significant component of quartz and perhaps altered feldspar. An $S_2$ cleavage is well developed in the mafic matrix. Thin layers of sandy quartz-feldspar matrix are also present, but they have been boudinaged during strong compressional deformation.

The mafic-matrix conglomerate becomes more dominant farther south, i.e. in the area east and south-southeast of Yellow Aster where a larger area of conglomerate with mafic matrix is mapped. Exposures extend for about 5 km. The aerial photograph pattern for these rocks is similar to that of areas of metabasalt. However, the mafic conglomerate does not outcrop as well as the felsic conglomerate but forms low, rubble-covered hills where granitoid clasts (mostly pebbles and boulders) stand out due to differential weathering or occur as rounded to semi-rounded float.

### *Depositional environment*

Durney (1972), Marston & Travis (1976) and Bunting & Williams (1979) discussed the depositional environment of the Jones Creek Conglomerate. The nature of the poorly sorted angular clasts and transitional zone of fragmented monzogranite in the unconformity embayments suggest a local source for the conglomerate from an eroding upland area comprising the monzogranite in the west. Thus Durney (1972) interpreted the basal conglomerate as valley-fill talus. Away from the unconformity, the well-rounded, closely packed clasts in the conglomerate indicate a high-energy environment (Jagodzinski et al. 1999). Bunting & Williams (1979) suggested the conglomerate sourced a rapidly eroding upland area. The erosion materials were transported over a very short distance via talus slopes and small alluvial fans to a high-energy shoreline of a rapidly subsiding, fault bounded, elongate trough. The more distal conglomerate probably represented river and beach gravel (Jagodzinski et al. 1999).

### *Age of the Conglomerate*

A sandstone sample (GSWA sample 118937) of the Jones Creek Conglomerate sequence at AMG 590620 was analysed by SHRIMP U–Pb zircon dating in 1996 and 1999 (Nelson 1997a & 2000). Nelson (2000) interpreted a 2667 ± 6 Ma age as the maximum depositional age of the sandstone. This interpretation is consistent with the age of 2665 ± 5 Ma for the conglomerate reported by Krapez et al. (2000), and with the geological context of the area.

### *Hydraulic breccia*

In the felsic component of the Jones Creek Conglomerate, hydraulic breccias are present in a low and flat outcrop at AMG 592563 (GA site 97965023), about 3 km north-northwest of Yellow Aster, and in diamond drillcore from about 1.2 km south-southeast of Yellow Aster (AMG 601529).

At AMG 592563 there are fragmented medium-grained granitic rocks. The clasts are essentially of granitic composition, in a quartzofeldspathic matrix with some biotite. The jigsaw-fit fractures shown in Figure 9 are diagnostic of hydraulic breccia. The planar fracturing in the west part of outcrop is also typical of hydraulic breccia. Some of the biotite in the quartzo-feldspathic matrix may be of hydrothermal origin.

Hydraulic breccia also occurs in diamond drillcore from about 1.2 km south-southeast of Yellow Aster (AMG 601529). At this locality, the clasts are predominantly porphyritic granitoid with some fine-grained sedimentary and basaltic rocks. The matrix is biotite rich and of possible hydrothermal origin. A hydraulic fracturing origin for the breccias has been suggested (Pirajno F., 1995, pers. comm.). The drillhole also intersected gold mineralisation. The host rocks, including the apparent hydraulic breccias, were mapped as part of the Jones Creek Conglomerate (Bunting & Williams 1977, Liu et al. 1996). It is not clear whether the hydraulic fracturing occurred before or after the sedimentation although a likely timing is that the hydraulic fracturing post-dated the sedimentation.

## Low- to medium-grade metamorphic rocks *(Ala, Alb, Ald, Alf, Alfq, All, Alm, Alqm)*

Where the protolith of some low- to medium-grade metamorphic rocks cannot be recognised due to

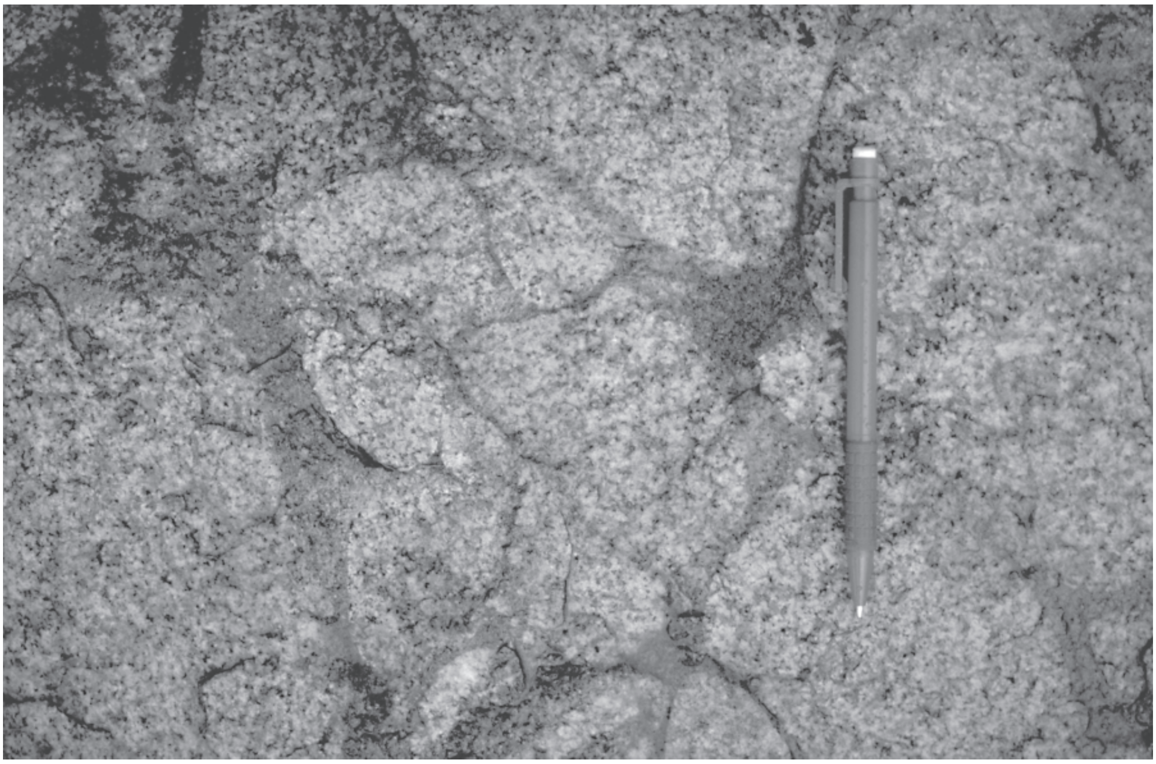


**Figure 9. Photograph showing jigsaw fit of clasts in a granitic hydraulic breccia, 3 km north-northeast of Yellow Aster (AMG 592563, pencil is 14 cm in length)**

the high degree of deformation and recrystallisation, the prefix *Al* is used with a suffix indicating the characteristic mineralogy. Many of these rocks are identified from rock chips obtained from shallow drilling. Where the rocks are almost wholly clay, and either massive or schistose, they are mapped as *Alb*. Quartz is absent or minor. Five out of the six *Alb* units were mapped in the WANGGANNOO area, including northeast of Bronzewing gold mine, southeast of Mount Grey and east of the massive basalt (*Abb*) unit at Stirling Peaks.

Amphibolite of probable metasedimentary origin (*Ala*) is mapped east of Mount McClure, north of Beale Well, and northwest of Ninnis Well. The north-trending unit east of Mount McClure was described in Liu et al. (1998). It is a layered plagioclase–hornblende–clinopyroxene–quartz-rich rock. This unit is markedly more leucocratic than the deformed mafic rocks that bound it to the east and west. It shows a pronounced layering, streaky or discontinuous, which is defined by both variations in composition and grain size. It has been extensively recrystallised and is mainly fine- to very fine-grained with thin (up to 5 mm wide) coarser layers containing various combinations of plagioclase, quartz, amphibole and clinopyroxene. Jagodzinski et al. (1999) reported quartz-rich amphibolite (*Ala*) that forms three outcrops northwest and north of Beale Well.

About 2.5 km north of Mount Goode, at AMG 599503, pelitic schist (*Ald*), which is associated with quartzofeldspathic schist, contains altered andalusite and cordierite porphyroblasts (Liu et al. 1998: fig. 11). Pale blue andalusite porphyroblasts are mostly a few millimetres wide, up to 1–2 cm long, and randomly oriented. Cordierite porphyroblasts appear as round brown patches of alteration products 1–2 cm in diameter.

Quartz–feldspar schist (*Alf*) occurs at several places in the Mount Keith–Six Mile Well area in the Mount Keith greenstone belt, and around Woorana Soak in the Yandal greenstone belt. In outcrop, the schist is heavily weathered to a yellow, fine- to very fine-grained quartz–clay rock with relict schistosity. Fresh rock in a RAB drillhole at AMG 578782 consists of small phenocrysts of saussuritized plagioclase and broken and partly recrystallised quartz in a very fine-grained groundmass of chlorite, quartz, plagioclase, epidote, and muscovite. The rock is a deformed and metamorphosed dacitic or tonalitic porphyry; the considerable extent of the exposures suggests that the precursor was a felsic volcanic.

Heavily weathered quartz–feldspar schist in the form of schistose clay rock with clear quartz eyes is mapped as *Alfq* east of the north sector of the Mount McClure Fault. Two such units are near the granite–greenstone contact south-southwest of

Mount McClure mining centre and one is north of Beale Well. The quartz eyes are interpreted as relict quartz phenocrysts, consistent with a felsic volcanic origin.

It should be noted that the unit terms *Alf* and *Alfq* were not used in the GSWA's 1:100 000 geological maps (DARLOT, SIR SAMUEL and DEPOT SPRINGS), in which rocks with the definitions of *Alf* and *Alfq* were probably mapped as felsic schist (*Afs*). No attempt was made to rationalise these rock units in the compilation of the SIR SAMUEL 1:250 000 geology map.

Chlorite schist (*All*) occurs west of Vivien Well near the southern map boundary in the Agnew greenstone belt and identified from drill holes south-southeast of Mount White. Muscovite schist (*Alm*) occurs in the Mount Keith – Six Mile Well area of the Mount Keith greenstone belt and west of Woorana Soak in the Yandal greenstone belt. Quartz–muscovite schist (*Alqm*) occurs south of Mount Keith and 5 km west-northwest of Vivien Well. It has also been identified from drill holes in metasedimentary rocks south-southeast of Mount White.

## Granitoids

### *(Ag, Agb, Agc, Agd, Agdq, Age, Agf, Agfo, Agg, Agm, Agmp, Agn, Agp, Ags, Agt, Agu, AgWA, AgWE, AgWEf)*

Archaean granitic rocks, mostly biotite monzogranite, dominate the granite–greenstone geology on SIR SAMUEL, but are in general either poorly exposed or strongly kaolinised. Outcrops are mostly limited to low-lying, variably weathered patches in areas of granitoid-derived sand to variably kaolinised outcrops in breakaway country below eroded silcrete duricrust surfaces, and to isolated, relatively fresh, pavements and tors. Significant areas of excellent outcrop do occur, however, including the majority of the Barr Smith Range, and the area around Mt Blackburn.

Undivided and/or unassigned granitic rocks (*Ag*) commonly comprise deeply weathered, mostly kaolinised and locally silicified, granitoid, typically associated with breakaways, but also include regions of poor exposure and some unvisited outcrops. On GA's 1:100 000 maps, i.e. YEELIRRIE, MOUNT KEITH, WANGGANNOO, areas of outcrop of strongly kaolinised granitic rocks of indeterminate lithology have been subdivided on the basis of dominant grainsize or texture, using both quartz grains and relict textures, into either fine- (*Agf*), medium- (*Age*), coarse-grained (*Agc*), mixed fine- to coarse-grained (*Agu*), or porphyritic (*Agp*) varieties.

Other, non-lithological classifications of granitoids (for strongly weathered to fresh outcrop) are based on structural characteristics, in particular the degree of structural and metamorphic overprint of mostly granitoid precursors. These structural units are largely confined to DEPOT SPRINGS and SIR SAMUEL. They include undivided foliated granitoids (*Agfo*; only used on GSWA's 1:100 000 maps), strongly foliated granitoids with locally developed gneissic textures or incipient banding (*Agn*), strongly foliated and locally gneissic granitoids with interleaved greenstone rocks (*Agb*), and areas of banded gneiss and/or gneissic granitoid (*An*). Banding developed in these rocks, indicated by variations in grains size, phenocryst content, and/or mineral content, reflect original lithological variation (e.g. granitoid dykes, enclaves, pegmatites, aplites, igneous layering and schlieren) and, in areas of higher grade and/or strain, metamorphic & structural effects (e.g. metamorphic segregation).

The foliated to gneissic granitic units typically occur along the margins of granitoid masses. One example is the large arcuate north-south zone (7–15 km wide), of strongly deformed granitoid, west of the Waroonga Shear Zone in the southwestern part of SIR SAMUEL, clearly visible on aeromagnetic images. Although mostly poorly exposed, relatively good outcrop occurs in the region west of the New Holland openpit, comprising strongly deformed gneissic and/or foliated granodiorite and granite, which contain thin discontinuous zones of amphibolite (either remnant mafic dykes or greenstone rocks), and both concordant and discordant granitoid dykes and pegmatites. Another example includes the strongly foliated and greenstone-intercalated zones (*Agb*) that occur along both the eastern and western margins of the granitoid mass separating the Agnew–Wiluna and Yandal greenstone belts, described in detail by Liu et al. (1998). Here, foliated and/or lineated greenstone, mostly of amphibolite-facies, occurs as lenses within strongly deformed granitoid. A sample of gneissic granitoid from one such outcrop west of the Parmelia openpit has a SHRIMP U–Pb zircon age of 2738 ± 6 Ma (Nelson 1998). This is one of the oldest recorded granitoid ages found in the Eastern Goldfields Province. Available geochemistry (Geoscience Australia, unpublished data) suggests that the dated sample is part of the High–HFSE group of Champion & Sheraton (1997). Granitoids of this group have a strong spatial relationship with contemporaneous (and in part co-genetic) felsic volcanic rocks, raising the possibility of volcanics (and, hence, greenstone) of similar age in the region. Interestingly, Nelson (1997a) reports an age of 2720 ± 14 from a deformed felsic volcanic rock from the Rocky's Reward nickel mine, which although younger is within experimental error of the age for the gneiss near the Parmelia openpit. Similarly, a tonalitic phase of the Kathleen Valley Gabbro has a SHRIMP U–Pb zircon age of 2736 ± 3 Ma (Black L.P., 2000, written comm.), all suggesting the presence of older greenstone (to 2750 Ma) within the region.

The dominant lithology on SIR SAMUEL is monzogranite (*Agm*). These are typically undeformed to variably foliated and/or lineated, biotite-bearing (<5–10%) granitoids, which, locally, may have minor amphibole (up to a few percent). Minor muscovite and accessory fluorite may also be present, e.g. at Mt Blackburn – the latter relatively common in the Low–Ca group granitoids (see below). Textures vary from equigranular to porphyritic, and include a distinctive moderately to strongly K-feldspar porphyritic (*Agmp*) variety, best seen in the Barr Smith Range area. Grainsize varies from fine- to coarse-grained, with many of the monzogranites comprising larger medium-coarse grained units containing sparse to locally common pods and dykes of variably porphyritic fine and fine-medium monzogranite. Good examples of these relationships can be seen in the Hannans Bore region (south-central MOUNT KEITH area), and in many of the outcrops in the south-central part of the DEPOT SPRINGS 1:100 000 sheet. Another feature of these granitoids (and many of the less deformed granitoids in the Eastern Goldfields), best seen in the excellent outcrop of the Barr Smith Range, are the manifestations of igneous flow layering. These include good phenocryst alignment, cryptic banding (defined by changes in grain size and biotite-content), and the presence of biotite schlieren. The latter comprise typically elongate (to several metres) but thin (<5 cm) wispy layers largely of biotite and accessory phases. They may occur sparsely throughout a unit or be locally concentrated. Their origins are equivocal; they may represent either disrupted (strung-out) enclaves, or some forms of cumulate.

SHRIMP U–Pb zircon ages for monzogranite units include 2685 ± 7 for the High–Ca granitoid (*Agmp*) west of Jones Creek Conglomerate (west of Six Mile Well) (Nelson 1997a), and a ca. 2652 Ma age (Black L.P., 2000, written comm.) for the Low–Ca granitoid (*Agmp*) 2.5 km southeast of Hannans Bore.

Less common, more mafic granitic units in the SIR SAMUEL area include hornblende–biotite and biotite granodiorite (to monzogranite) (*Agg*) and biotite tonalite (*Agt*), the majority intrusive into greenstones. These units include the strongly weathered granodiorite body, readily visible on aeromagnetic images, in the Kens Bore region (*Agg*; description in Nelson 1997a), the biotite granodiorite (shown on the map as *Ag*) 5 km west of the Kens Bore body, and the biotite tonalite (*Agt*) 10 km north-east of the Kens Bore body. The first two have similar SHRIMP U–Pb zircon ages of 2669 ± 6 (Nelson 1997a) and ca. 2666 Ma (Black L.P., 2000, written comm.). The Weebo Granodiorite, comprising a coarse-grained titanite–biotite–hornblende granodiorite phase (*AgWE*), and a fine-grained marginal variant of similar mineralogy (*AgWEf*), both described in detail by Westaway & Wyche (1998), also intrudes greenstones of the Yandal belt but has a slightly younger SHRIMP U–Pb zircon age of 2658 ± 7 Ma (Nelson 1997a). Granodiorite marginal to greenstones or intrusive into other granitoids includes the titanite–hornblende–biotite granodiorite (*Agg*), east of Melrose Homestead (Westaway & Wyche 1998), with a SHRIMP U–Pb zircon age of 2666 ± 6 Ma (Nelson 1997a), and the strongly foliated to banded titanite–hornblende–biotite granodiorite (*Agg*) occurring in the western part of the Barr Smith Range.

Alkaline granitoids on SIR SAMUEL, include titanite–hornblende–pyroxene and titanite–pyroxene syenite to quartz syenite (*Ags*), which outcrop in the Woorana Soak and Red Hill regions, on WANGGANNOO (Johnson 1991, Lyons et al. 1996, Smithies & Champion 1999), and the Wadarrah Quartz Monzonite (*AgWA*) – a titanite–biotite–hornblende quartz monzonite on DARLOT (Johnson 1991, Westaway & Wyche 1998). Both the syenitic rocks and the quartz monzonite exhibit some textural variation, a common feature of syenitic rocks in the Eastern Goldfields (Johnson 1991, Smithies & Champion 1999). Variations include the amount and type of phenocrysts, different mineral proportions, especially amount of feldspar, and grainsize variations. Good examples include outcrops of the Woorana Soak body (e.g. AMG 228593, east of the telecommunications tower) and in the Red Hill body. Similarly, Johnson (1991), who mapped the outcrops of the Red Hill body in great detail, describes multiple units of pyroxene syenite, syenodiorite, quartz syenite, and alkali granite. The Woorana Soak body and the Wadarrah Quartz

**Table 1. Summary of geological, petrographic and age data for granitoid groups of the northern Eastern Goldfields Province. Modified from Champion (1997)**

| *Group* | *Lithologies* | *Fabric & textures* | *Characteristic features* | *Age (Ga)* | *Examples* |
|---|---|---|---|---|---|
| High–Ca | biotite ± minor amphibole, titanite; granodiorite, trondhjemite & monzogranite | gneissic (locally migmatitic); foliated and/or lineated to non-foliated; strongly feldspar-phyric to equigranular | sodic compositions (i.e. high $Na_2O$); low to moderate radiometric response; common irregularly-zoned plagioclase in thin section | mostly 2.72–2.655 | granitoid along Barr Smith Range; strongly foliated granitoids west of the Genesis and New Holland gold deposits |
| High–HFSE | biotite ± amphibole, pyroxene, titanite; monzogranite & syenogranite, minor granodiorite | foliated to non-foliated; rare gneiss; feldspar-phyric to seriate | mostly high silica (74–77 wt% $SiO_2$); often amphibole- (and/or pyroxene-) bearing despite silica-rich compositions; often spatially associated with felsic volcanics | 2.685–2.66 | Weebo granodiorite; west of the Mt Joel and Greenstone Hill areas |
| Mafic | amphibole, biotite ± pyroxene; diorite, tonalite, trondhjemite, granodiorite | foliated to non-foliated; amphibole-feldspar-phyric to equigranular | mafic compositions (<60–70 wt% $SiO_2$); common to abundant amphibole (5–20%) with pyroxene and/or biotite; common well-zoned plagioclase in thin section | mostly 2.69–2.66 | granodiorite at Kens Bore, and south of Anxiety Bore |
| Low–Ca | biotite, ± allanite, titanite, fluorite, muscovite; monzogranite, minor granodiorite, syenogranite | non-foliated to locally strongly foliated and/or lineated; feldspar-phyric to equigranular | potassic compositions (high $K_2O$, $K_2O/Na_2O$), with high Rb, La, Ce, Zr; high radiometric response; common accessory fluorite, titanite and allanite, best seen in thin section; general lack of zoning in plagioclase. | mostly 2.655–2.63 | granitoids in the Mt Blackburn region; granitoid near Leinster; strongly foliated granitoid at Ryans Well |
| Syenite | titanite, amphibole, green pyroxene; syenite, quartz syenite, quartz monzonite | foliated to non-foliated; locally gneissic; alkali feldspar ± amphibole-phyric to equigranular | common to abundant pink to grey K-feldspar, common green pyroxene and/or hornblende, minor quartz (<10–15%) | mostly 2.655–2.64 | Wadarrah Quartz Monzonite; quartz syenite at Red Hill, and near Woorana Soak |

Monzonite have similar SHRIMP U–Pb zircon ages of 2644 ± 13 and 2643 ± 6 Ma, respectively (Nelson 1997a). Westaway & Wyche (1998) also report a small clinopyroxene quartz monzonite outcrop on DARLOT (AMG 368450, not shown on the map).

Other small outcrops include diorite to monzodiorite (*Agd*), porphyritic microdiorite (AMG 401081, not shown on map), both on DARLOT, and a number of quartz monzodiorite to quartz diorite (*Agdq*) outcrops around and south of Yellow Aster on SIR SAMUEL 1:100 000 (mostly not shown on the map).

## *Classification*

Champion & Sheraton (1997) subdivided the granitoids in the northern Eastern Goldfields Province, on the basis of petrography and geochemistry, into 5 groups, namely, High–Ca (>60% by area of total granitoids), Low–Ca (>20–25%), Mafic (<5–10%), High–HFSE (<5–10%), and Syenitic groups (<5%). Geochemical and petrographic features of each group are listed in Table 1. This scheme ignores previous structural classifications, in particular the use of pre- and post-folding terminology (e.g. Bettenay 1977, Champion & Sheraton 1993, Witt & Davy 1997) that has been demonstrated by subsequent geochronology to have many inconsistencies (Champion 1997), largely reflecting the inherent difficulties in interpreting structural histories of granitoids in poorly outcropping terranes.

High–Ca group granitoids on SIR SAMUEL are mostly (hornblende–) biotite monzogranite and lesser hornblende–biotite granodiorite. They include the majority of the granitoids immediately west of the Agnew–Wiluna greenstone belt, including the belt of strongly foliated granitoids that extend north from west of the Genesis and New Holland gold deposits (*Agb*, *Agfo*), the strongly lineated granitoids in the Nuendah area (*Agmp*), and less deformed to undeformed granitoids along the Barr Smith range (*Agmp*, *Agg*). Other High–Ca granitoids include around Mt Pasco (*Agf*), east of Melrose homestead (*Agg*, *Agm*), and east and northeast of Wonganoo homestead (*Agmp*, *Agg*).

Low–Ca group granitoids are relatively abundant on SIR SAMUEL, occupying the western half of the YEELIRRIE 1:100 000 sheet, most of the central region of granitoid between the Agnew–Wiluna and Yandal greenstone belts, the majority of granitoids between Mt Blackburn and west of Wonganoo homestead, and the granitoid near Leinster. Most units are biotite monzogranite and lesser biotite (± fluorite) syenogranite. Low–Ca granitoids are mostly non-foliated, but do include some strongly foliated members (e.g. the monzogranite at Ryans Well in the Yandal greenstone belt).

Members of the High–HFSE group within the northern Eastern Goldfields Province are commonly found associated with felsic volcanic rocks of similar geochemistry (Champion 1997). This is also the case for the Weebo Granodiorite (Westaway & Wyche 1998), in the Spring Well area. Other High–HFSE members include the granitoid along the western margin of the Yandal Greenstone Belt, in the area west of the Mt Joel to Greenstone Hill area, and as part of the gneissic to strongly foliated granitoids (*Agb*), west of the Dragon to Cockburn gold deposits.

Syenitic group members on SIR SAMUEL, include the syenite and quartz syenite at Woorana Soak and Red Hill, as well as the Wadarrah Quartz Monzonite (Westaway & Wyche 1998). Members of the Mafic Group, include the hornblende–biotite granodiorite at Kens Bore and south of Anxiety Bore (*Ag* on map), and numerous porphyries (intersected in diamond drillcore), all within the Yandal Greenstone Belt, and an unexposed granodiorite intersected in diamond drillcore from the Hurleys Reward area in the southern part of the Dingo Range greenstone belt.

### *Petrogenesis and implications*

Detailed petrogenetic models for these granitoid groups are discussed in Champion & Sheraton (1993, 1997), Champion (1997), and Smithies & Champion (1999); Witt & Davy (1997) also present broadly similar models for granitoids of the southern Eastern Goldfields Province. In brief, the majority of granitoids appear to be largely crustal-derived, especially the Low–Ca and High–HFSE groups. The origin of the High–Ca group granitoids, although not as unequivocal, requires their derivation by partial melting at high pressures, e.g. at middle to lower crustal depths in thickened crust (Champion & Sheraton 1997). More importantly, the available Sm–Nd isotopic data (Champion & Sheraton 1997) requires that the source rocks for the Low–Ca and High–Ca groups were distinctly different, i.e. not only were the Low– and High–Ca granitoids derived at different pressures but also from largely different protolith. The full significance of this is realised when coupled with the recognition that the granitoid groups themselves form a largely coherent chronology (see Table 1), from early (2720 to 2655 Ma) High–Ca granitoids, and localised Mafic and High–HFSE granitoid, to later (2660 and younger) Low–Ca and Syenitic granitoids. This sequence is interpreted to largely reflect the ‘post-tectonic’, i.e. post the main-orogenic shortening deformation event, nature of the syenitic and Low–Ca granitoids. This is interpreted to a fundamental change in tectonic environment post 2660–2655 Ma, from crustal thickening (shortening) and voluminous High–Ca granitoids, to a tensional environment favouring Low–Ca and syenitic magmatism (see also Smithies & Champion 1999). Smithies & Champion (1999) suggested that this post-2660 Ma magmatism, extending down to 2630 Ma and younger, represented an additional tectonothermal event in the eastern Yilgarn Craton, contemporaneous with lower-middle crustal high-grade metamorphism and regional gold mineralisation (e.g. Kent et al. 1996). Smithies & Champion (1999) further postulated that this thermal event might have resulted from lower-crustal delamination following crustal thickening during the main-orogenic shortening deformation event.

## Veins and dykes

*(a, d, e, g, p, po, q)*

Several aplite (*a*) dykes are mapped in the northeast part of the map sheet area, around Red Hill and east of Wonganoo. Small veins and dykes of granitoid (*g*) are generally most abundant near granite–greenstone contacts. Most are deeply weathered but they appear to be mainly biotite monzogranite. Mapped units can be found in the Barr Smith Range and east of Barwidgee. Diorite veins are mapped as *d*, e.g. at Stirling Peaks. Veins rich in epidosite/epidote are mapped as *e* south of Mount Joel and southeast of Red Hill in the WANGGANNOO area.

Pegmatite veins (*p*) are a common but minor phase in granitoid areas, e.g. at Mount Pasco, but they also occur in greenstones. About 2 km southwest of Mount Goode, they intrude metabasalt. In granitoid areas, they occur as both diffuse phases in the granitoid and late crosscutting veins.

Felsic porphyry dyke (*po*) is also a common but minor rock type. In most cases they are too small to be shown on the current map. Mapped larger dykes can be found 7–9 km north of Mount Keith, and near the north shore of Lake Miranda. In the latter locality, the dyke is about 3 m wide on a small hill. It contains both quartz and plagioclase phenocrysts. Although most of the dyke is little deformed, it is strongly foliated along its margins.

Quartz veins (*q*) are a minor component throughout the Sir Samuel area in both greenstones and granitoids. They are generally short and discontinuous outcrops, varying from a few centimetres to several metres wide. Larger veins occur in the Wild Cat Hills in the southwest part of the map area. Liu et al. (1998) considered that the quartz veins are mainly late Archaean in age as they are not observed to cut the large Proterozoic dykes in greenstones elsewhere in the Eastern Goldfields. Many of the larger veins are associated with sheared contacts between granitoids and greenstones. Gold mineralisation is often associated with quartz veins that were a major target for early prospectors.

## Greenstone belts and major faults

Greenstones in the Eastern Goldfields Province were subdivided into separate greenstone belts during the 1970's and summarised in Griffin (1990) based on their distribution, differences in the dominant rock types, and structural complexity. The belts were named primarily for ease of discussion, and boundaries are not everywhere well defined.

On Sir Samuel greenstone belts include the Yakabindie, Mount Keith–Perseverance, Agnew, Yandal, and Dingo Range greenstone belts (Figs 3, 5). The Yakabindie greenstone belt refers to the greenstone sequence west of the Miranda Fault (Fig. 3, Liu et al. 1998). Griffin (1990) interpreted the Agnew belt to be faulted against the Mount Keith–Perseverance belt, and the boundary fault was shown as the Sir Samuel Fault in Liu et al. (1998). The Jones Creek Conglomerate lies in a fault-bounded zone between the Yakabindie greenstone belt and the Agnew and Mount Keith–Perseverance greenstone belts (Fig. 3).

Much of the Sir Samuel area belongs to the Eastern Goldfields Province, with the western part (granitic, gneissic rocks, and perhaps the Yakabindie greenstone belt) probably belonging to the Southern Cross Province (see discussions below).

### Yakabindie greenstone belt

The Yakabindie greenstone belt consists of the layered Kathleen Valley Gabbro and the overlying, massive Mount Goode Basalt (Fig. 5a, Liu et al. 1998). Both units young towards the south and have a mainly steep to nearly vertical dip to the northwest. Rocks are little deformed except along the faults and shear zones that are a prominent feature in the Kathleen Valley Gabbro. The sequence is bounded by the north-trending Miranda Fault, and intruded by granitoid in the west.

The Kathleen Valley Gabbro is a layered sequence, varying from anorthosite in the north (lower part), to gabbro in the middle, to quartz-bearing gabbro and tonalite in the south (upper part). The upper part of the Mount Goode Basalt is characterised by patchy development of a plagioclase-phyric phase while its lower part is massive tholeiitic basalt. A tonalitic sample from AMG 583530 (GA site 97965402) from the differentiated upper part of the layered Kathleen Valley Gabbro has a SHRIMP U–Pb zircon age of 2736 ± 3 Ma (Black L.P., 2000, written comm.). This age for the Yakabindie greenstone belt suggests that the belt is older than much of other adjacent greenstone belts, which are inferred to be about 2705 Ma old or younger. The greenstone sequence of the Yakabindie belt appears to be unique in the area and does not appear to have equivalent sequences in the other greenstone belts in the area.

Two prominent faults, the Yakabindie Fault and the Highway Fault, both trending about 330º, cut the Mount Goode Basalt and the Kathleen Valley Gabbro (Fig. 5). In the Kathleen Valley Gabbro there are several small north-northwest-trending shear zones with apparent sinistral movement sense. Eisenlohr (1987, p.88) stated that these shear zones cut a locally developed northeast-trending foliation ($S_1$) parallel to the compositional layering of the gabbro. The Yakabindie Fault (Fig. 5) is defined by a 50–100 m wide shear zone in the Mount Goode Basalt, resulting in a well-developed, steep, northwest-trending mineral foliation at AMG 589448. The shear zone can be clearly seen on aerial photos. Basaltic rocks in the shear zone contain a pronounced foliation (334º/84ºNE[2]) and a steep, northwest-plunging mineral lineation (64º→335º [3]). In some outcrops the lineation is defined by elongate plagioclase aggregates after plagioclase phenocrysts. Basalt away from the shear zone is relatively undeformed.

Layering in the Kathleen Valley Gabbro changes from an overall east-northeast trend to a more north-

[2] 334º/84ºNE means 'strike = 334º, dip = 84ºNE'.

[3] 64º→335º means 'plunge = 64º to 335º'.

northeast trend in the vicinity of the Yakabindie Fault (Fig. 5). This suggests sinistral movement for the Yakabindie Fault during $D_{2-3}$, and is consistent with observations at Lake Miranda (AMG 593375), small-scale structures in the Highway Fault (AMG 589390), and the sigmoidal shape of the Koonoonooka monzogranite east of the Perseverance Fault (Figs 3–4). In thin section, an overprinting relationship between the prominent $S_2$ cleavage and earlier amphibole porphyroblasts also suggests sinistral movement (Liu et al. 1998: fig. 15).

Liu et al. (1998) presented evidence for three ductile deformation events from beach and low cliff outcrops on the southeastern end of the elongate island 3 km south of Bellevue gold mine (AMG 593375). Pillow structures in metabasalt (Liu et al. 1998: fig. 7) were flattened in earliest recognisable deformation ($D_1$). $S_1$ is steep to vertical and trends to the north-northeast. The flattened pillows are overprinted by the strong regional deformation ($D_2$) that produced the prominent steep, north-trending cleavage ($S_2$). Sinistral shear sense is indicated by the asymmetric shape of pressure shadows around plagioclase phenocrysts (Liu et al. 1998: fig. 13). Folding during $D_3$ resulted in formation of upright folds (e.g. felsic porphyry dyke exposed in the northeastern part of the island, Liu et al. 1998: fig. 12), and a spaced axial planar $S_3$ crenulation cleavage, which overprints the earlier $S_2$ cleavage formed by mineral segregation (Liu et al. 1998: fig. 14).

North of Mount Goode at AMG 599502, the sequence includes strongly foliated metabasaltic rocks and quartzofeldspathic schist with rounded cordierite porphyroblasts and randomly oriented andalusite porphyroblasts (Liu et al. 1998: fig. 11). The foliation in the mafic and quartzofeldspathic schists dips steeply west and trends northeast. The metamorphic grade is upper greenschist to lower amphibolite facies. Immediately to the west, across a fault parallel to the Miranda Fault, however, grey, fine-grained metabasalt (Mount Goode Basalt) is only slightly deformed with a lower (greenschist facies) grade of metamorphism. To the east, the Miranda Fault contact between metamorphosed basaltic rock and the metamorphosed felsic conglomerate is not exposed, but can be located to within 10 m in places. Rocks adjacent to the Miranda Fault are strongly foliated.

### *Miranda and Emu Faults*

The zone between the Emu and Miranda Faults is 1–5 km wide and houses the Jones Creek and Scotty Creek conglomerates that extend north-south for at least 80 km from west of Six Mile Well to west of Lawlers. The faults are poorly exposed, and are mainly inferred from geological and geophysical discontinuities (Fig. 5). The Miranda Fault joins the Waroonga Shear Zone in the south, which serves as the west boundary of the Scotty Creek Conglomerate.

### *Waroonga Shear Zones*

The Waroonga Shear Zone was named by Platt et al. (1978) and recognised as the contact between the granitic gneiss to the west and the Scotty Creek conglomerate to the east. In fact, there appear to be at least three major sub-parallel shear zones (Fig. 5a, Liu & Chen 1998a), including the original Waroonga Shear Zone mapped by Platt et al. (1978). As shown in Figure 5a, the Waroonga Shear Zone links with the Miranda Fault and serves as the west boundary of the Jones Creek and Scotty Creek conglomerates. In detail, the Middle Waroonga Shear Zone appears to link with the Ballard Fault extending from the Menzies–Kalgoorlie area in the south (Liu et al. 2000a, b). The West Waroonga Shear Zone extends north-south for at least 100 km.

In the area of the Waroonga Shear Zone, the West Waroonga Shear Zone, and to the west, there is a large corridor, up to 20 km wide, of highly deformed granitic rocks. The rocks contain an extensively developed foliation (schistosity $S_1$) and extend farther north of the shear zones, where the $S_1$ foliation was folded by $D_2$.

The West Waroonga Shear Zone has an arcuate geometry convex to the east (Fig. 5a, Liu et al. 2000b). Along its northern arm, the geometrical relationship between the shear zone and foliation indicates a sinistral movement. Along its southern arm, however, dextral movement has been reported (Platt et al. 1978). A gravity anomaly high extends from the greenstone in the east, across the Waroonga Shear Zone and West Waroonga Shear Zone, to the area of gneissic granitoid in the west, and is interpreted to indicate abundant greenstone below the granitoid. This and the convex-to-the-east trace of the shear zones suggest that it dips to the west. The opposite movement senses along its northern and southern arms indicate an eastward differential thrusting. Interpreted thrust duplexes suggest westward thrusting along the Eleven Mile Fault (Liu et al. 1996). The opposite movement along the Waroonga Shear Zone and the Eleven Mile Fault is considered to be due to east–west-directed compressional deformation during $D_2$.

Farther south, the Waroonga Shear Zone appears to join the Ballard Fault (parallel to the Ida Fault) from the Menzies–Kalgoorlie region (Fig. 1, Liu & Chen 1998b). The Ida Fault has been considered to be a major tectonic boundary between the Southern Cross and the Eastern Goldfields provinces (Swager et al. 1995). Taking this into consideration, the Waroonga Shear Zone, and the Miranda, Emu, and Erawalla faults may be the boundary between the two provinces in the SIR SAMUEL and WILUNA areas. The Yakabindie greenstone belt, therefore, may belong to the Southern Cross Province, with the Jones Creek Conglomerate deposited along province boundary faults. Farther north in the WILUNA area, the Erawalla Fault separates the Coles Find greenstone belt in the west from the Wiluna greenstone belt in the east.

Alternatively, the boundary of the Southern Cross and Eastern Goldfields provinces may extend northward along the Ida Fault in the MENZIES area, to along the west boundary of the Coles Find greenstone belt on WILUNA (e.g. Myers 1997). This is not evident, however, in the 400 m line-spacing aeromagnetic data housed in GA. If the boundary is along this zone, it has been disrupted and concealed by granitic plutons.

## Agnew greenstone belt

The Agnew greenstone belt is faulted against the Mount Keith–Perseverance greenstone belt along the Sir Samuel Fault. It is characterised by several macroscopic folds including the Lawlers Anticline, Mount White Syncline, and Leinster Anticline (Fig. 5a). These folds are separated by faults. In the western part, greenstones are interleaved with the Jones Creek Conglomerate and granitoid in a fault-bounded zone adjacent to the Waroonga Shear Zone.

The Lawlers Anticline is clearly evident on images of aeromagnetic data for LEONORA and SIR SAMUEL. The greenstone sequence is dominated by metamorphosed mafic and ultramafic rocks and contains minor interbedded, fine-grained metasedimentary rocks. Foliation is steep to vertical and trends north-northwest with a consistent north-plunging stretching lineation (Liu 1997). In the SIR SAMUEL area, however, the anticline is poorly exposed beneath lateritic duricrust in the area west of Vivien Well.

The Mount White Syncline is a tight, upright syncline, consisting of metabasalt, medium-grained metagabbro and thin layers of metamorphosed fine-grained sedimentary rocks (Fig. 5a). The metasedimentary rocks are poorly exposed but their distribution is reasonably well established from patterns on aerial photographs and images of aeromagnetic data. The best exposures of the sequence are around Mount White. The Mount White Syncline is structurally higher than the Lawlers and Leinster anticlines. A similar relationship is interpreted for the greenstone sequences.

The Plonkys Well area, west of the Sir Samuel Fault and east of Plonkys Fault (Fig. 5a, Liu et al. 2000a), contrasts with the Perseverance area in that it comprises mainly metabasalt, with subordinate metagabbro and some thin layers of fine-grained metasedimentary rocks that define macroscopic folds. There are few ultramafic rocks in this area, and the overall range of rock types and the structural style are similar to the Mount White Syncline area.

The Leinster Anticline (Fig. 5a) plunges shallowly to north-northwest. The greenstone sequence here is dominated by metamorphosed high–Mg and tholeiitic basalt, komatiite, dolerite and gabbro, and is well exposed in the western limb of the fold. The Halfway Fault separates these rocks from the Lawlers Anticline and Mount White Syncline. Foliation ($S_{2-3}$) on the western limb is steep to vertical and trends north-northwest. A moderate to steep north-northwest plunging $L_2$ mineral elongation lineation is developed in the area south-southeast of Leinster Downs. Greenstones on the eastern limb have been intruded by the Leinster monzogranite. The foliation trends on the eastern limb are to the west-northwest, suggesting that they have been folded by and so predate the formation of the Leinster Anticline. A shallow to moderate south-plunging mineral elongation lineation in the western limb of the fold probably relates to $D_3$ strike-slip movement along the Halfway Fault.

The mafic and ultramafic-dominated sequence in the core of the Lawlers Anticline is interpreted as continuing through the Mount White Syncline into the Leinster Anticline across the Vivien and Halfway Faults (Bunting & Williams 1979, Marston 1984). Thus, the greenstone sequence in the Agnew greenstone belt is interpreted to consist of (1) a mafic (basalt and gabbro) and ultramafic sequence in the lower part, (2) a package of poorly exposed felsic volcanic/volcaniclastic and sedimentary rocks in the middle, and (3) a sequence of basalt and thin sedimentary units with minor gabbro in the upper part.

## Mount Keith–Perseverance greenstone belt

The Mount Keith–Perseverance greenstone belt extends for more than 150 km from Perseverance in the Sir Samuel area to north of Wiluna in the Wiluna area. In the Sir Samuel area, it is bounded by the Perseverance Fault against granitic rocks to the east. Its west boundary is faulted against granitic rocks along the Erawalla Fault to the north, the Jones Creek Conglomerate along the Emu Fault from west of Six Mile Well to west of McDonough Lookout, and the Agnew belt along the Sir Samuel Fault in the south (Fig. 5).

This belt trends north-northwest, parallel to most of the faults and foliation within the belt. Many rocks are strongly deformed and contain a well-defined foliation. Almost all contacts between different rock types are faulted or sheared. Eisenlohr (1992) described the contrasting deformation between the western (Yakabindie) belt and eastern (Mount Keith–Perseverance) belt, i.e. most rocks in the east belt are highly deformed while most rocks in the west belt are little deformed. Locally, however, there are less-deformed areas where primary textures and relationships are preserved as a result of strain partitioning.

The Mount Keith–Perseverance greenstone belt can be divided into two sections along the Six Mile Fault based on greenstone associations and structure. The northern section, from north of Wiluna through Mount Keith to Six Mile Well, has a relatively simple structure and greenstone sequence. Macroscopic folds are largely absent in this section, particularly from Charles Well to Six Mile Well. In the southern section between the Emu–Sir Samuel Faults and Six Mile–Perseverance Faults, however, there are a number of macroscopic folds (Fig. 5a).

### *Perseverance and Erawalla Faults*

The north-northwest-trending Perseverance Fault can be mapped geologically and interpreted from aeromagnetic data for at least 200 km (Figs 1, 3). It is interpreted to constitute part of the Keith–Kilkenny lineament that continues further south with a total length of more than 400 km. The position of the Perseverance Fault in Figure 3 follows Liu & Chen (1998a). This position differs from Martin & Allchurch (1976) and Bunting & Williams (1979), who placed the Perseverance Fault running across the Mount Keith–Perseverance greenstone belt from east of McDonough Lookout to west of Six Mile Well, and continuing further north along the west boundary of the greenstone belt to the WILUNA area.

Liu et al. (1995) named the west boundary fault of the Wiluna greenstone belt as the Erawalla Fault. It continues south to west of Six Mile Well, where it joins with the Emu Fault as the east boundary of the Jones Creek Conglomerate and the newly named Six Mile Fault. The Six Mile Fault continues across the Mount Keith–Perseverance greenstone belt to join the Perseverance Fault east of McDonough Lookout (Fig. 5a, Liu et al. 2000a). The Six Mile Fault has an outcrop expression of quartz veins, and is considered to be a relatively later structural feature than the greenstone boundary faults, such as the Erawalla and Perseverance Faults.

On Sir Samuel, the Erawalla Fault appears to dip steeply to the east, as inferred from foliation east of Cork Tree Flat Well. A shallowly (2–15º) plunging mineral lineation is present in suitable rock types. The greenstone belt in the Mount Keith–Six Mile Well area is very narrow, only about 2 km wide. The gravity data are consistent with the suggestion that the greenstone belt dies out at depth. Considering the structures along, and the opposite dips of the east-dipping Erawalla Fault and the west-dipping Perseverance Fault in the Cork Tree Flat Well–Mount Keith–Six Mile Well area, it is suggested that these two faults underwent significant sinistral strike-slip movement during $D_3$ transpression.

The Perseverance Fault is better termed a shear zone. For example, east of the mapped Perseverance Fault on Sir Samuel, there is a zone of highly deformed granitic rocks varying from 1 to 6 km wide. The zone is a mixture of highly deformed granitoid and granitic gneiss with interleaved amphibolite. Gneissic granitoid is mapped towards the southern boundary of the map sheet. There are also small outcrops of gneissic granitoid east of the Perseverance nickel mine.

In the greenstones west of the Perseverance Fault, a zone up to 1 km wide of amphibolite, which is interleaved with abundant lenses of highly deformed granitic rocks, is commonly developed. West of Mount Pasco foliated and lineated amphibolite (*Abam*), which includes lenses of strongly deformed granitoids (granitic bodies and apllite dykes), has been mapped. Foliation is steep to sub-vertical along the Perseverance Fault.

Several northwest- to north-northwest-trending faults join the Perseverance Fault in the Six Mile Well–Perseverance area. South of Perseverance, for example, are the Sir Samuel, Plonkys, and Eleven Mile Faults. A thrust duplex was interpreted between the Plonkys and Eleven Mile faults and suggests westward thrusting (Liu et al. 1998a), i.e. greenstones were thrusted over granitoids.

Eisenlohr (1992) described two mineral lineations, one plunging steeply to the south-southeast and the other plunging shallowly to the north, in the Mount Keith–Perseverance greenstone belt. The steeply south-southeast-plunging lineation is observed only adjacent (less than 0.5–1 km) to the granite–greenstone boundary, is developed both in greenstones and granitoids, and is a mineral elongation lineation. Rocks near the granite–greenstone contact are characterised by an intense foliation. S–C fabrics and pressure shadows suggest sinistral displacement. Outside the area of intensively deformed rocks along the Perseverance Fault, Eisenlohr (1992) reported a shallow north-plunging lineation, and a sub-vertical north-trending foliation that is present in all but the most competent rock types.

The fault-bounded greenstone area, between the Six Mile Fault and Perseverance Fault, west of Meredith Well (Fig. 5a) consists of strongly deformed amphibolite and fine-grained metasedimentary rocks interleaved with deformed lenses of granitoid, some of which are porphyritic. Fine-grained amphibolite at AMG 634557 developed a strong foliation ($S_2$: 347º/70º SW) with a steep south-plunging $L_2$ mineral lineation (66º→196º). Immediately to the north-northwest (AMG 633560) are $S_2$ foliated amphibolites that were folded into $D_3$ open upright folds with a nearly vertical axial planes and fold hinges plunging 12º to the south-southeast.

In the area ~1.5 km west of Mount Pasco is a north-northwest-trending strip (0.5 km wide and 3–4 km long) of amphibolite (*Abam*) in contact with fine-grained metasedimentary rocks (*Ash*). In the area around AMG 623604 dark grey, fine-grained amphibolite is strongly foliated and often lineated. The foliation is probably a composite $S_{2-3}$ in the form of a closely spaced (<1 mm) cleavage or schistosity. On the foliation is a common steeply north- or south-plunging $L_2$ mineral lineation defined by alignment of fine-grained amphibolite and plagioclase (all < 0.5 – 1 mm). Folded small quartz veins have fold hinges parallel to this steep lineation in amphibolite. At several locations a sub-horizontal crenulation overprints the steep composite $S_{2-3}$ foliation and steep $L_2$ mineral lineation, and is interpreted to have developed during post-$D_3$ deformation.

### *Mount Keith–Six Mile Well section*

This area is generally very poorly exposed with regional geological interpretation and stratigraphic correlation dependent on aeromagnetic data and information from drilling. Previous studies suggest that the ultramafic rocks can be correlated from Six Mile Well, through Mount Keith, to the Honeymoon Well ultramafic complex (Dowling & Hill 1990, 1992, Hill et al. 1995, Gole et al. 1996).

Dowling & Hill (1990, 1992) recognised three packages of ultramafic rocks, Eastern, Central and Western Ultramafic Units, at the Mount Keith nickel mine area. Distinctly different volcanic facies are present within the three major ultramafic units. The Eastern Ultramafic Unit consists of very thick cumulate flow units of dominantly olivine orthocumulates, and is characterised by lenticular bodies of olivine adcumulate-mesocumulate showing similar relationships to those at Six Mile Well (Hill et al. 1995). The Central Ultramafic Unit contains thick cumulate flow units and thin differentiated flow units, and the Western Ultramafic Unit consists primarily of thin differentiated flow units. The major ultramafic units vary in thickness and continuity along strike, dip steeply to the west and young in the same direction. Easterly younging directions have been determined in the Western Ultramafic Unit, to the west of Mount Keith, indicating the presence of a synclinal axis running up the belt. In places, the major units are juxtaposed as a result of faulting (Hill et al. 1995).

The Mount Keith ultramafic complex is underlain by a series of discontinuous thin ultramafic flow units, separated from the main complex of felsic tuffs. The detailed stratigraphy of this part of the section is suggestive of virtually simultaneous bimodal felsic–ultramafic volcanism, with these basal komatiite units representing precursor episodes to the major eruptive event that produced the Mount Keith complex (Hill et al. 1995).

At Six Mile Well there are also three similar komatiite packages separated by volcaniclastic metasediments. The three packages at Six Mile Well can be correlated north through Mount Keith to Honeymoon Well (Dowling & Hill 1990, Gole et al. 1996). The lowermost Unit, the Eastern Ultramafic Unit, contains several mineralised olivine adcumulate lenses. The complex is concordant with the west-facing stratigraphy and has a steep southeasterly plunge (Hill et al. 1995).

The highly magnetised ultramafic units can be used as a stratigraphic marker from the Six Mile

Well area to the Honeymoon Well ultramafic complex and probably further north to the area west of Wiluna. A high–Mg basalt unit, also readily interpreted from the aeromagnetic data, can be used as a second stratigraphic marker from the Wiluna area to the area a few kilometres west of Charlie Well near the north map boundary of SIR SAMUEL (Liu et al. 1995). Using these markers, and aided by interpretation from outcrop mapping, drillhole information and aeromagnetic data, from west to east, five packages of rocks can be depicted from Six Mile Well, through Mount Keith nickel mine, to Charlie Well on SIR SAMUEL.

1. Sedimentary rocks, with some sandstone and conglomerate, that occur along Erawalla Fault that continues to west of Wiluna (Liu et al. 1995).
2. Metamorphosed ultramafic rocks that are more or less continuous to the Honeymoon Well complex and further north to west of Wiluna.
3. Metamorphosed felsic volcanic/volcaniclastic rocks, that may be conformable to ultramafic rocks to the west and high–Mg metabasalt to the east in the area west of Honeymoon Well and Charlie Well (Fig. 5b), although the contacts are not exposed and may have been deformed. The felsic rocks are interpreted to be faulted against the Perseverance Fault in the area from Mount Keith to Six Mile Well.
4. High–Mg metabasalt (Fig. 5b) that does not crop out on SIR SAMUEL but is readily interpreted from aeromagnetic data about 4 km west of Charlie Well and continues onto WILUNA. East of the high–Mg metabasalt are outcrops of tholeiitic metabasalt that is intruded by an oval shape monzogranite pluton south of Charlie Well (Fig. 5b).
5. East of the fault from southeast of Honeymoon Well and west of Charlie Well (Fig. 5b) is a mixed package of metamorphosed basalt and gabbro, foliated basaltic rocks, interleaved foliated granitic rocks and amphibolite. BIF rafts occur in granitic rocks near the Perseverance Fault about 2–3 km northeast of Charlie Well.

The five packages of rocks on SIR SAMUEL are correlated with the Wiluna sequence recognised by Liu et al. (1995) from Wiluna to Mount Way. The Wiluna sequence is overall west-younging. Local east-younging is due to minor folding, probably associated with faults.

Although there is evidence for multiple deformation events in the Mount Keith–Six Mile area (Liu et al. 1995, Gole et al. 1996, Jagodzinski et al. 1999) geological relationships indicate a relatively simple greenstone sequence.

In the Mount Keith nickel mine area, Bongers (1994) reported some $D_1$ structures that include gently southerly dipping chloritic cleavage and folded but originally east-striking veins in ultramafic rocks. Later structures in the Mount Keith–Six Mile area are characterised by a steep north-northwest-trending $S_2$ foliation and a gently plunging lineation in the foliation (Jagodzinski et al. 1999). Shear bands, C–planes, boudins, and vergence of small folds indicate a consistent sinistral sense of shear. Folds in rafts of BIF in the granitoid east of the Perseverance Fault east of Mount Keith are gently plunging, and show a vergence indicating west-block-up, i.e. greenstone (to west) up and over granitoid (to east). In contrast, Eisenlohr (1992) suggested that the eastern granitoid is upthrust over the greenstones to the west. The granite–greenstone contact dipping towards the greenstone belt along the Perseverance Fault as inferred from foliation measurements along the fault is consistent with Jagodzinski et al. (1999). Post-$D_2$ structures include small-scale, steeply-plunging open to isoclinal folds and kink bands (Jagodzinski et al. 1999).

### *Perseverance–McDonough Lookout section*

The geology of the Perseverance–McDonough Lookout area, and for some 15 km further to the north, is different from the Six Mile Well–Mount Keith–Wiluna area. The differences include less metamorphosed felsic volcanic/volcaniclastic rocks, and the presence of prominent 'cherty' ridges of fine-grained siliceous metasedimentary rocks, which define macroscopic folds.

Between the Emu and Six Mile Faults south of Six Mile Well is a syncline defined by metagabbro, tholeiitic and high–Mg metabasalt, and metamorphosed ultramafic rocks including peridotite, komatiite and tremolite schist. Naldrett & Turner (1977) called the structure the 'Serp Hill syncline'. It plunges shallowly to the north-northwest and has a wavelength of about 1.5 km. About 12 km north-northwest of the Perseverance nickel mine around Mount Sir Samuel is an upright regional tight to isoclinal antiform developed in cherty units. The fold axis plunges shallowly (~ 30º) to the north-northwest. It crops out over an area about 1.5 km east-west and nearly 5 km north-south. It is considered to be a $D_2$ fold because on its east limb are earlier small (metre-scale) recumbent $D_1$ folds with east-plunging fold axes

(Liu et al. 1996, 1998).

Felsic volcanic/volcaniclastic rocks appear to be a minor component in the Perseverance–McDonough Lookout area in general, although they are mapped and may be a significant part of the sequence in the area around the Perseverance and Rocky's Reward nickel mines. The greenstone sequence and structural styles correlate well from Perseverance to the area around McDonough Lookout (see also Naldrett & Turner 1977; Bunting & Williams 1979; Marston 1984), and further north to the area between the Six Mile Fault and Emu Fault south of Six Mile Well.

The Perseverance ultramafic complex is a body of amphibolite-facies metamorphosed ultramafic rocks of komatiitic affinity consisting of spinifex-textured flows, layered olivine orthocumulate and mesocumulate and a central body of coarse-grained olivine adcumulate (Barnes et al. 1995). The complex overlies a sequence of thin cumulate flow units that host the Perseverance and Rocky's Reward nickel deposits (Barnes et al. 1988a, Gole et al. 1989). It is overlain by a mixed sequence of highly deformed komatiite, high–Mg basalt, and felsic volcanic rocks, truncated by the Perseverance Fault. The entire sequence is overturned, faces to the east, and dips 70–80º to the west.

Ultramafic rocks in the Perseverance area are dated at ca. 2702–2707 Ma (Hill & Campbell, unpublished data, cited in Libby et al. 1998). Nelson (1997a) reported a 2720 ± 14 Ma age for a deformed felsic volcanic rock 200 m stratigraphically below the ultramafic rocks. The ultramafic rocks in the Perseverance area are correlated with those in the Mount Keith–Six Mile Well section of the greenstone belt, those in the Agnew greenstone belt, and the major ultramafic units dated to be around 2705 Ma in the southern part of the Eastern Goldfields (Nelson 1997b).

Rocks in the Perseverance area have undergone three major deformations (Libby et al. 1997, 1998). $D_1$ produced thrusting and isoclinal and recumbent folding that resulted in top-to-the-north stacking of the greenstone sequence and intercalation of rocks units. $D_2$ marked a change to a regime of east-northeast to west-southwest bulk inhomogenous shortening, and resulted in the development of regional-scale upright folds and intensely deformed zones in which primary lithological layering was transposed. $D_3$ is expressed by the development of laterally extensive north-northwest- and north-northeast-trending strike-slip shear zones and associated folds and thrusts. Despite of the multiple deformation history in the Perseverance area, however, the greenstone sequence there is overall east facing (Hill et al. 1995, Libby et al. 1998).

## Yandal greenstone belt

The north- to northwest-trending Yandal greenstone belt extends for more than 200 km from the south edge of Sir Samuel to the Wiluna area. During the past decade the Yandal belt has emerged as a significant gold-rich mineral province with its gold endowment increasing from ~1 Moz in 1990 to over 14 Moz in 2000 (Phillips et al. 1998b, Phillips & Anand 2000).

The greenstone sequence is difficult to establish for the Yandal greenstone belt because of very poor exposure in most parts of the belt. However, Phillips et al. (1998b) proposed a three-part greenstone sequence for the northern Yandal belt from Jundee to Bronzewing. Their lower sequence refers to the BIF unit along the west margin of the belt in the Jundee–Lake Violet area. A middle sequence refers to the mafic–dominated mafic-ultramafic association, including the locally named "Bronzewing Komatiite", while their upper sequence refers to the dacite-dominated felsic volcanic/volcaniclastic package in the Lake Violet area.

On Sir Samuel, the southern Yandal greenstone belt can be broadly divided into three zones, separated by major north-south faults (Figs 3, 6). The western zone, between the Mount McClure Fault and the Ockerburry Fault Zone, includes a regional north-northwest-trending antiform, the Bronzewing antiform with a wavelength of about 10–15 km east-west and a curved axial trace in the area east of Bronzewing, and Kens Bore granodiorite (Fig. 3). Locally a few hundred metres northeast of Bronzewing, a smaller scale south-plunging 'Hook antiform' forms part of the more complex Bronzewing antiform. Liu & Chen (1998a) interpreted the Bronzewing antiform as a $D_2$ structure, based on regional interpretation and structural observation east of Kens Bore. About 1.8 km east-northeast of Kens Bore (AMG 090589) are some silica cap rocks and fine-grained siliceous and ferruginous metasedimentary rocks near the hinge of the Bronzewing antiform. The metasedimentary rocks are interbedded shale and siltstone and clearly show bedding. Within about 30 m, bedding changes from 063º/75ºSE in the east to 279º/75ºSW in the west. In places an early cleavage ($S_1$) is sub-parallel to the bedding. In others, $S_1$ is vertical at a small angle (< 15º) clockwise from the bedding. Both bedding and $S_1$ are folded by the antiform. The $S_1$ cleavage has also been crenulated probably during $D_3$ (axial plane of crenulations 035º/65ºSE and hinge of crenulations 72º→155º).

The western zone appear to consist of three packages of greenstone:

1. Immediately east of the Mount McClure Fault, in the area north-northwest of Mount McClure, is a 0.5–1.0 km wide zone of dominantly felsic schists. At Mount McClure, and to the south along the Mount McClure Fault, is a mixed sequence of chert units (fine-grained siliceous metasedimentary rocks), and foliated metamorphosed felsic volcanic/volcaniclastic, sedimentary and basaltic rocks.
2. The above sequence is overlain by a large area of mafic-dominated mafic–ultramafic rocks between Mount McClure and the Kens Bore granodiorite. The sequence is east-younging, based on sedimentary structures and differentiation layering in a gabbroic sill. Relationships between sedimentary and mafic rocks displayed in drill core from the Mount McClure gold mines also indicate younging to the east (Westaway & Wyche 1998).
3. A package of felsic volcanic/volcaniclastic rocks in the area between the Paul Well–Tony Well area and Ockerburry Fault Zone, based on limited drill core data and interpretation of aeromagnetic data.

These three packages appear to correlate with those proposed by Phillips et al. (1998b). In this correlation, the Bronzewing komatiite correlates with the komatiitic ultramafic rocks in the Lotus and Cockburn gold deposits, and south of the Kens Bore granodiorite. If this is correct, the Bronzewing to Lotus–Cockburn area may be, structurally, a $D_2$ fold (i.e. the Bronzewing antiform) which refolded a $D_1$ fold. The $D_1$ fold axial trace would be somewhere between Bronzewing and Lotus and Cockburn gold deposits. Alternatively, structural continuity in the Bronzewing to Lotus–Cockburn area may have been disrupted by a major fault, such as the Lotus Fault.

The central zone, the Ockerburry Fault Zone, consists of mostly highly deformed felsic volcanic/volcaniclastic rocks, with some mafic rocks in the south and minor ultramafic rocks in the area about 6 km west of Woorana Soak. This fault zone has a clear linear expression in the magnetic data (Figs 3–4). It appears to die out towards the north boundary of the Sir Samuel map sheet boundary, thus, the eastern and western zones merge.

The eastern zone, between the Ockerburry Fault Zone and the Ninnis and Rosewood Faults, comprises 30–40% of felsic volcanic/volcaniclastic rocks and 60–70% basaltic and doleritic rocks. Based on younging evidence, and structural interpretation, in the Spring Well–Darlot area, it appears that in the east zone is a broad north-northeast-trending $D_3$ synform which overprinted north-northwest-trending $D_2$ folds such as the ones in the Darlot area.

Hill et al. (1990) suggested that the thick komatiite units in the Eastern Goldfields Province represent one short period of extrusive activity. Komatiite is suggested to have formed in a single event around 2705 Ma in the Eastern Goldfields, and can be used as a stratigraphic marker in mapping (Nelson 1997b). If this is true for the komatiitic ultramafic rocks in the Bronzewing to Lotus–Cockburn area, then greenstones in this area may correlate with those in the Darlot area, where a porphyritic rhyolite sample was dated at 2702 ± 5 Ma (Nelson 1997a). Furthermore, if the highly deformed felsic volcanic/volcaniclastic rocks in the Ockerburry Fault Zone correlate with those felsic rocks in the Spring Well–Darlot zone, then the entire southern Yandal greenstone belt may be a complex synclinorium.

### *Mount McClure Fault*

The Mount McClure Fault trends approximately north-south along the western boundary of the southern Yandal greenstone belt. It separates interleaved, deformed granitoid and greenstone of mostly amphibolite facies to the west and dominantly greenschist facies greenstones to the east. Hammond & Nisbet (1992) suggested normal faulting during early extension along the fault that uplifted amphibolite facies rocks into contact with greenschist facies rocks. This view is consistent with observation of a S–C fabric in granitic mylonite west of the Mount McClure Fault that indicates granitoid (west block) upward and greenstone (east block) downward movement.

East of Bogada Bore, a poorly preserved northwest-trending greenstone sequence that includes recrystallised ferruginous and siliceous metasedimentary rocks ("chert"), a thin ultramafic unit and strongly deformed metabasalt may represent the western limb of a shallow southeast-plunging ?$D_2$ antiform (Wyche S., 1995, pers. comm.). The core of the structure is occupied by strongly deformed granitoid rock with a shallow southeast-plunging mineral lineation. At AMG 994286, a shallow southeast dipping $S_1$ foliation (044º/13ºSE) is observed in highly deformed granitoid. The eastern limb may have been sheared out by an interpreted fault west of the Mount McClure Fault. Outcrop through this area is very patchy and a faulted contact between the antiform and the main north trending greenstone belt may be concealed beneath the extensive regolith cover.

In the area north and south of Hartwell Well, an approximately north-south strike, moderate to steep (40–80º) easterly dipping foliation/schistosity ($S_{2–3}$) is commonly developed in several rocks, with or without a steeply south-plunging mineral lineation ($L_3$?). The moderate to steep south-plunging mineral lineation along the fault is consistent with reverse movement along the fault during local compressional deformation (Chen et al. 2001).

## *Cocks–Satisfaction Zone*

The Cocks–Satisfaction Zone, west of the Mount McClure Fault, is a 5–12 km wide zone of highly deformed interleaved granitoid and lenses of greenstone. Deformed granitoid containing lenses of foliated mafic rocks (*Agb*) and interleaved foliated mafic rocks with lenses of felsic rocks (*Abg*) are best exposed west of the northern section of the Mount McClure Fault. These rocks have a distinct north-northwest-trending pattern on aerial photographs and images of aeromagnetic data. The granitic rocks are dominated by medium-grained foliated to strongly foliated and lineated monzogranite, with mylonite developed in places. The greenstones in these interleaved units (*Agb*, *Abg*) are mostly strongly foliated amphibolite. In the south, the zone is poorly exposed and the interpreted geology is almost entirely based on aeromagnetic data (Figs 3–4).

Foliation in both granitoid and greenstone dips moderately to steeply east. However, in places, the foliation is gently dipping (mainly to the south), probably parallel to the original granite–greenstone contact. The foliation is defined by the alignment of biotite and feldspar, and contains a prominent mineral lineation plunging gently to the south and south-southeast. The contact-parallel foliation was locally folded into open, upright folds with hinges plunging 15–20º to the south and south-southeast.

The foliated granitoids in this zone have been mapped as gneiss in previous studies. Bunting & Williams (1979) considered them as orthogneiss. The current study, however, suggests that they are deformed granitoid. A sample from west of the Parmelia open pit indicates a crystallisation age of 2738 ± 6 Ma (Nelson 1998), which probably represent a phase of granitic magmatism earlier than the greenstone formation in the region.

## *Ockerburry Fault Zone*

The Ockerburry Fault Zone is the most prominent among several north- and north-northeast-trending faults in the southern Yandal greenstone belt. It is 2–8 km wide, and about 150 km long, with a Z-sigmoidal pattern clearly indicated in images of aeromagnetic data (Figs 3–4). The rock association in the fault zone appears to be dominantly felsic volcanic/volcaniclastic. At its southern end, it merges with the Perseverance Fault–Mount George Shear Zone in a highly deformed zone a few kilometres wide (Fig. 1). To the north, the fault zone dies out near the map sheet boundary (Fig. 3).

Both sinistral and dextral movement senses have been observed along the Ockerburry Fault Zone (Vearncombe 1998, Chen et al. 2001, this study). The most prominent movement sense indicator is the magnetic pattern of granitoids northwest of Bundarra, east of the southern end of the fault zone (Figs 3–4, Liu & Chen 1998a). Here, an early foliation ($S_1$) has been folded into a north-northwest-trending $D_2$ fold. The $S_1$ foliation on the west limb was dragged into the Ockerburry Fault Zone, indicating dextral shear. However, the overall architecture of the fault zone shows a Z-sigmoidal pattern, which was probably shaped by sinistral movement during $D_3$ transpression. This is consistent with the shallowly plunging mineral lineation and slickenline on a steeply dipping cleavage, together with steeply plunging S-asymmetric folds, suggesting a sinistral strike-slip movement in the Ockerburry Hill area (Chen et al. 2001).

West of Ockerburry Hill, banded chert horizons are interbedded with shale and siltstone (*Ash*). A gently south-dipping, bedding-parallel, slaty cleavage ($S_1$) in shale and siltstone is well preserved around the hinges of upright, north-trending $D_{2–3}$ folds, that have wavelengths ranging from a few centimetres to tens of metres (Fig. 10, Chen et al. 2001). The rocks locally contain a mineral lineation plunging 5–25º to the south and south-southeast. Gently south-dipping thrust surfaces, parallel to the bedding of banded chert, are accompanied by numerous south-plunging slickenlines, and minor normal faults dipping 20º to the north, which indicate a northerly transport direction. This is supported by locally preserved north-verging recumbent folds defined by bedding.

East of the Ockerburry Fault Zone are several north-northeast-trending folds. Three larger ones

A)

B)

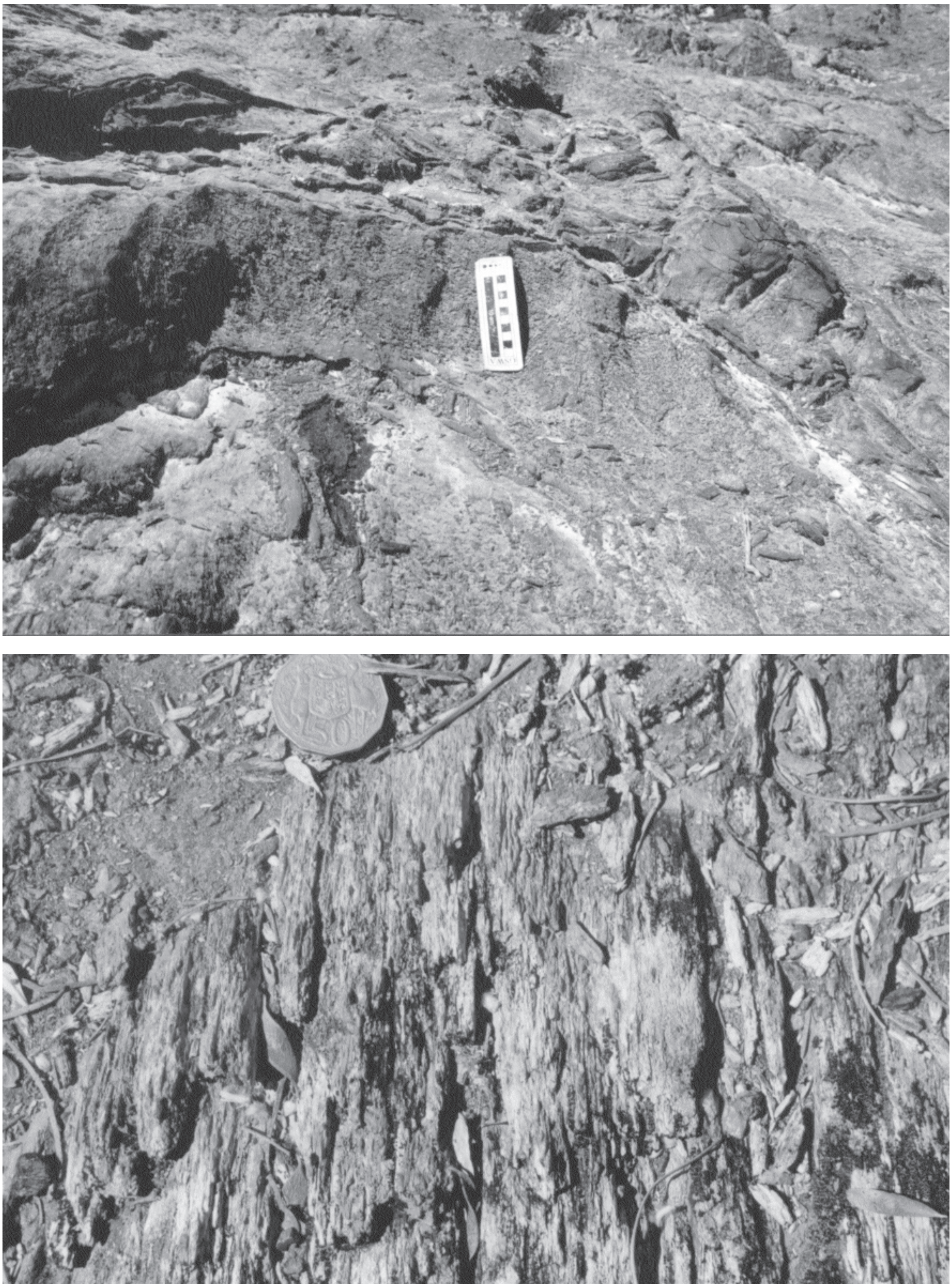


**Figure 10. Photographs of $D_1$ structures in the Ockerburry Hill area: A) Gently dipping $S_1$ slaty cleavage folded by an open $D_2$ fold. Intersection lineation between $S_1$ and $S_2$ plunges 5° to south-southeast. Siltstone interbedded with shale. 4 km northeast of Ockerburry Well. Scale bar is 10 cm (Photograph by S.F. Chen); B) $S_1$ foliation in siltstone folded by an open $D_2$ fold plunging gently (5°) to south-southeast. North of Ockerburry Hill. Diameter of coin is 3 cm (Photograph by S.F. Chen)**

are shown in Figures 3 and 6. The axial traces of these folds are at a large angle (40–50°) to and appear to post-date those of the large scale north-west-trending $D_2$ folds at Bronzewing and Darlot, and are considered to be $D_3$ folds. Chen et al. (2001) relate these folds and the north-northeast-trending faults including the Ockerburry Fault Zone to the development of the Yandal compressional jog during $D_3$ transpression.

### *Ninnis Fault*

The north-northwest-trending Ninnis Fault marks the eastern boundary of the Yandal greenstone belt, and is part of the Celia lineament. In the Sir Samuel area, it splays into several faults in the areas around Mount Grey, Woorana Soak, and Ninnis Well (Fig. 6). The deflection pattern of these faults against the Ninnis Fault suggests significant sinistral displacement along the Ninnis Fault.

#### *Ninnis Well area*

Rocks around Ninnis Well are strongly deformed. In a 1.5 km-wide high-strain zone, adjacent to the Ninnis Fault, amphibolite is interleaved with various schists derived from felsic volcanic, sedimentary and granitoid rocks (Chen et al. 2001). They contain a pervasive foliation ($S_{2–3}$) trending north-northwest (332–345°) and dipping steeply (82–88°) to the west-southwest, parallel to the fault. A steeply plunging $L_2$ mineral lineation (60–85° to SSE) is also present, mainly in amphibolite close to the granite–greenstone contact. A shallowly plunging $L_3$ mineral lineation (25–28° to SSE) is prominent throughout various rock types within the high–strain zone. A pervasive schistosity in a narrow zone of mylonitic monzogranite adjacent to the contact contains a mineral lineation pitching 30° to the south-southeast. The fault pattern and deflection of structural trends in the greenstones, adjacent to the Ninnis Fault, is consistent with sinistral strike-slip displacement (Figs 4, 6). Locally, the shallow $L_3$ lineation overprints the steep $L_2$ lineation.

#### *Woorana Soak area*

In the vicinity of Woorana Soak, the Ninnis Fault is a zone, nearly 1 km wide, of highly deformed rocks including quartz–feldspar schist (*Alf*), amphibolite (*Abam*) and deformed granitic rocks. The quartz–feldspar schist is mostly deeply weathered, often in the form of quartz–clay rock interleaved with some grey shale or quartz–sericite schist. A strong foliation in the form of a schistosity trends north-northwest and dips steeply to northeast to sub-vertical, parallel to the granite–greenstone contact. Schistosity is best developed in the light grey quartz–muscovite schist.

About 200 m west of Woorana Soak, low outcrops of strongly foliated fine-grained mafic rocks contain an intense layering 0.5–2 cm wide (339°/87°NE). About 250 m south of Woorana Soak, in a small north-northwest creek, are outcrops of intensively deformed granitic rocks with a strong foliation ($S_2$: 335°/78°SW) and a stretching lineation ($L_2$: 53°→184°). In the hilly area to the east are rocky outcrops of little or weakly deformed monzogranite. This monzogranite is considered to be the protolith for the intensively deformed granitic rocks in the creek described above.

In the area about 2–3 km north, northeast to east of Woorana Soak, there are several units mapped as syenite (*Ags*), one of which has been dated at 2644 ± 13 Ma (Nelson 1998), consistent with many syenite ages in the Eastern Goldfields.

#### *Mount Grey Fault*

The Mount Grey Fault links the Ninnis Fault and Ockerburry Fault Zone (Fig. 6). Along the granite–greenstone boundary west of Mount Grey is a zone of thinly banded tonalitic, gneissic granitoid that crops out discontinuously for 10 km in a north-northwest-trending zone as part of the Ockerburry Fault Zone. The gneissic rock is very similar to the adjoining granitoid to the east, and is, therefore, considered to be the deformed parts of those units (Stewart A.J., 1999, pers. comm.). In the gneissic granitoid there is a shallow (15–20°), south-plunging mineral lineation. This shallow lineation is probably related to the strike-slip movement of the Ockerburry Fault Zone.

The Ockerburry Fault Zone is around 2 km wide in the area west of Mount Grey, as deduced from the highly deformed rocks in scattered outcrops and as interpreted from aeromagnetic data. In the southern section of Tom's Gossan (silica cap rock after ultramafic rocks, Lyons et al. 1996) at AMG 152586 (GA site 94968954), the hinge of a small fold plunges 18º south. The 'S' vergence of this fold indicates sinistral movement in the fault zone. However, in foliated basaltic rocks about 1 km to the south-southwest at AMG 149576 (GA site 94968951), S–C fabric in schistosity (005º/60ºNW) indicates dextral shearing. At AMG 172619 (GA site 94967732), there are a small exposure and a drillhole into felsic schist with a schistosity of 020º/67ºSE. The rocks here contain a strong stretching lineation (35º→187º). S–C fabric in the schist indicates dextral shearing, which is consistent with the S-vergence of a cm-scale small fold in quartz-rich layer. The hinge of this fold measures 45º→177º (Stewart A.J., 1999, pers. comm.).

It is difficult to comment on these opposite movement senses (sinistral and dextral) because of the lack of timing evidence on these structures in the deformation history of the area. It is possible that the Ockerburry Fault Zone moved in opposite directions during different stages of the history. On the other hand, the wedge-shape greenstone block between the north-northeast-trending Mount Grey Fault and the north-northwest-trending Ninnis Fault (Fig. 6) may have moved southward as an 'escape' block during $D_3$ transpression. This would have resulted in dextral movement along the Mount Grey Fault (see above) and sinistral movement along the Ninnis Fault (Chen et al. 2001). A similar explanation may apply to the opposite movement directions in the Ockerburry Fault Zone described above.

### *Rosewood Fault*

The Rosewood Fault splays off Ninnis Fault and trends south-southeast. The granite–greenstone contact is mapped in the Rosewood Well area (Fig. 6). At this locality, Wyche & Westaway (1996) mapped a prominent fault 200–300 m west of the contact. Along the fault is an approximately 300 m-wide, high-strain zone. Amphibolite is interleaved with intensely foliated monzogranite and later, undeformed granitoid dykes. A prominent foliation ($S_{2-3}$) trends 315–328º and dips 65–84º to the southwest, with a locally preserved $L_2$ mineral lineation pitching 72º to the northwest (Chen et al. 2001). About 50 m northeast of the contact, medium to coarse-grained quartz monzonite is relatively undeformed.

## *The Yandal compressional jog*

Chen (1998) and Chen et al. (1998, 2001) discussed compressional jogs in the north Eastern Goldfields, a structural pattern not previously recognised. According to these authors, a compressional jog is a configuration of stepover strike-slip faults, with a transfer fault that runs diagonally to link the boundary strike-slip faults. One of these jogs is the Yandal compressional jog in the southern Yandal greenstone belt (Figs 3, 6). The other two are the Laverton and Duketon jogs. The compressional jogs are considered to have been finally shaped during $D_3$ transpression (Chen et al. 2001).

The Yandal compressional jog is defined by the north-northwest-trending Perseverance Fault and Ninnis Fault, with the north–south-trending Ockerburry Fault Zone running diagonally within the rhombic southern Yandal greenstone belt (Chen et al. 1998, 2001). East and west of the fault zone there are several approximately north–south-trending faults including the Mount McClure and Gardiner Faults, which are probably also shear zones. The jog is approximately 60 km wide, and can be subdivided into three parts as discussed before. Internal structures within the jog are dominated by north- to north-northeast-trending folds and reverse faults, accompanied by a widespread axial planar foliation.

Both dextral and sinistral movement is apparent on the Ockerburry Fault Zone as discussed earlier. Dextral movement might be associated with $D_2$ compression, while sinistral movement is attributed to strike-slip movement during $D_3$ transpression Chen et al. (2001). The Mount McClure Fault is interpreted to dip moderately to steeply the east. Reverse movement is inferred from the moderately to steeply south-plunging lineation in east dipping foliation.

Three macroscopic folds east of the Ockerburry Shear Zone (Figs 3, 6), are representative of more widespread mesoscopic upright folds in the area (Westaway & Wyche 1998). They are part of a complex north-northeast-trending synclinorium that overprints north-northwest-trending $D_2$ folds within the southern Yandal greenstone belt (Figs 3, 6). Internal arcuate reverse faults are interpreted from aeromagnetic data, parallel to the fold axial traces and main foliation surfaces in the area between the Rosewood Fault and Ockerburry Fault Zone. The deflection pattern of these faults against the boundary Ninnis Fault and the Gardiner and Mount McClure faults against the boundary Perseverance Fault implies that their development is closely related to the sinistral strike-slip on the boundary faults (Figs 3, 6).

## Dingo Range greenstone belt

The Dingo Range greenstone belt has an arcuate geometry convex to the west. North of Dingo Range on Sir Samuel it trends approximately north-northeast onto Wiluna and Kingston. In the Dingo Range area and to the south, it trends approximately south-southeast onto Duketon (Fig. 7).

Contacts between the greenstone belt and granitoids are partly intrusive and partly faulted, with the majority of intrusive contacts sheared during the major deformation events. For example, the eastern contact of the belt north of Mount Harold near the east margin of the Sir Samuel area appears to be intrusive (from aeromagnetic data), however, rocks at AMG 443794 near the contact

**Figure 11. Photograph of isoclinal $D_1$ fold in cherty rocks in the Dingo Range (AMG 433808, coin is 2 cm in diameter)**

are strongly deformed, and mapped as chlorite schist derived from ultramafic rocks (*Aul*).

The Dingo Range consists of two prominent ridges of siliceous metasediments (chert and BIF, mapped as *Ac*). The prominent structure here is the Dingo Range antiform, which extends from the Dingo Range to the Mount Harold area. Bunting & Williams (1979) considered this structure as an anticline, based on the 'northerly dip of bedding around the fold closure in the Dingo Range, parasitic folds in chert bands, northerly plunging mineral elongation lineation associated with axial plane foliation, and facing from pillows and graded bedding in the vicinity of Wonganoo'. However, based on structural data and interpretation of the 400 m line-spacing aeromagnetic data (Fig. 7), Liu & Chen (1998a) interpret this structure as a $D_2$ antiform that folded an earlier recumbent fold ($D_1$). This is consistent with structural observations on the eastern limb of the antiform. Considering the northerly younging evidence in the vicinity of Wonganoo of Bunting & Williams (1979), the current interpretation means that rocks south-southeast of the Dingo Range young to south-southeast towards Mount Harold.

At the eastern end of Dingo Range, in the area around AMG 432811, there is a mesoscopic synform mapped by Lyons et al. (1996). It is about 200 m wide northeasterly and 500 m northwesterly. It plunges shallowly to the northwest. A small isoclinal $D_1$ fold is observed at the southern part of the mesoscopic synform's hinge area (Fig. 11). It is about 10 cm across ($S_0$: 310º/80ºSW, $S_1$: 310º/80ºSW, hinge: 76º→143º) with $S_2$ fractural cleavage nearby, trending north-northwest. At AMG 433809, an $L_1$ intersection lineation ($S_1/S_0$) has been folded around a $D_2$ antiform ($S_2$ axial plane: 321°/85°SW, hinge: 80°→322°; Fig. 12). Small $D_3$ folds (wavelength 10–20 cm) have near vertical axial planes trending about 343º. An $L_3$ intersection lineation ($S_3/S_0$), parallel to $D_3$ fold hinges, plunges at 64°→162°. At several locations, $S_2$ fracture cleavages (sub-vertical, trending north-northwest) crosscut both limbs of the mesoscopic synform (Fig. 13).

The Dingo Range antiform is sheared against the granitoid to the west. In the area between Dingo Range and Red Hill, are several outcrops of felsic gneiss (*An*), sheared granitic rocks (*Ag*) and ultramafic rocks (*Aus*, *Czu*). They develop a nearly vertical, strong foliation trending north-northwest, parallel to the greenstone belt boundary. Part of the eastern boundary of the antiform is also thought to be sheared against granitic rocks. At AMG 442793 are some small outcrops of chlorite schist (*Aul*) after ultramafic rocks in a small creek. These rocks have a well developed schistosity $S_2$ (347º/66ºSW). Fine-grained basaltic rocks (*Ab*), some

**Figure 12. Photograph of folded intersection lineation in cherty rocks in the Dingo Range (AMG 433809, pencil is 14 cm in length)**

200 m to the west, are also foliated. The sheared granite–greenstone boundary is thought to be immediately east of the mapped unit of chlorite schist (*Aul*).

The prominent ridges in the Mount Harold area are mainly light coloured chert (*Ac*) and some BIF. These rocks clearly define a northwesterly plunging antiform. The two limbs appear to have been sheared close to the position of axial plane as revealed from images of aeromagnetic data and exploration drilling. Parasitic folds are mapped on both limbs and plunge steeply northwest (see also Lyons et al. 1996).

At AMG 475678 there is a mesoscopic, $D_2$ parasitic fold of banded chert (*Ac*), with a wavelength about 10 m in outcrop. The axial plane ($S_2$) measures about 326º/64ºSW, however the fold does not develop an axial planar cleavage probably due to the very competent cherty lithology. A narrow-spaced (1–2 mm) fracture cleavage ($S_3$: 352º/80ºNE) crosscuts the fold close to the hinge area.

Felsic schist (*Afs*) occurs between the folded chert unit (*Ac*) immediately north and about 1.1 km northeast of Mount Harold. It appears that the rocks between the folded chert unit are mainly deformed and metamorphosed felsic volcanic and/or volcaniclastic rocks, apart from some chert pebble conglomerates about 1 km northeast of Mount Harold (Fig. 8).

If the structural interpretation for the Dingo Range antiform to be a $D_2$ antiform refolded recumbent $D_1$ fold is correct, then a simple stratigraphic sequence can be speculated. The lower part in the Dingo Range consists of mainly basalt and ultramafic rocks, and some chert and BIF

**Figure 13. Photograph of sub-vertical fractural cleavages in cherty rocks in the Dingo Range (AMG 432809, pencil is 14 cm in length)**

among the lower-most part of the sequence. The upper part of the sequence, in the Mount Harold area, consists of felsic volcanic/volcaniclastic rocks above a chert/BIF layer and minor chert-pebble conglomerate. The felsic volcanic/volcaniclastic and sedimentary in the area north-northwest of Wonganoo may correlate with the felsic volcanic/ volcaniclastic rocks in the Mount Harold area.

## Stratigraphic correlation with the Kalgoorlie and Leonora–Laverton areas

In the Kalgoorlie area, some 400 km to the south, a simple stratigraphy has been described, consisting of (1) a lower basalt unit overlain by (2) a komatiite unit followed by (3) an upper basalt unit and then (4) a felsic volcanic and sedimentary rock unit, which are (5) all unconformably overlain by a clastic sedimentary unit (Swager et al. 1995).

Hallberg (1985) presented a synthesis of the geology in the Leonora–Laverton area immediately to the south and southeast of the SIR SAMUEL area. Although he did not produce a regional stratigraphy, Hallberg (1985) divided rocks in the Leonora–Laverton area into a lower sequence (Association 1) with abundant ultramafic rocks and rare felsic volcanic rocks, and an upper sequence (Association 2) with only rare ultramafic rocks and abundant felsic volcanic rocks.

In the Agnew–Wiluna, Yandal, and Dingo Range greenstone belts, it appears that there is a general trend of (1) predominantly mafic and ultramafic rocks in the lower part of the greenstone sequence, while (2) the upper part is dominantly felsic volcanic/volcaniclastic and sedimentary rocks. This trend is broadly comparable with those in the Kalgoorlie and Leonora–Laverton areas, although in detail, the greenstone sequences are different.

Polymictic conglomerate is present in the Agnew–Wiluna greenstone belt and comparable with similar rocks in the Leonora–Laverton area (e.g. Yilgangi conglomerate) and the Kalgoorlie area (e.g. Penny Dam conglomerate). Such conglomerate is absent in the Yandal and Dingo Range greenstone belts.

## Deformation history

Below is a synthesis of deformation history for the Sir Samuel area (Fig. 3, Table 2), mainly after Liu et al. (1998), Liu & Chen (1998a, b) and Chen et al. (2001).

### First deformation event ($D_1$)

The earliest recognisable structures ($D_1$) include bedding-parallel foliation, tight to isoclinal folds, and faults. They are typically recognised in areas where they are at high angles (e.g. east-northeast-trending) to the regional north-northwest-trending $D_2$ structures, and are often overprinted by the latter. Elsewhere they are difficult to distinguish unless overprinting relationships are available.

Examples of regional $D_1$ structures in the Sir Samuel area include

(a) flattening of basalt pillows near the north shore of Lake Miranda;

(b) east plunging isoclinal fold in chert about 13 km NW of Perseverance (Liu et al. 1996, 1998);

(c) bedding-parallel foliation in shale in the Ockerburry Hill area (Fig. 10);

(d) bedding-parallel $S_1$ foliation and associated tight to isoclinal $D_1$ folds refolded by the $D_2$ Lawlers Anticline (Platt et al. 1978); and,

(e) isoclinal fold refolded by the north-northwest-trending $D_2$ antiform at Dingo Range (Fig. 7).

These $D_1$ structures are similar to those reported elsewhere in the northern Eastern Goldfields, including southwest of Melita (Witt 1994), and recently recognised as $D_1$ structures in the Benalla Hill area (Stewart 1998).

### Second deformation event ($D_2$)

Regional east-northeast–west-southwest–directed orogenic shortening during $D_2$ resulted in the development of prominent north-northwest-trending folds, faults and greenstone belts. Some north-northeast-trending shear zones/faults may be earlier structures reactivated during $D_2$. Regional $D_2$ folds have wavelengths of 5–30 km and are accompanied by upright, axial planar foliation ($S_2$). The steeply dipping $S_2$ foliation is sometimes associated with a steeply plunging $L_2$ lineation (Chen et al. 2001).

The deformation intensity is heterogenous because of rock type differences and strain partitioning. Overprinting relationships between $D_2$ structures and $D_1$ and/or $D_3$ structures are locally preserved. For example, near the north shore of Lake Miranda at the southeastern end of an island 3 km south of Bellevue gold mine, pillows in metabasalt were strongly flattened and aligned in a north-northeast direction (parallel to $S_1$). The flattened pillows were transected by a strong, north-trending and nearly vertical cleavage ($S_2$), which was in turn overprinted by $D_3$ upright folds and $S_3$ spaced axial planar crenulation cleavage trending about 330º.

In some cases a steeply plunging lineation ($L_2$) is developed, which is sometimes locally overprinted by a shallowly plunging $L_3$ mineral lineation, for example along the Ninnis Fault (Chen et al. 2001).

Regional $D_2$ folds and associated $S_2$ axial planar foliation can be correlated across Sir Samuel, as well as the entire north Eastern Goldfields Province in terms of their style, scale, orientation, and timing of associated granitoid emplacement. Using $D_2$ folds, and particularly $S_2$ foliation, as reference structures, earlier or later structures in different areas can be identified, but with difficulties due to the lack of overprinting relationships in some cases. Correlation of earlier and later structures in different areas may be problematic as it is not known if they developed at the same times.

Some $D_2$ faults and shear zones show evidence of reverse movement, for example, along the Perseverance and Ninnis faults. Some dextral movement observed along the north-northeast sector of the Ockerburry Fault Zone might have occurred during $D_2$, which was responsible for dragging $S_1$ foliation into the fault zone east of its southern termination.

The Jones Creek Conglomerate formed post-$D_1$ and probably early syn-$D_2$. The conglomerates were deformed in late $D_2$ and contain the regional $S_2$ foliation.

**Table 2. Structural and metamorphic history of the Archaean granite-greenstones on the SIR SAMUEL 1:250 000 sheet area**

| | *Major features* | *Metamorphism* | *Comments* |
|---|---|---|---|
| Post-$D_3$ | East-trending normal faulting and fracturing; Subhorizontal crenulations | Some faults and fractures filled with quartz veins and metasomatic alteration involving growth of amphibole | Small granitoid bodies intruded post-$D_3$ |
| $D_3$ | Regional transpression resulted in N-, NNE- to NE- trending folds, faults and shear zones predominantly within local compressional areas defined by NNW- trending sinistral strike-slip regional faults | Greenschist facies recrystallization mainly in shear zones, local retrogression | Shaped crustal architecture of granite–greenstones; 2640 ± 5 Ma |
| $D_2$ | Regional ENE-directed compression produced dominant NNW-trending folds, wide-spread axial planar foliation, and regional scale reverse faults associated with deposition of polymictic conglomerates in compressional basins, and emplacement of granitoids | Peak metamorphism late during or post-$D_2$; Randomly oriented andalusite porphyroblasts; Major regional greenschist facies, local amphibolite facies | ENE-directed compression produced much of the crustal architecture of the granite–greenstones; Major phase of granitoid intrusion pre- to syn-$D_2$; 2660–2670 Ma |
| $D_1$ | Tight to isoclinal folds, bedding sub-parallel foliations and faults, commonly recognised at high angles to regional $D_2$ NNW-trending structures | ? low- to medium grade regional | Intrusion of granitoids comagmatic to late stages of felsic volcanism; ~ 2685 Ma |
| pre-$D_1$ | Deposition of main greenstone succession | | Volcanic-associated Ni mineralization |

## Third deformation event ($D_3$)

$D_3$ is a transpressional deformation event, apparently progressive from the orogenic compression during $D_2$. It resulted in the development of regional north- to northeast-trending folds, faults, and shear zones. Some north- to northeast-trending structures were initiated in $D_3$, but others may be reoriented earlier structures (Chen et al. 2001). The north- to northeast-trending $D_3$ structures were predominantly situated in local compressional areas, including

(a) within newly recognised compressional jogs (e.g. Yandal compressional jog) defined by north-northwest-trending, sinistral strike-slip faults or shear zones (Chen 1998, Chen et al. 2001), and

(b) wedge-shape areas defined by north- to north-northeast-trending and north-northwest-trending regional faults, e.g. in the area south of Mt Grey, and in the Melita area (Witt 1994, Liu & Chen 1998a).

Similar north- to northeast-trending structures developed in $D_3$ are also reported in fault termination areas of regional north-northwest-trending faults, e.g. in the Kilkenny area (Chen 1998, Chen et al. 1998, 2001). In some cases the upright foliation may be a composite $S_{2–3}$ foliation, but locally preserved overprinting evidence (e.g. near north shore of Lake Miranda) suggests that $D_3$ was a separate deformation event.

The north-northeast-trending Ockerburry Fault Zone merges with the north-northwest-trending Perseverance and Ninnis Faults. East and west of the Ockerburry Fault Zone are several north- to north-northeast-trending faults, the current geometry of which were also shaped during $D_3$. Several north-northeast-trending folds with wavelengths of 0.5–1 km east of the Ockerburry Fault Zone were probably developed during $D_3$. The sigmoidal geometry of the Koonoonooka monzogranite between the Perseverance and Gardiner faults and the Z-sigmoidal pattern of the several regional faults between the Perseverance and Ninnis Faults were finally shaped by the $D_3$ transpression.

## Post-$D_3$ deformation

Post-$D_3$ structures are dominated by east-trending normal faults and fractures. Some of the faults displace north-northwest- to north-northeast-trending $D_2$ and $D_3$ structures, greenstone belts and gold-bearing veins. Some structures are filled with mafic–ultramafic dykes of probable Proterozoic age. Kink folds and sub-horizontal crenulations that post-date $D_3$ structures occur in many locations. However, their relationship with the post-$D_3$ faults is not clear.

## Metamorphism

There is evidence for three phases of regional metamorphism in the Sir Samuel area. The earliest recognisable metamorphic event is that associated with the development of $D_1$ fabrics (foliation and lineation). Evidence for this event is only locally preserved, so it is not possible to estimate the extent of this event. The metamorphic grade during this event is in the range of greenschist to amphibolite faces as deduced from the relict fabric in shales and relict amphibole crystals of an early fabric that were overprinted by $S_2$ foliation.

The most prominent metamorphic event is the regional metamorphism associated with $D_2$ orogenic compression and emplacement of voluminous granitoids (mostly monzogranite). This is evident in the low- to medium-grade (greenschist to amphibolite facies) metamorphism in all greenstones that accompanied the development of cleavages ($S_2$) axial planar to $D_2$ folds and the schistose rocks along shear zones. Amphibolite facies metamorphism is mostly restricted to near (up to 1–2 km) granite–greenstone contacts where amphibolite commonly develops a foliation and mineral lineation. Further away from the contact, the metamorphic grade is commonly low grade, to greenschist facies assemblages.

Cordierite porphyroblasts and randomly oriented andalusite porphyroblasts from north of Mount Goode suggest that the highest temperatures (peak metamorphism) were reached after development of the prominent cleavage, some time either late during or after $D_2$, but prior to $D_3$. $D_3$ caused some retrogression and the development of strong fabrics in regional-scale ductile faults such as the Waroonga Shear Zone, Perseverance Fault and Mount McClure Fault.

Peak metamorphic conditions were about 550ºC and 3 kb in the Perseverance mine area (Gole et al. 1987). Komatiites have been metamorphosed to olivine–tremolite–chlorite–cummingtonite assemblages, with enstatite, anthophyllite, talc, and prograde antigorite in the more magnesian rocks, depending upon metamorphic fluid composition. Retrogression of metamorphic olivine to serpentine is common.

Regional metamorphism, particularly that during $D_2$ orogenic compression, is largely a contact metamorphism on a regional scale, with the highest metamorphic grade (amphibolite facies) almost always along granite–greenstone boundaries. This suggests that granitic magmas contributed much to the heat budget of regional metamorphism in the region. Metamorphic events during $D_1$ and $D_3$ may also be related to granitoid emplacement. The close association of regional metamorphism and granitoid emplacement is consistent with the suggestion that granitoids were the heat sources for regional metamorphism (Binns et al. 1976, Archibald et al. 1981, Hill & Campbell 1993).

# Proterozoic geology

Proterozoic rocks, other than dykes, only crop out in the southwest part of the Sir Samuel area, i.e. in the DEPOT SPRINGS sheet area. In the area north of the Langford Well, there are Proterozoic flat-lying polymictic conglomerate and arkosic sandstone and mudstone of the Kaluweerie Conglomerate (*PKc* and *PKs*). Some thin, linear mostly east-west features that cut across the regional geological trends in the aeromagnetic data have been interpreted as Proterozoic mafic dykes (*Pdy*) because of their similarity to the aeromagnetic patterns of Proterozoic dykes in other parts of the Eastern Goldfields. Although locally exposed as ridges, such as in the granodiorite unit south of Daylight Well in the southeast corner of Sir Samuel, the majority of dykes are covered by surficial deposits. The dykes are mainly fine- to medium-grained dolerite and gabbro, although range in composition from pyroxenite, through gabbro norite, to granophyre.

Present exposure of the Kaluweerie Conglomerate forms an east-trending belt 15 km long by 1.5 km wide, and is described in detail by Allchurch & Bunting (1976). The maximum exposed thickness is 25 m (Bunting & Williams 1979), although in drillholes 10 km west of Kaluweerie Hill the conglomerate is 35 m thick. Two lithological units are mapped, polymictic conglomerate (*PKc*) and arkosic sandstone and mudstone (*PKs*). The conglomerate generally forms a lower unit, whereas the mudstone is dominant in the upper unit. Important features are the high proportion of mechanically unstable clastic grains (e.g. carbonate, epidote, chlorite, amphibole, and felsic lava) in the sand fraction, and the variety of igneous and metamorphic rock types in the conglomerate. Bedding structures in both the conglomerate and mudstone are poorly developed. Allchurch & Bunting (1976) consider the sequence to be locally derived from the west, possibly in a partly confined channel or as a valley-fill deposit.

# Palaeozoic geology

## Permian sedimentary rocks

### *(PAf, PAg, PAl)*

Three areas of clastic sedimentary rocks interpreted as Permian in age occur on SIR SAMUEL: in the Barr Smith Range in the northwest, ~6 km northeast of Yandal in the central east, and in the area around Ockerburry Hill in the southeast. These rocks have been correlated with the Paterson Formation of the Officer Basin (MacLeod 1969, Lowry et al. 1972, Bunting & Williams 1979).

The most extensive exposures are around Ockerburry Hill where a Permian sequence is locally well-exposed (Westaway & Wyche 1998). Away from the Ockerburry Hill, the Permian is typically represented by float of mainly granitoid boulders, which are probably erosional remnants of a tillite unit. Recent mineral exploration drilling in the southwest suggests that there may be more extensive Permian sequence under Cainozoic cover in the vicinity of the Ockerburry Fault.

Polymictic conglomerate (*PAg*) occurs mainly as a boulder float on low, rounded hills. Clasts can be more than a metre across, and are commonly faceted. Most are composed of granitoid and include foliated, massive, porphyritic and non-porphyritic varieties. Other clasts are composed of felsic and mafic volcanic rock, metasedimentary rock including BIF and chert, and vein quartz. The conglomerate appears to overlie a fine- to medium-grained, poorly sorted, medium-bedded, immature, quartz-rich sandstone but the relationship is not clear in outcrop (Westaway & Wyche 1998). There is a disconformity between the conglomerate and the overlying, thinlybedded claystone and siltstone unit. The poor sorting, faceting of the clasts, and wide variety of clast types, none of which are found in outcrop in the surrounding region, suggest that the source for the conglomerate is remote and the conglomerate is probably a glacial deposit.

Claystone and siltstone (*PAl*) disconformably overlie the conglomerate and have been described by MacLeod (1969). The succession consists of thinly bedded to laminated siltstone overlain by well-bedded sandy claystone, mudstone, and siltstone. The total thickness is about 50 m. An outcrop 2.5 km east-southeast of Ockerburry Hill (AMG 116168) contains well-developed, ribbon-like, sinuous trace fossils in bedding planes; scattered, monaxon-type sponge spifules; and fragments of an organism with regular rows of very fine nodules (10 rows to 1 mm). These fragments may represent decalcified moulds of a thin, sheet-like bryozoan. This fossil assemblage suggests that the rock is younger than early Ordovician, and is consistent with a Permian age (Webby B.D., 1996, pers. comm., cited in Westaway & Wyche 1998). The lower part of this unit contains distinctive and spectacular Liesegang banding and is known as ‘Weebo Stone’ (MacLeod 1969).

Loose, rounded cobbles of mainly undeformed fine- and coarse-grained granitoid, together with lesser amounts of vein quartz and metasedimentary rocks overlie Archaean rocks 7–8 km north-northwest of Mount McClure (AMG 977466). The cobbles range in size from 4 to 30 cm, but are generally 5–10 cm across. Some of the cobbles have flat surfaces that have been interpreted as glacigene facets. Bunting & Williams (1977, 1979) correlated these isolated sedimentary rocks and scree outcrops, along with more substantial, essentially flat-lying, sequences elsewhere in the SIR SAMUEL area, with Early Permian fluvioglacial rocks of the Paterson Formation of the Officer Basin.

Sandstone, pebbly to boulderly siltstone, and conglomerate (*PAf*), also of the Paterson Formation, occur in northwest on the YEELIRRIE 1:100 000 sheet (Champion & Stewart 1998). These rocks largely comprise mostly strongly kaolinised, and locally silicified, fine to granular quartz sandstones, with local quartz pebbles from 1 to 5 cm wide. The sandstones are crudely horizontally laminated, and are mostly poorly sorted, becoming better sorted higher in the sequence. Grains are sub-angular to sub-rounded. Beds non-conformably overlie Archaean granitoids, with irregular contacts and infilling of original granitoid topography. The sandstones generally form thin (1–5 m) sequences that are topographically expressed as flat, commonly treeless, ‘terraces’. These have been interpreted as Permian, although may, indeed, be younger.

# Cainozoic geology

The SIR SAMUEL area is dominated by a relatively stable, ancient landscape, developed on deeply weathered rocks, mostly Archaean. Consolidated and unconsolidated Cainozoic regolith units are widespread. Most of these units have been developing since the Tertiary, and include a veneer of unconsolidated Quaternary material. The type of Cainozoic unit, including its distribution and thickness are closely related to the landform and the source material. For example, ferruginous units are common in areas of greenstone. The Cainozoic units in the Sir Samuel area can be broadly classified into four categories: residual, proximal, distal, and active alluvial systems.

Residual varieties developed on pre-existing weathered rock and include ferruginous lateritic duricrust (*Czl*), silica caprock developed over ultramafic rocks (*Czu*) and silcrete over granitoid (*Czz*). Duricrust units over mafic greenstones (*Czl*) are commonly ferruginous with a reddish-brown to black colour, while those on granitoid (*Czz*) are usually silica-rich and paler in colour. The latter varies substantially in thickness, often occurring with kaolinised granitoid (*Czzg*).

Proximal units include colluvial deposits developed on slopes and low hills and regions around these features. They include degraded lateritic duricrust and massive ironstone rubble (*Czf*) in iron-rich source areas; areas of deeply weathered granitoid (*Czg*); quartz vein rubble and debris (*Czq*); and colluvial deposits of gravel and sands as sheetwash and talus (*Czc*).

The more distal colluvial deposits contain significant clay and fine sand and can form extensive sheetwash fans (*Cza*). Extensive sandplains (*Czs*) are dominated by unconsolidated red, quartz-rich sand and typically overlie granitoid rocks. Where dunes are present, they are stable and well vegetated with spinifex and a variety of small trees and shrubs. A degraded duricrust surface formed on deeply weathered granitoid rocks has been observed beneath the sandplain in several areas, e.g. at Leinster townsite.

Deposits of saline and gypsiferous evaporites, clay and sand (*Czp*) occur in Lake Miranda and Lake Darlot. Sand, silt, clay and gypsum (*Czd*) form stabilised dunes in and around the lakes. Calcrete (*Czk*) crops out around Lake Miranda, in the lake system southeast of Yeelirrie, and in the northeast part of Lake Darlot in the Sir Samuel area. It also developed in the alluvial valley east of Lake Miranda, and in the broad drainage valley south of Mount McClure. Silt, sand and gravel in halophyte flats adjacent to playas (*Czh*) are mapped in Lake Maitland in the northwest. Kopi (*Czy*) – lithified gypsum and clay in mounds and dunes – are mapped in the lake area northeast of Yakabindie. A large area of sand plain (*Czsv*) occupies an alluvial valley adjacent to and east of Lake Miranda. This material and the associated lake deposits define the channel of the Carey Palaeoriver (Hocking & Cockbain 1990).

The drainage basin associated with the Darlot lake system contains areas of calcrete (*Czk*), and eolian and alluvial sheets and dunes made up of sand, silt, and clay (*Czb*). These deposits are cut by both ancient and present drainage channels resulting in a strongly reticulated land surface, leaving a series of mounds, typically only a few metres high, covered in dense vegetation. These remnant mounds produce a distinctive pattern that is clearly visible on aerial photographs and satellite images. This pattern has a west-northwesterly trend, and is most evident in the area south of Lake Darlot. Scattered throughout the *Czb* units are numerous small claypans of which only the larger bodies have been delineated.

Alluvial deposits (*Qa*) occur along active fluvial channels and on floodplains. Small claypans (*Qac*) may be part of the active system.

# Economic geology

Sir Samuel is a major mining centre in the northeastern Yilgarn Craton. Resources in the area include nickel, gold, silver, copper, corundum, and tin (Table 3). Gold and nickel are the major mining activities in the area, principally from several mining centres: gold – Bronzewing, Mount McClure, Darlot–Centenary, Bellevue, New Holland–Genesis; nickel – Mount Keith, Leinster (includes Perseverance and Rocky's Reward) and Cosmos. Several uranium prospects associated with valley-fill sediments of the palaeodrainage system are reported on Sir Samuel. Minor base metal prospects have been identified in the Agnew–Wiluna greenstone belt.

## Gold

Gold has been mined from the Sir Samuel area since the 1890's from centres within the Agnew and Mount Keith–Perseverance greenstone belts and, more recently, from the Yandal greenstone belt, e.g. Bronzewing, Mount McClure and Darlot–Centenary. The combined identified resources at publication date are estimated at about 400 t of gold (GA's OZMIN database, Table 3).

Prior to the late 1980s, the Yandal greenstone belt was largely neglected for gold exploration probably due to the limited exposure and poor understanding of the geology of the belt. In 1986, Minsaco Resources recognised the Yandal belt to be closely akin to gold-prospective greenstone belts

**Table 3. Mineral commodity statistics for the Sir Samuel 1:250 000 sheet area (from GA's OZMIN database as of April 2000)**

| *Deposit* | | *1:100k sheet* | *Easting* | *Northing* | *Status* | *Production to (t)* | | *Remaining resource (t)* | | *Grade (g/t***)* | *Total (t)* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bellevue | Au | 3042 | 258 900 | 6940 200 | Closed | 25.360 | Mar 1997 | | | | 25.360 |
| Bronzewing | Au | 3143 | 302 300 | 6969 000 | Operating | 27.149 | Dec 1998 | 23 280 000 | | 3.9 | 117.941 |
| Centenary | Au | 3142 | 330 500 | 6923 100 | Operating | | | 8 400 000 | | 7.7 | 64.680 |
| Cosmos | Co | 3042 | 260 500 | 6944 500 | Deposit | | | 401 000 | measured | .12% | 480 |
| Cosmos | Cu | 3042 | 260 500 | 6944 500 | Deposit | | | 401 000 | measured | .36% | 14440 |
| Cosmos | Ni | 3042 | 260 500 | 6944 500 | Deposit | | | 401 000 | measured | 8.2% | 32880 |
| Darlot | Au | 3142 | 329 400 | 6914 000 | Operating | 18.546 | Dec 1998 | 11 852 000 | combined | 4.56 | 72.591 |
| Genesis | Au | 2942 | 253 700 | 6902 400 | Closed | 1.358 | Jan 1998 | 668 000 | measured & indicated | 2.6 | 3.095 |
| Lake Maitland | U | 3143 | 310 100 | 6993 700 | Deposit | | | 11 600 000 | estimated | .05% | 5800 |
| Leinster* | Ni | 3042 | 273 800 | 6920 600 | Operating | 327791 | Dec 1998 | 246 300 000 | measured, indicated & inferred | .73% | 2125781 |
| Mt Keith | Ni | 3043 | 256 700 | 6985 600 | Operating | 147094 | Dec 1998 | 516 800 000 | combined | .56% | 3041174 |
| Mt McClure** | Au | 3043 | 295 100 | 6965 400 | Operating | 18.682 | Dec 1998 | 17 138 000 | combined | 1.84 | 50.216 |
| New Holland | Au | 2942 | 253 700 | 6901 700 | Closed | 3.116 | Jan 1997 | 8 454 400 | measured & indicated | 7.12 | 63.311 |
| Yakabindie | Ni | 3043 | 260 300 | 6963 800 | Deposit | | | 214 700 000 | measured & indicated | .51% | 1094970 |
| Yellow Aster | Au | 3042 | 259 800 | 6954 500 | Closed | 1.700 | Jan 1997 | | | | 1.700 |

**NOTES:** * Leinster includes Perseverance & Rocky's Reward Ni mines; ** Mt McClure includes Lotus, Cockburn, Success, Permelia, Challenger & Dragon Au deposits; *** Grade unit is g/t unless indicated otherwise

elsewhere in the Eastern Goldfields Province. In the following few years, there was accelerated exploration in the Yandal belt, resulting in the discovery of several major gold deposits including Jundee–Nimary, Bronzewing, the Mount McClure deposits (including Lotus, Cockburn, Success, Parmelia, Challenger, and Dragon), and Centenary.

All greenstone sequences host gold mineralisation, with only minor gold reported from the granitoid-gneiss domains between the greenstone belts. Gold is found in a range of host rocks, including Fe-rich tholeiitic basalt, differentiated dolerite, metasedimentary rocks and conglomerate, and felsic porphyry dykes. Gold mineralisation is structurally controlled and probably introduced late in the evolution of the Archaean granite–greenstone terrains (Phillips et al. 1998b, Vearncombe 1998, Phillips & Anand 2000). The majority of deposits show similar features to gold deposits elsewhere in the Eastern Goldfields Province and have collectively been described as 'late-orogenic structurally controlled' (Witt & Vanderhor 1998) or 'orogenic' (Groves et al. 1998) gold deposits. Many of the deposits have exploitable lateritic gold mineralisation in regolith above primary mineralisation (e.g. Bronzewing). The discovery of some deposits, particularly in the Yandal greenstone belt, is largely the result of advances in remote sensing and regolith sampling and analysis (Phillips & Anand 2000). Placer gold deposits are rare on Sir Samuel and, where recognised, are closely associated with known lateritic or primary mineralisation.

## Bronzewing gold deposits

The Bronzewing gold deposits occur west of the north-northwest-trending Bronzewing antiform (Fig. 6), were discovered by RAB drilling in 1992 and include three zones: Western, Central and Discovery (Phillips et al. 1998a). Locally the deposits lie several hundred metres southwest of the Bronzewing komatiite-defined, north trending Hook antiform. Structurally, the deposits are in north- or north-northeast-trending shear zones. The Western zone is in a north-northeast-trending shear zone just west of the Bapinmarra dolerite sill. The Central and Discovery zones are within 100–300 m east of the sill in north-trending shear zones linked by subsidiary shears. Locally, however, anastomosing pattern of shear zones resulted in intra-shear pods of less deformed rocks. Greenstone in the mine area is dominated by west-younging tholeiitic basalt with sporadic pillow structures and thin sills (Phillips et al. 1998a). In the Bronzewing area, the mineral assemblage (i.e. actinolite–plagioclase) indicates peak metamorphic conditions below the amphibolite–greenschist facies boundary.

A broad, well-defined, alteration halo surrounds the Bronzewing gold deposit (Phillips et al. 1998a). Unaltered rocks have an actinolite–plagioclase assemblage. The halo comprises an outer zone of chlorite–calcite alteration, followed inwards by a zone of ankerite–biotite alteration and a zone of muscovite–pyrite alteration proximal to mineralisation. Gold occurs in quartz veins in mafic schist where the shear zones converge and diverge (Phillips et al. 1998a).

There appear to be multiple phases of gold mineralisation at Bronzewing. Isoclinal folding of the mineralised quartz vein of the Western zone suggests ductile deformation after mineralisation. However, Phillips et al. (1998a) consider that the major mineralisation in the Bronzewing area is superimposed upon north-trending ductile shear zones. Orebody outlines and boundaries are influenced by brittle northeast- and east-southeast-trending cross faults and fractures.

## Mount McClure gold mining centre

The Mount McClure mining centre consists of six deposits localised along a zone of about 25 km, i.e. Lotus and Cockburn localised along a fault passing north of Anxiety Bore, and Success, Parmelia, Challenger, and Dragon localised west of the Mount McClure Fault. The deposits were discovered between 1987 and 1990, with production from 1992 to 2001. The geology of these deposits is summarised in Otterman & Miguel (1995) and Harris (1998).

Lotus and Cockburn deposits occur along a major north-northwest-trending shear zone, the Lotus Fault (Liu et al. 2000a). The fault consists of several step-over faults that tend to follow particular rock units and contacts. The greenstone sequence comprises an overturned, east-younging, metamorphosed rock package from basal ultramafic rocks, through tholeiitic basalt and basaltic tuff, to andesitic and dacitic tuff and lava. These rocks are interbedded with sulphidic cherty tuff and some clastic sedimentary units (Harris 1998).

Gold mineralisation occurs in a variety of rock types in the Lotus and Cockburn deposits. In the southwest part of the Cockburn deposit, higher-grade gold mineralisation is associated with a massive sulphide-chert horizon and within metakomatiite. In the northeastern part of Cockburn, however, significant gold mineralisation is found in metamorphosed dolerite and felsic rocks. At Lotus, gold mineralisation is hosted by dolerite, mafic and felsic volcanic rocks. Gold occurs in quartz–carbonate–chlorite veins, which are commonly tightly folded but sub-parallel to foliation. At Cockburn, however, gold is associated with a stockwork of irregular quartz–carbonate ± chlorite veins. Bismuth minerals, galena, molybdenite, and scheelite occur in the veins with highest gold grades. Pervasive chlorite–biotite–carbonate alteration is common in strongly mineralisation zones. At both Lotus and Cockburn, zones of epidote veins, accompanied by pervasive hematite alteration, occur in all rock types and are interpreted to be unrelated to gold mineralisation. Late-stage quartz–calcite–chlorite–sulphide veins are associated with strong carbonate–chlorite alteration.

The other four deposits (Success, Parmelia, Challenger, and Dragon) lie about 2–3 km east of the Mount McClure Fault. Success, Parmelia and Challenger are at the same stratigraphic horizon of strongly foliated, weakly- to moderately-graphitic felsic cherty tuff, which is overlain by a foliated, fine-grained, chloritic metasedimentary rocks (Harris 1998). Metabasalt units and thin metadolerite intrusions are also present. The footwall is a strongly foliated, metamorphosed dacitic felsic volcanic/volcaniclastic rock. Gold mineralisation is associated with numerous quartz (with minor carbonate–chlorite) veins to 10 cm thick, sub-parallel to the foliation. The veins are commonly boudinaged and/or folded. Disseminated pyrite–arsenopyrite (<10%) and trace to minor chalcopyrite–sphalerite are associated with the mineralisation zone, which shows moderate to strong biotite–chlorite–carbonate–sericite metasomatic alteration.

The Dragon deposit is hosted by rocks slightly higher in the east-facing stratigraphic succession (Harris 1998). Upper greenschist to amphibolite facies metamorphism and strongly developed foliation have largely destroyed the primary rock textures. The structurally and inferred stratigraphic footwall unit is a tholeiitic basalt. Breccias and carbonate alteration are common in the southern part of the deposit. In the north of the deposit, the basalt unit has been mylonitised, then annealed to form a crudely laminated, coarse-grained rock with abundant diopside. Overlying the footwall unit is a coarse-grained, ultramafic schist (interleaved with bands of graphitic schist) comprising talc, chlorite, carbonate, anthophyllite and phlogopite, to 25 m thick, that is the main host for gold mineralisation. The hangingwall sequence comprises basalt and dolerite. Gold mineralisation is mainly confined to the lower half of the ultramafic unit, including its graphitic zones, and associated with thin quartz veins, generally sub-parallel to the foliation, with minor to 5% disseminated pyrite and arsenopyrite. Prominent north-striking white quartz veins, which do not contain significant gold values, cut the mineralised zone.

## Darlot–Centenary mining centre

In the Darlot district, gold mineralisation was first mined in 1894 and included quartz veins, placers and alluvials (Bunting & Williams 1976). Historical records indicate that between 1894 and 1910, the area was one of the richest alluvial goldfields in the Yilgarn. Recorded historical production from 1898 to 1913 of approximately 30 000 t at 15.8 g/t gold was from high-grade, quartz vein-hosted deposits; alluvial production is unknown (Bucknell, 1997). Modern exploration began in the area in the early 1980's, with open pit mining commencing at Darlot in 1988, and underground mining in 1995. The Centenary deposit was discovered 1.2 km east of Darlot mine in 1996, and underground mining commenced in 1998. The geology of the deposits is summarised by Bucknell (1997) and Krcmarov et al. (2000).

The Darlot–Centenary area is part of the eastern Darlot domain in the southern Yandal greenstone belt (Krcmarov et al. 2000). Stratigraphy comprises a lower basaltic package with minor interflow metasedimentary units, overlain by metamorphosed intermediate to felsic volcanic and metasedimentary rocks. A series of dolerite sills and dyke-like bodies intrude the sequence. The area is characterised by early thrust repetition of the stratigraphy, subsequent north- the north-northwest-trending folds and later shearing along north-northwest to northwest-trending faults. East-west and northeast-trending faults crosscut the dominant north-northwest fabric and, in places, younger intermediate dykes and lamprophyres intrude along these faults (Krcmarov et al. 2000). All rocks were metamorphosed to greenschist facies assemblages.

The Darlot–Centenary deposit is localised in the moderately dipping western limb of the shallowly north-northwest plunging, Darlot syncline. Gold mineralisation is contained in late-tectonic, brittle- to brittle-ductile structures in two sub-parallel systems – the Darlot and Centenary orebodies (Krcmarov et al. 2000). The Darlot orebody is hosed in mafic and felsic volcanic rocks, whereas Centenary is hosted by the 600 m thick, differentiated Mount Pickering dolerite sill. The Darlot orebody consists of laminar, sheeted quartz veins and en echelon arrays of shallowly southwest-dipping quartz veins, and the Centenary orebody is an en echelon array of shallowly west-southwest-dipping quartz veins. In both orebodies, gold mineralisation occurs in 1–3 m thick, albite–ankerite–sericite–pyrite alteration selvedges around quartz–carbonate–chlorite–sulphide (pyrite–pyrrhotite–galena) veins, as well as sited within the veins.

## Bellevue gold deposit

The Bellevue gold deposit, situated in the Yakabindie domain of the Agnew–Wiluna greenstone belt, commenced as an underground mining operation in 1987 after some shallow open cut mining (Brotherton & Wilson 1990). It is situated towards the southern end of the Mount Goode Basalt, west of the Miranda Fault-bounded Jones Creek Conglomerate unit. Tholeiitic metasbasalts, in part plagioclase-phyric, of the Mount Goode Basalt is the host to gold mineralisation. Gold mineralisation occurs in north- to northwest-trending, west-dipping, shear zones and associated quartz veins and breccias. Gold is associated with massive and disseminated sulphides, principally pyrrhotite with minor pyrite and chalcopyrite. Free gold is rarely observed. Sulphides occur in both quartz breccias and surrounding mylonitic metabasalt. In the latter situation the sulphides are associated with the shear foliation, or disseminated within the matrix. Thin quartz veins are present within the shear zones.

## New Holland and Genesis gold deposits

The New Holland and Genesis deposits are localised in the Scotty Creek conglomerate in the Agnew domain of the Agnew–Wiluna greenstone belt. Gold was discovered in 1894 in the Agnew area, with historic production from the New Holland deposit from 1989 to 1946. Exploration in the late 1980s and early 1990s led to discovery of Genesis deposit and additional resources in the Hew Holland area (Inwood, 1998). Gold production from the Genesis, New Holland and New Holland South ore bodies is from a combination of open pit and undergrounds methods.

The Scotty Creek conglomerate is a 1500 m thick sequence that trends north to north-northwest and contains bedding that dips steeply and faces west. The conglomerate comprises of fine- to coarse-grained sedimentary rocks, metamorphosed to greenschist facies assemblages, and displays cyclic graded beds from very coarse grained pebbly sandstones and conglomerates, through fine- to medium-grained sandstones to fine-grained sandstones and siltstones (Inwood 1998). Clasts range from predominantly ultramafic-derived in the basal part of the conglomerate to arkose and granitoid-clast conglomerate. Mineralisation in the New Holland and Genesis deposits is hosted by medium- to coarse-grained sandstone units composed of detrital quartz, feldspar and minor pebbles of granitoid, with little or subeconomic mineralisation in finer-grained units.

Gold mineralisation is closely associated with quartz veining in the medium- to coarse-grained sandstone units. Mineralisation is associated with high-grade, shallow northeast-dipping quartz veins and low-grade, steeply south-dipping veins (Inwood 1998). High-grade, shallow northeast-dipping quartz veins are grouped into two vein-sets: quartz–calcite and feldspar–quartz veins (D'Ercole 1992). Quartz–calcite veins comprise of quartz, calcite and biotite with minor microcline, albite, arsenopyrite and chlorite. Quartz forms >60% of the veins. Feldspar–quartz veins comprise microcline, quartz, albite and minor biotite, arsenopyrite and chlorite, with feldspar forming over 50%. High-grade quartz veins at New Holland contain up to 3% galena. The steeply south-dipping veins at Genesis are characterised by a lack of arsenopyrite and lower gold grades (Inwood 1998).

Wallrock alteration associated with the two types of mineralisation at New Holland and Genesis is poorly developed. Biotite, quartz, calcite and arsenpyrite are characteristic alteration minerals, with muscovite and chlorite associated in zones of high-grade, sheared quartz veins at New Holland and strong shearing and lower grades at Genesis (D'Ercole 1992, Inwood 1998).

## Nickel

Nickel sulphide mineralisation in the Sir Samuel area is restricted to ultramafic rocks in the Agnew–Wiluna greenstone belt. Mineral exploration has resulted in many significant nickel deposits, including Six Mile Well at Yakabindie and Cosmos, as well as the currently exploited Mouth Keith deposit in the north of the Sir Samuel area, and the Perseverance and Rocky's Reward deposits at Leinster.

Hill et al. (1996) described two types of nickel mineralisation. Type I deposits comprise orebodies of massive and/or matrix sulphide ore hosted by komatiite, and include Perseverance and Rocky's Reward. Matrix ore refers to ore with olivine crystals in a continuous matrix of sulphide. Nickel grade is generally higher (2–20% Ni) in massive sulphide ore, with matrix ore containing about 1–5% Ni (average 2.3%). Type II deposits are larger, lower grade orebodies comprising accumulations of disseminated sulphide in the central zone of large olivine cumulate bodies, and include Mount Keith and the Six Mile Well prospect at Yakabindie. Sulphide is fine-grained and grades are generally <1% Ni and consistently average 0.6% Ni.

### Mount Keith nickel deposit

The Mount Keith nickel deposit is a large tonnage, low grade (0.5–1.5% Ni) disseminated nickel sulphide deposit hosted by layered adcumulate–mesocumulate ultramafic body. Mount Keith was discovered in 1968, and openpit mining began in 1994. Mineralisation extends for over 2 km along strike and continues to a depth of at least 500 m, and contains in excess of 450 Mt of ore at a grade of 0.60% Ni (Hopf & Head 1998). The deposit was described in detail by Burt & Sheppy (1975), Marston (1984), Dowling & Hill (1993) and Hopf & Head (1998).

The mineralisation occurs in the easternmost of three komatiite units, the Eastern ultramafic unit of Dowling & Hill (1990), in an overall west-facing greenstone sequence, which was metamorphosed to mid-greenschist facies. The host komatiite unit has a minimum thickness of about 650 m and is completely serpentinised. The unit can be divided into three lithologically distinct zones: (1) a basal olivine orthocumulate; (2) a central zone of unmineralised, coarse-grained olivine adcumulate which grades upwards to a layered olivine-sulphide adcumulate–mesocumulate which hosts the Mount Keith orebody; and (3) an upper orthocumulate which contains zones of differentiated gabbroic rocks (Hopf & Head 1998).

There are two distinct nickel-bearing assemblages: (a) pentlandite–pyrrhotite ± magnetite, and (b) pentlandite–millerite ± heazlewoodite ± magnetite. The pentlandite–pyrrhotite ± magnetite assemblage is dominant and represents the primary magmatic assemblage. Primary nickel-bearing sulphides occur in lobate aggregates in the interstices between former olivine grains (Hopf & Head 1998).

At Mount Keith, nickel mineralisation is interpreted to have developed within a large active komatiite lava channel (Dowling & Hill 1990, Hill et al. 1996). The nickel ore formed when crystallisation of olivine led to sulphur saturation in the melt and exsolution of sulphide melt. A large proportion of total nickel may have been originally contained in igneous olivine. Subsequent reactions involving olivine after initial crystallisation is considered to be an important factor in upgrading the nickel content of ore. Further enrichment of nickel occurred during serpentinisation and carbonation during which nickel was released from olivine (Hopf & Head 1998).

### Perseverance and Rocky's Reward nickel deposits

The Perseverance deposit (formerly Agnew deposit) is the world's largest Type I nickel deposit, as well as the largest known occurrence in the Yilgarn Craton where significant volumes of both high-grade Type I (massive and disseminated) and low-grade Type II (weakly disseminated) nickel sulphide mineralisation coexist (Hill et al. 1996, Libby et al. 1998). The deposit was discovered in 1971 and underground mining commenced in 1976. The Rocky's Reward deposit is located 2 km north of Perseverance and was discovered in 1984 (De-Vitry et al. 1998). Production at these deposits to June 1996 yielded 13.8 Mt of ore at a grade of 2.27% Ni, and Proved and Probable Reserves are over 37 Mt at a grade of 1.75% Ni (De-Vitry et al. 1998, Libby et al. 1998). The deposits have been described by Martin & Allchurch (1975), Marston (1984), Barnes et al. (1988b), De-Vitry et al. (1998) and Libby et al. (1998).

The greenstone sequence in the Perseverance–Rocky's Reward area includes komatiite, high–Mg basalt and felsic volcanic/volcaniclastic rocks, all metamorphosed to amphibolite facies. The sequence is overall east-younging, although local west-facing indicators are recorded (Libby et al. 1998).

A prominent geological feature in the Perseverance area is the Perseverance ultramafic complex west of the Perseverance Fault. The complex is a zone of thickening in the regionally extensive ultramafic horizon and consists of a thick accummulation of olivine-rich ultramafic rocks (mesocumulate to adcumulate), flanked by orthocumulate-dominant, spinifex-textured komatiite. The complex is 700 m thick (east–west), 2 km north-south, and at least 1100 m and probably much more in vertical extent (Barnes et al. 1988a).

The Perseverance orebody is at a perturbation in the western contact of the ultramafic complex in an area that has undergone significant structural modification (Libby et al. 1998). The orebody is a zone of high-grade massive and disseminated mineralisation situated within an extensive sheet of weakly disseminated mineralisation. The sheet of weak mineralisation is confined to the stratigraphic base of the ultramafic complex. The Perseverance deposit occupies a structurally complex position within the weakly mineralised sheet, in which deformation has resulted in folding of the orebody, remobilisation of mineralisation into fault bounded lodes and fold hinges and dismemberment of the main disseminated mineralisation. Within the mine environment, the disseminated mineralisation forms a distinct shoot that plunges 70º to the south. In contrast, the massive sulphide mineralisation occurs in a series of individual, fault-bounded sheets that generally dip steeply to the west and strike north (Libby et al. 1998). The ultramafic body hosting the Rocky's Reward massive sulphide ore is correlated with and interpreted to be tectonic slice of that at Perseverance (De-Vitry et al. 1998). Sulphide minerals at Perseverance and Rocky's Reward include pyrrhotite, pentlandite, minor chalcopyrite and pyrite, and trace gersdorffite. Pentlandite and pyrite increase in relative abundance in the disseminated ores (Barnes et al. 1988a).

The thick Perseverance ultramafic complex is interpreted as the product of a large komatiite lava channel complex, and important for the formation of massive sulphide ores (Barnes et al. 1988b) in a similar way to that at Kambalda (Groves et al. 1986). Ore grade mineralisation formed during the same volcaninc event as the sheet of weakly disseminated mineralisation (Libby et al. 1998), with the orebody representing a subchannel lava channel complex. Variations in the primary rock types of the ultramafic complex are interpreted to reflect changes in the processes and conditions within the channel during lava flow (Libby et al. 1998). Subsequent deformation resulted in faulting, folding and imbrication of the orebody and remobilisation of massive sulphide mineralisation, including tectonic displacement of a large fragment of the orebody to form the Rocky's Reward deposit.

## Copper

Some 420 t of copper was mined from the Kathleen Valley area between 1909 and 1967 (Liu et al. 1998). The copper mineralisation, commonly with gold and silver, is in pyrite–chalcopyrite–quartz veins within mafic hosts spatially related to north-northwest-trending shear zones in Kathleen Valley Gabbro and Mount Goode Basalt (Bunting & Williams 1979). Copper also occurs in the Mount Keith nickel deposit, but has not been exploited.

## Corundum

Corundum has been mined from aluminous metasedimentary rocks interlayered with mafic rocks at AMG 586571 (Carter 1976). The mine produced 55 t of ore in 1952 (only recorded production).

## Tin

Two minor occurrences of tin were noted by Bunting & Williams (1979). A cassiterite-bearing lepidolite–albite pegmatite 3 km south-southwest of Kathleen Valley and another small deposit 400 m southwest of the Sir Samuel townsite were worked between 1945 and 1953 and produced 8 t of ore containing 0.2 t of tin.

## Uranium

Several calcrete-hosted uranium prospects localised in palaeodrainage systems are present on SIR SAMUEL. The Lake Maitland deposit, located on WANGGANNOO, contains over 11 Mt at a grade of 0.05% U and has been described by Lorimer (1973) and Bunting & Williams (1979). The Yeelirrie deposit, just west of the SIR SAMUEL area, has been described by Dall'Aglio et al. (1974), Langford (1974), Mann (1974) and Bunting & Williams (1979), and contains an estimated 30 Mt of ore at an average grade of 0.15% (46 kt of $U_3O_8$).

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## Appendix

# Gazetteer of localities on Sir Samuel

| *Locality* | *AMG (E)* | *AMG (N)* | *Locality* | *AMG (E)* | *AMG (N)* |
|---|---|---|---|---|---|
| Albion Downs | 241 700 | 6978 700 | Mount Grey | 317 700 | 6966 400 |
| Alf Well | 297 900 | 6981 000 | Mount Harold | 346 900 | 6968 700 |
| Barr Smith Range | northwest | | Mount Joel | 306 500 | 6987 100 |
| Barwidgee | 293 800 | 7008 000 | Mount Keith | 256 300 | 6991 900 |
| Beale Well | 291 800 | 6974 200 | Mount Keith Ni mine | 256 700 | 6985 600 |
| Bellevue Au mine | 258 900 | 6940 200 | Mount Mann | 258 300 | 6958 000 |
| Bogada Bore | 296 800 | 6928 200 | Mount McClure | 301 600 | 6939 900 |
| Boundary Well | 306 500 | 6927 400 | Mount McClure office | 295 100 | 6965 400 |
| Bronzewing Au mine | 302 300 | 6969 000 | Mount Mundy | 347 400 | 6955 900 |
| Centenary Au mine | 330 500 | 6923 100 | Mount Pasco | 264 100 | 6960 400 |
| Challenger Au mine | 299 300 | 6949 200 | Mount Roberts | 265 400 | 6915 300 |
| Charlie Well | 253 300 | 7006 600 | Mount Sir Samuel | 268 000 | 6932 300 |
| Chooweelarra Rock | 273 300 | 6951 200 | Mount White | 261 300 | 6914 400 |
| Cockburn Au mine | 296 200 | 6965 100 | New Holland Au mine | 253 700 | 6901 700 |
| Cork Tree Flat Well | 242 200 | 7009 300 | Ninnis Well | 324 700 | 6948 000 |
| Cosmos Ni deposit | 260 500 | 6944 500 | Ockerburry Hill | 309 800 | 6917 700 |
| Darlot Au mine | 329 400 | 6914 000 | Old Brilliant Well | 270 800 | 6906 600 |
| Dayling Well | 340 200 | 6912 800 | Overland Well | 311 900 | 6912 100 |
| Desperation Well | 305 200 | 6946 500 | Parmelia Au mine | 297 400 | 6952 800 |
| Dragon Au mine | 302 700 | 6942 600 | Paul Well | 306 200 | 6941 300 |
| Dingo Range | northeast | | Perseverance Ni mine | 273 800 | 6920 600 |
| Express Bore | 296 500 | 6972 800 | Plonkys Well | 263 500 | 6928 300 |
| Genesis Au mine | 253 700 | 6902 400 | Rocky's Reward mine | 273 000 | 6923 600 |
| Ginnabooka Well | 298 600 | 6939 000 | Rosewood Well | 335 900 | 6917 600 |
| Kens Bore | 306 900 | 6958 100 | Satisfaction Bore | 292 400 | 6955 100 |
| Hartwell Well | 303 900 | 6918 400 | Success Au mine | 296 500 | 6954 800 |
| Hope Bore | 315 700 | 6929 700 | Six Mile Well | 260 500 | 6963 400 |
| Kathleen | 259 400 | 6954 500 | Spring Well | 318 800 | 6912 900 |
| Katherine Well | 317 000 | 6941 400 | Spinifex Well | 303 000 | 6991 400 |
| Leinster | 273 400 | 6909 700 | Stirling Peaks | east | |
| Leinster Downs | 264 200 | 6917 300 | Top Mile Well | 303 500 | 6990 200 |
| Letter Box Well | 248 200 | 6999 500 | Vivien Well | 260 900 | 6903 100 |
| Lotus Au mine | 295 300 | 6966 700 | Wadarrah Rocks | 335 100 | 6918 900 |
| McArthurs Bore | 272 300 | 6928 800 | Wonganoo | 335 300 | 6996 900 |
| McDonough Lookout | 265 200 | 6942 000 | William Well | 261 100 | 6944 900 |
| Meredith Well | 265 300 | 6953 000 | Woorana Soak | 321 400 | 6957 400 |
| Melrose | 333 100 | 6909 400 | Yakabindie | 256 200 | 6947 200 |
| Mica Mica Waterhole | 318 000 | 6919 000 | Yakabindie Ni deposit | 260 300 | 6963 800 |
| Miranda Well | 265 700 | 6934 200 | Yandal | 317 100 | 6949 800 |
| Mount Blackburn | 335 400 | 6947 500 | Yandal Lagoon | 319 000 | 6936 500 |
| Mount Doolette | 315 600 | 6916 200 | Yandal Well | 318 000 | 6936 500 |
| Mount Goode | 260 000 | 6947 800 | Yellow Aster | 259 800 | 6954 500 |