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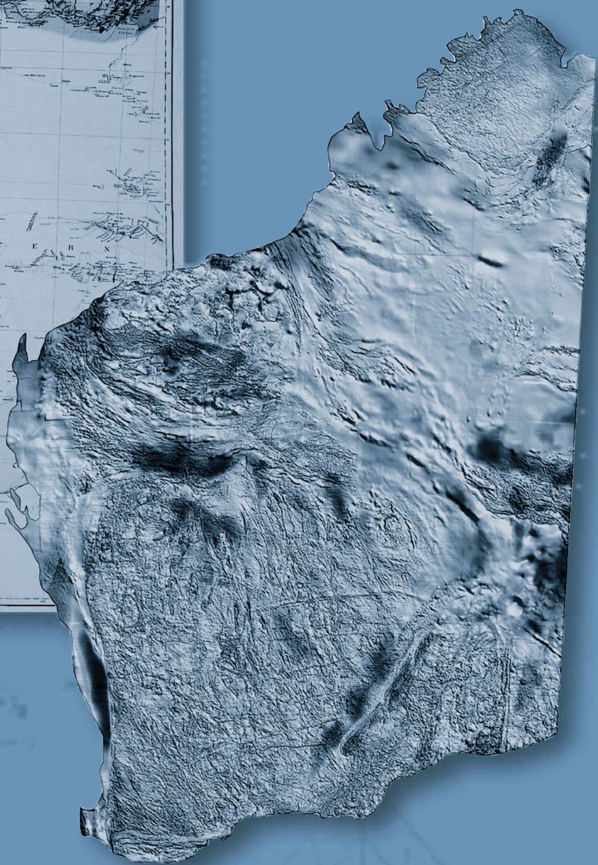
MINERAL OCCURRENCES AND EXPLORATION ACTIVITIES IN THE ARUNTA–MUSGRAVE AREA

by P. B. Abeysinghe



Geological Survey of Western Australia

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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P. B. Abeysinghe

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Mineral occurrences and exploration activities in the Arunta–Musgrave area

by

P. B. Abeysinghe

Abstract

This Record provides a commentary to accompany a CD-ROM that contains GIS-based databases for mineral exploration activities (EXACT) and mineral occurrences (WAMIN) within the Arunta–Musgrave study area. The CD-ROM also includes geology, regolith, topographic and tenement data, and geophysical and remote-sensing images. This package of data has been compiled as a major initiative to improve access to minerals and mineral exploration information in Western Australia.

The Arunta–Musgrave study area is located along the eastern border of Western Australia, bounded by latitudes 20–27°S and longitudes 126–129°E. The area includes parts of the following tectonic units: the Palaeoproterozoic Granites–Tanami Complex, the Palaeoproterozoic to Mesoproterozoic Arunta Orogen, the Mesoproterozoic Musgrave Complex, the Neoproterozoic Officer Basin, the Neoproterozoic Redcliff Pound Group, the Neoproterozoic to Phanerozoic Amadeus Basin, the Phanerozoic Canning Basin, and the Phanerozoic Gunbarrel Basin.

Eighty-nine (89) mineral occurrences have been recorded in the Arunta–Musgrave area, with the majority in the Musgrave Complex, and most of the remaining occurrences in the Canning and Amadeus Basins. The most significant mineral deposits are the lateritic nickel deposits at Wingellina that were discovered in the 1950s and assessed during the 1960s. Since 2000, there has been renewed exploration at Wingellina, and the most recent resource estimate shows measured, indicated, and inferred resources of 227 Mt at 1% nickel. The mineralization is within regolith developed over the layered mafic and ultramafic intrusions of the Giles Complex, within the Musgrave Complex. In the vicinity of the lateritic nickel deposits, there is a chrysoprase deposit from which there has been intermittent production. Significant nickel sulfide mineralization has also been discovered recently at the Nebo and Babel deposits in the west Musgrave area, and this has stimulated considerable interest in exploration for similar mineralization throughout the Giles Complex.

Other important mineral commodities known in the Arunta–Musgrave area are vanadium, cobalt, and copper that occur within the Musgrave Complex. The most significant of these are vanadium occurrences that are associated with titaniferous magnetite bands in the Jameson gabbro intrusion. Copper mineralization is known from numerous localities in the Musgrave Complex, commonly in association with fluorite, lead, zinc, silver, agate, and gold. In a number of localities north of Mount Destruction, seven microdiamonds were recovered from three loam samples, and one microdiamond from a drillhole sample that has possibly intersected weathered kimberlite. Other mineral commodities known in the Arunta–Musgrave area are gypsum and phosphate. No significant mineralization has yet been found in those parts of the Granites–Tanami Complex and the Arunta Orogen that lie within the study area; however, the prospectivity of these tectonic units is considered to be high for gold discoveries, based on analogies with significant gold mineralization to the north and east of the area. The Geological Survey of Western Australia and Geoscience Australia jointly released airborne geophysical data over the west Musgrave region covering parts of the SCOTT and COOPER 1:250 000 sheets in late 2002, and part of the west Tanami region covering the northern half of the LUCAS 1:250 000 sheet in early 2003.

KEYWORDS: mineral occurrence, mineralization, nickel, cobalt, vanadium, copper, chrysoprase, diamonds, fluorite, lead, zinc, gold, gypsum, phosphate rock, Musgrave Complex, Arunta Orogen, Granites–Tanami Complex, Amadeus Basin, Canning Basin, Officer Basin, Gunbarrel Basin, regolith.

Introduction

Present study

This Record describes the mineral prospectivity of the Arunta–Musgrave area, a remote region of Western Australia where there has been relatively little exploration activity compared to other parts of the State. The area is located along the central-eastern border of Western Australia, and encompasses a number of tectonic units that include the Granites–Tanami Complex, the Arunta Orogen, the Amadeus Basin, the Musgrave Complex, and parts of the Canning, Officer, and Gunbarrel Basins (Fig. 1).

The main purpose of this Record is to provide GIS-based databases for mineral exploration activities (EXACT) and mineral occurrences (WAMIN). These databases have been developed as a major initiative to improve access to information on minerals and mineral exploration in the Western Australia.

Details of mineral exploration, mineral occurrences, and other geoscientific information for the study have been compiled from the following sources:

- the large dataset of open-file statutory mineral-exploration reports held in the Western Australian mineral exploration (WAMEX) database at the Department of Industry and Resources (DoIR);
- the database of Western Australia's mines and mineral deposits (MINEDEX) held at the Department of Industry and Resources;
- books, journals, and industry publications and datasets;
- regional geological surveys, airborne geophysical datasets, and remote-sensing datasets.

This Record is accompanied by digital datasets on a CD-ROM. The Record presents a brief review of the regional geology of the area and comments on known mineral occurrences. The geological review incorporates information from publications relating to adjacent areas in the Northern Territory and South Australia to provide the most recent understanding of the main tectonic units that straddle the State borders: i.e. the Granites–Tanami Complex, the Arunta Orogen, the Amadeus Basin, and the Musgrave Complex.

The accompanying CD-ROM contains datasets for the following: mineral occurrences (WAMIN database); spatial index of exploration activities (EXACT database); digitized geology; and digitized regolith. It also includes files of geophysical, remote-sensing, mining tenement positions, and topographic data. The CD-ROM contains the files necessary for viewing the data in the ArcView GIS environment plus a self-loading version of the ArcExplorer software package modified to suit this particular dataset. Metadata statements on the geological, geophysical, and topographic datasets are also provided.

Appendix 1 gives brief descriptions of the digital datasets included on the CD-ROM. Appendix 2 defines the terms used in the Geological Survey of Western Australia (GSWA) mineral occurrence database (WAMIN) and mineral-exploration activity database (EXACT).

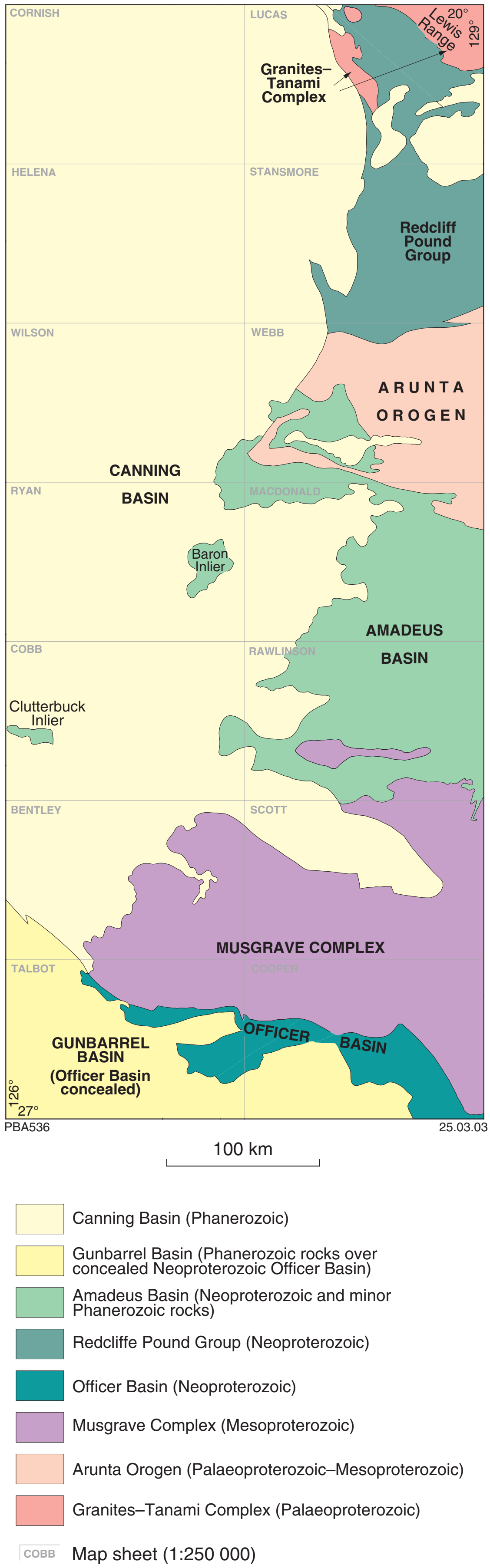

Figure 1. Tectonic units of the Arunta–Musgrave area

Location

The Arunta–Musgrave area (henceforth referred to as Arunta–Musgrave) is located along the central-eastern border of Western Australia, and is bounded by latitudes 20–27°S and longitudes 126–129°E. The area is covered by the fourteen 1:250 000-scale map sheets of CORNISH*, LUCAS, HELENA, STANSMORE, WILSON, WEBB, RYAN, MACDONALD, COBB, RAWLINSON, BENTLEY, SCOTT, TALBOT, and COOPER (Fig. 1).

The Arunta–Musgrave area is very sparsely populated except for the Aboriginal settlement at Warburton, located near the western end of the Warburton Range (Fig. 2). Warburton is connected with Laverton, 500 km to the southwest, by a moderately good dirt road. Another track connects Warburton with Wingellina, a mineral exploration camp some 240 km to the east, near the South Australian border.

Limited rainfall records indicate that Warburton has a mean annual rainfall of 216.6 mm and the Giles meteorological station north of Wingellina has an average of 181.9 mm. Surface water is almost non-existent and consists of occasional rockholes that contain little water for only short periods after rain.

Previous work

Reconnaissance exploratory work in the Musgrave region of the study area was carried out by GSWA as far back as 1916 (Talbot and Clarke, 1917). The areas investigated during 1916 include the Warburton, Cavenagh, Barrow, and Townsend ranges. In 1936, GSWA was involved in an expedition team (financed by Border Reefs Ltd, Sydney) that explored the areas around Rawlinson Range in Western Australia, Petermann Range in the Northern Territory, and other adjoining areas, to locate a gold reef, popularly known as 'Lasseter's Reef', which, however, was not found (Ellis, 1937). The first systematic geological mapping of the Arunta–Musgrave area was carried out from 1968 to 1978 by the Bureau of Mineral Resources (BMR; later the Australian Geological Survey Organisation (AGSO), and now Geoscience Australia) and GSWA. The following 1:250 000 map sheets (Fig. 1) with Explanatory Notes were produced during 1968–78: CORNISH (Crowe et al., 1978a; Crowe, 1978), LUCAS (Crowe et al., 1978b; Crowe and Muhling, 1977), HELENA (Yeates and Walton, 1977; Yeates, 1977), STANSMORE (Blake et al., 1976; Blake and Yeates, 1976), WILSON (Towner and Chan, 1978; Towner, 1978a), WEBB (Blake, 1976; Blake, 1977a), RYAN (Towner and Young, 1978; Towner, 1978b), MACDONALD (Wells, 1968b; Wells, 1968a), COBB (van de Graaff and Lamberts, 1974; van de Graaff, 1975), RAWLINSON (Wells and Forman, 1966; Forman, 1965), BENTLEY (Daniels et al., 1971; Daniels, 1970), SCOTT (Daniels, et al., 1970a; Daniels, 1972), TALBOT (Daniels et al., 1970b; Daniels, 1971a), and COOPER (Daniels et al., 1970c; Daniels, 1971b). GSWA has also published Bulletin 123 (Daniels, 1974) giving detailed descriptions of the geology and mineral resources of the Blackstone region in the Musgrave Complex area. Memoir 3 published by GSWA (Geological Survey of Western Australia, 1990) also gives descriptions of the tectonic units found in the study area. The BMR have also published Bulletin 197 (Blake et al., 1979) on the geology of the Granites–Tanami region.

More recently, the BMR published Bulletin 236 (Korsch and Kennard, 1991) on the geology and geophysics of the Amadeus Basin in central Australia. In 1995, a special issue of the AGSO Journal of Australian Geology and Geophysics (volume 16, numbers 1 and 2) was devoted to the mafic–ultramafic Giles Complex and its environs, in the western Musgrave 'Block' of central Australia. In addition, in 1996 AGSO published Bulletin 239 (Glikson et al. 1996) that provides a detailed study of the western Musgrave 'Block', with special reference to the mafic–ultramafic Giles Complex. During 1999, Geoscience Australia produced airborne digital datasets for the WEBB and RAWLINSON map sheets.

In December 2002, GSWA and Geoscience Australia jointly released airborne geophysical data over the west Musgrave region covering parts of the SCOTT and COOPER 1:250 000 sheets (Fig. 3). The data includes both new survey data flown for GSWA by Fugro Airborne Surveys in 2002 and private company data flown by Kevron Geophysics over the Jamieson Range‡ in 1998. In February 2003, the two organizations also released airborne geophysical data over parts of the west Tanami region that included the northern half of the LUCAS 1:250 000 sheet (Fig. 3)†.

GSWA has also published a number of commodity-specific studies of the State that include information relating to the study area. These publications are Mineral Resources Bulletins 11 (Baxter, 1978), 13 (Marston, 1979), and 14 (Marston, 1984) that respectively provide information on vanadium, copper, and nickel mineralization in the Musgrave Complex. Daniels (1967) also produced an interim report on vanadium mineralization in the Jamieson Range area. Tyler et al. (1998) discussed the geology and mineral deposits of the Proterozoic in Western Australia, which includes mineralization patterns in the Musgrave Complex.

Past exploration activities in the area have been concentrated mainly around Wingellina, Tollu, and Cavenagh Range on COOPER, Warburton Range on TALBOT, Mount Destruction on RAWLINSON, and Jamieson Range on SCOTT (Fig. 2). However, since the mid-1990s exploration activity has increased in all parts of the Arunta–Musgrave, including the northern sheets of CORNISH, LUCAS, HELENA, STANSMORE, WILSON, WEBB, and MACDONALD. In many of these areas exploration has been limited to airborne surveys, and ground follow-up exploration has yet to be carried out. Approximately 65% of the open-file mineral exploration information in the Arunta–Musgrave is from exploration carried out from the 1990s onwards.

There has been recent renewed interest in nickel, gold,

* Capitalized names refer to 1:250 000 map sheets.

† Copies of digital data are available from Geoscience Australia (e-mail: sales@ga.gov.au") and also from e.bookshop online from the Department of Industry and Resources (www.doir.wa.gov.au).

‡ Jamieson Range supersedes Jameson Range in previous GSWA publications.

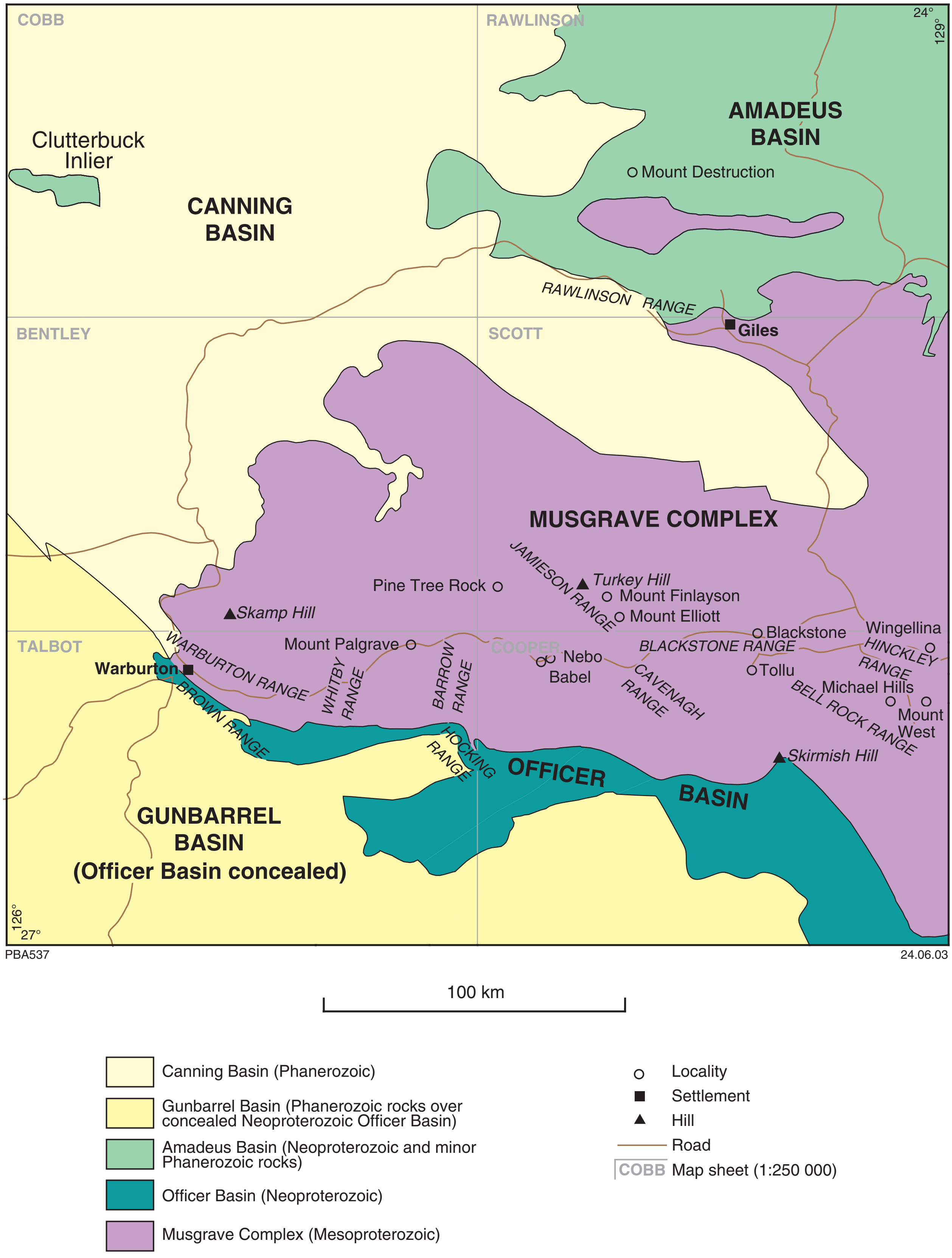

Figure 2. Localities in the Musgrave Complex and adjacent tectonic units

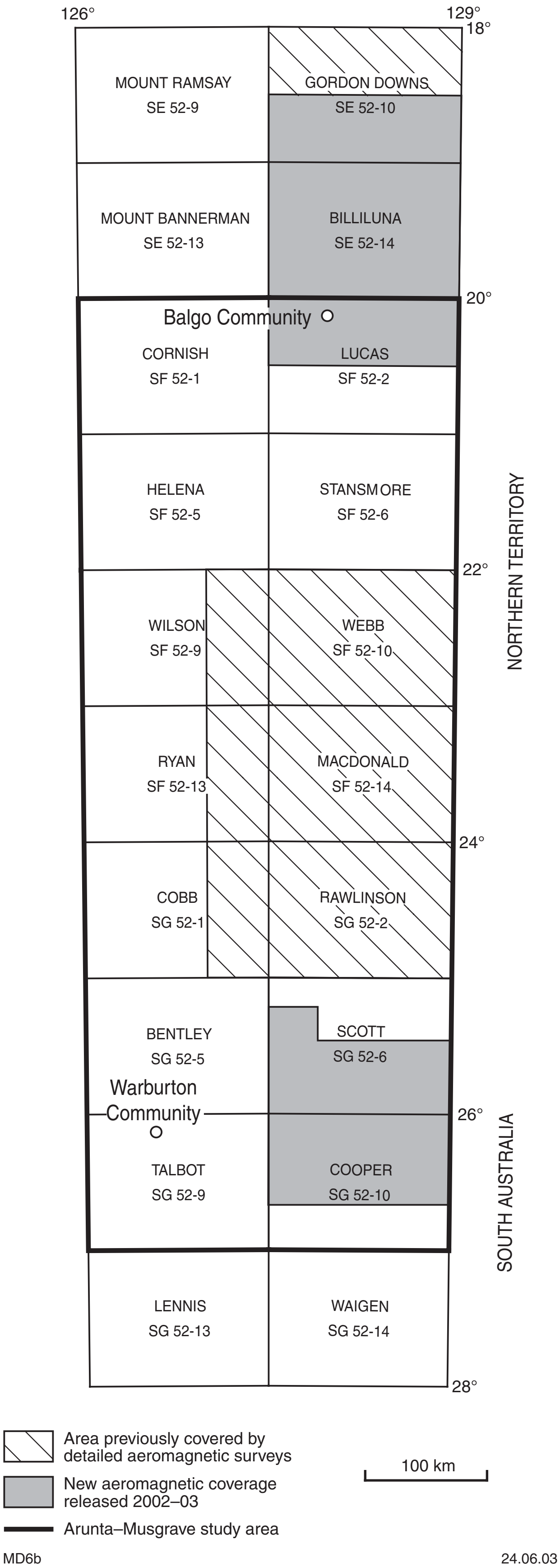

Figure 3. Areas of digital data for airborne geophysical surveys released by GSWA and Geoscience Australia

and base metal exploration in the Musgrave Complex on COOPER, SCOTT, BENTLEY, and TALBOT. This followed the discovery of nickel sulfides in the west Musgrave area by Western Mining Corporation (WMC) in 2000. This discovery consists of a large mineralized nickel-sulfide system with a possible strike length exceeding 4.5 km (WMC Ltd, 2002). Companies currently exploring in the region include WMC, WRF Securities, Acclaim Exploration, Normandy Exploration, Anglo Australian Resources, ReLode, Minex (Australia), West Musgrave Mining, Cobra Resources, Mitchell River Exploration, Eastern Goldfields Exploration, Frugal Mining, Loded, Farno, Broadlake Holdings, Paylode, Hamill Resources, Viper Resources, Allhawk Nominees, Hinckley Ranger, Falconbridge (Australia), and Gutnick Resources. Aurora Gold, with BHP, are involved in exploration activities in the Mount Webb area. Some companies have also been exploring for diamond on areas within RAWLINSON and STANSMORE in the central and northern parts of the Arunta–Musgrave area.

Regional geology

The Arunta–Musgrave includes the following tectonic units: a small portion of the Palaeoproterozoic Granites–Tanami Complex; a small part of the Palaeoproterozoic to Mesoproterozoic Arunta Orogen; the Mesoproterozoic Musgrave Complex; a small eastern strip of the Neoproterozoic Officer Basin; the Neoproterozoic Redcliffe Pound Group; a small part (about one-tenth of the total area) of the Neoproterozoic to Phanerozoic Amadeus Basin; the eastern part of the Phanerozoic Gunbarrel Basin; and the eastern part of the Phanerozoic Canning Basin (Fig. 1).

The digital geological data on the CD-ROM accompanying this Record are based on the 1:500 000 interpreted bedrock geology of Western Australia (Vanderhor and Flint, 2001). The regolith layer was compiled from the fourteen 1:250 000 map sheets covering the Arunta–Musgrave area. The summary of the geology of the Arunta–Musgrave area that follows is discussed under the headings of the main tectonic units, from the oldest to the youngest. The various rock units of the Arunta–Musgrave area and stratigraphic correlations of the Palaeoproterozoic to Mesozoic rocks are shown in Appendices 3 and 4 respectively.

Granites–Tanami Complex

The Palaeoproterozoic Granites–Tanami Complex in Western Australia is equivalent to the Tanami Complex described by Blake et al. (1979), Plumb (1990), Mayer (1990), and Nicholson (1990), and was previously referred to as the Billiluna Complex by Myers (1990a). The most recent work on the complex has been undertaken in the Tanami region of the Northern Territory, which is the easterly extension of the Granites–Tanami Complex. The results of these recent investigations are to be found in Lovett at al. (1993), Page et al. (1995), Smith et al. (1998), Tunks and Marsh (1998), Slater (2000a,b), Hendrickx et al. (2000), Wygralak et al. (2001), Wygralak and

Mernagh (2001), Vandenberg et al. (2001), and Dean (2001). Other relevant publications for the Tanami region include Blake (1974, 1977b, 1978), Cooper and Ding (1997), and Gibbons and Webb (1997).

The Tanami region has a similar geological history to the Pine Creek Orogen and the Tennant Creek Province of the Northern Territory, and the eastern Halls Creek Orogen of Western Australia (Tyler et al., 1995, 1998; Wygralak et al., 2001; Hendrickx et al., 2000; Vandenberg et al., 2001; Dean, 2001). The oldest rocks of the Tanami region consist of isolated inliers of Archaean gneiss and schist (Page et al., 1995; Wygralak et al., 2001). Sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon geochronology indicates protolith ages of c. 2510 Ma with high-grade metamorphism at c. 1882 Ma (Page et al., 1995; Wygralak et al., 2001). The c. 1882 Ma event has been related to the Barramundi Orogeny in the Pine Creek Orogen (Wygralak et al., 2001) and is considered to be the maximum age for rift initiation, basin formation, and deposition of the overlying orogenic sequences. These orogenic sequences are represented by deformed volcanic rocks and sedimentary rocks of the MacFarlane Peak and Tanami Groups. The MacFarlane Peak Group consists of mafic volcanic rocks, turbiditic sandstone, siltstone, and minor calc-silicate rocks. The Tanami Group consists of basal quartzite; the Dead Bullock Formation that comprises carbonaceous siltstone, graphitic shale, minor iron-rich banded iron-formation (BIF) and chert; and the turbiditic Killi Killi Formation (Wygralak et al., 2001). The youngest detrital zircon population within the Killi Killi Formation is c. 1840 Ma, thus providing a maximum depositional age for this formation (Crispe et al., 2002).

The portion of the Granites–Tanami Complex that lies within the current study area is relatively small and is located in the northeastern and central parts of LUCAS (Fig. 1). The Granites–Tanami Complex is flanked to the west and south by the Neoproterozoic Redcliff Pound Group.

The main rocks of the complex are those of the Palaeoproterozoic Killi Killi Formation (Hendrickx et al., 2000), which was previously known as the Killi Killi 'beds' (Blake et al., 1975). The Killi Killi Formation consists of metasedimentary and metavolcanic rocks that were thought to be lateral equivalents of the Mount Charles, Nanny Goat Creek, Nongra, and Helena Creek 'beds' (Blake et al., 1979). The rocks in the Killi Killi Formation include greywacke, arenite, siltstone, siltstone, and minor volcanic rocks (Blake et al., 1979). On LUCAS, the Killi Killi Formation rocks are commonly iron-stained to brown or yellowish brown where weathered, and are purplish to greenish grey where fresh, and the metavolcanics are generally reddish brown where weathered (Crowe and Muhling, 1977).

The Mesoproterozoic Lewis Granite that outcrops in the Lewis Range (Fig. 1) in the Granites–Tanami Complex on LUCAS intrudes the Killi Killi Formation. The granite is overlain by the Gardiner Sandstone. The Lewis Granite was initially dated at 1720 ± 8 Ma by the whole-rock Rb–Sr method (Page et al., 1976); however, more recent SHRIMP U–Pb zircon dating suggests that the intrusion age is between 1815 and 1790 Ma (Crispe et al., 2002). The granite forms prominent (up to 80 m high) scarps along the northern and eastern sides of the Lewis Range (Crowe and Muhling, 1977), and commonly contains phenocrysts over 1 cm long of microcline and subordinate plagioclase. The granite is well exposed north and east of Point Nelligan, where it appears in a lit-par-lit injection zone in which sheets of granite alternate with layers of greywacke of the Killi Killi Formation; the latter has been thermally metamorphosed to a micaceous hornfels (Blake et al., 1979).

Arunta Orogen

The Palaeoproterozoic–Mesoproterozoic Arunta Orogen (Fig. 1) includes an extensive heterogeneous assemblage of deformed rocks occurring mostly in the Northern Territory, with only a small portion in Western Australia (Myers, 1990a). The geology of the Arunta Orogen (Arunta Province in the Northern Territory) has been discussed by Blake et al. (1979), Stewart et al. (1984), Shaw et al. (1984), Myers (1990a), Williams et al. (1991), Blake (1993), Blake et al. (1994), Young et al. (1995a,b), Collins and Shaw (1995), Bagas and Smithies (1997), Rudge (1998), Wyborn et al. (1998), Wygralak and Bajwah (1998), Mawby et al. (1999), Collins (2000), Edgoose et al. (2001), Pietsch (2001), Hoatson (2001), and Geoscience Australia (2002).

Rocks in the Arunta Orogen have been divided into three tectonic provinces — Northern, Central, and Southern Provinces based on differences in stratigraphy, structure, and metamorphic history (Stewart et al., 1984; Shaw et al., 1984), and separation by major deformation zones. In Western Australia, the Arunta Orogen is represented by a portion of the Northern Province and a small part of the Southern Province separated by the Redbank Thrust (Tyler et al., 1998). In the Northern Province, the equivalent of the c. 1880 Ma Yuendunu tectonic event (Young et al., 1995a; Collins and Shaw, 1995) produced upright tight isoclinal folding of turbiditic sandstones and mudstones of the Lander Rock beds (Stewart et al., 1984). The Stafford tectonic event in the Northern Province of the Arunta Inlier produced localized very low pressure and high-temperature metamorphism, and associated compressive deformation and granite intrusion at c. 1829 Ma (Vernon et al., 1990; Collins and Shaw, 1995). The Strangeways Orogeny (Collins and Shaw, 1995) may have been related to the northerly subduction of oceanic crust, and the accretion of volcanic and magmatic arcs, between c. 1780 and 1730 Ma (Zhao and McCulloch, 1993; Zhao and Bennett, 1995; Myers et al., 1996). In the Northern Province of the Arunta Inlier, this orogeny was accompanied by voluminous granite intrusion before and during metamorphism.

In Western Australia, tightly folded quartz–mica schist and quartzite have been metamorphosed to greenschist facies. These metamorphic rocks are inferred to be unconformably overlain by the Pollock Hills Formation, which comprises a lower pile (400 m) of felsic volcanic rocks and an upper sequence (600 m) of arenite, tuffaceous sandstone, siltstone, and conglomerate. The volcanic rocks are thought to be comagmatic with the Mount Webb Granite and are unconformably overlain by the Heavitree

Quartzite of the Amadeus Basin in the south (Blake et al., 1979). The Mount Webb Granite consists of several types of unaltered granite, sodic–calcic-altered granite, sericite-altered granite, and aplite. SHRIMP U–Pb zircon dating of three samples of the Mount Webb Granite yielded ages of 1643 ± 4, 1639 ± 5, and 1639 ± 5 Ma, indicating that they all belong to one magmatic system (Wyborn et al., 1998).

The Southern Province of the Arunta Orogen is poorly exposed in Western Australia (Tyler et al., 1998). To the east, it consists of amphibolite-facies quartzofeldspathic gneisses unconformably overlain by siliceous and aluminous metasedimentary rocks (Stewart et al., 1984; Black and Shaw, 1995). The rocks in the Southern Province are younger than those of the Central and Northern Provinces, and were derived in part from granites intruded after c. 1680 Ma. Black and Shaw (1995) suggested that the Southern Province formed as a separate terrane. Deformation and metamorphism during the Argilke tectonic event occurred between 1680 and 1650 Ma, and northerly directed ductile shearing and thrusting were followed by granitic intrusion at c. 1600 Ma during the Chewings Orogeny (Collins and Shaw, 1995). The northern boundary of the Southern Province of the Arunta Inlier is formed by the Redbank Thrust Zone, along which uplift took place at 1500–1400 Ma during the Anmatjira uplift phase (Shaw and Black, 1991).

Hoatson (2001) subdivided the mafic–ultramafic intrusions of the Arunta Province in the Northern Territory into three groupings: western, central, and eastern on the basis of lithologies, metamorphic structural histories, degree of fractionation, and limited geochronology. These intrusions form large metagabbroic bodies, folded high-level mafic sills, steeply dipping amphibolite sheets, and relatively undeformed ultramafic plugs with alkaline and tholeiitic affinities. Metamorphic grades range from granulite to subamphibolite facies. Mapping by the Northern Territory Geological Survey suggests that the western group of intrusions are related to the 1635 ± 9 Ma Andrew Young Igneous Complex. Intrusions of the central group were emplaced prior to the main granulite metamorphic events that affected the Mount Hay and Strangways regions at c. 1780–1760 Ma and c. 1730–1720 Ma. The eastern group comprises both pre-orogenic and relatively undeformed intrusions of variable form and composition (Hoatson, 2001).

Musgrave Complex

The Mesoproterozoic Musgrave Complex represents the southeastern part of the northwesterly trending Paterson Orogen. It represents a Mesoproterozoic crystalline basement domain and is equivalent to the Musgrave Block in South Australia and the Northern Territory. The Musgrave Complex has been discussed by Sprigg and Wilson (1959), Daniels (1974, 1975a,b), Gray (1978), Gray and Compston (1978), Camacho (1989), Pharaoh (1990), Myers (1990b), Ballhaus and Berry (1991), Maboko et al. (1991), Clarke et al. (1992), Sun and Sheraton (1992), Clarke and Glikson (1992), Ballhaus (1992, 1993), Major and Conor (1993), Stewart and Clarke (1993), Stewart (1994a,b; 1995a,b; 1998), Glikson et al. (1990, 1994, 1995, 1996), Walter et al. (1995), Camacho and Fanning (1995), Sheraton and Sun (1995, 1997), Ballhaus and Glikson (1995), Clark et al. (1995), Camacho (1997), Tyler et al. (1998), White et al. (1999), Camacho and McDougall (2000), and Camacho et al. (2001).

The Musgrave Complex is flanked by the Phanerozoic Canning Basin to the west and northwest, the Neoproterozoic to Middle Palaeozoic Amadeus Basin to the north, and the Neoproterozoic Officer Basin to the south and southwest (Fig. 1; Tyler and Hocking, 2001). It consists of four major lithotectonic units: the Olia Gneiss north of the Woodroffe Thrust, basement gneisses south of the Woodroffe Thrust, the Giles Complex, and the Bentley Supergroup.

Felsic igneous rocks (c. 1550 and c. 1380 Ma), together with subordinate sedimentary and mafic igneous rocks, formed protoliths of the high-grade metamorphic rocks south of the Woodroffe Thrust. Granulite-facies metamorphism and deformation at c. 1200 Ma involved mostly penetrative pure shear during D_1 and D_2 at greater than 750°C and 5 ± 1 MPa. Metamorphism was associated with emplacement of post-D_1, pre-D_2 orthopyroxene granites ('charnockites') and post-D_2 granitoids, including rapakivi types (1184 ± 4 Ma) and syenites. Leuconorite was emplaced at 1176 ± 5 Ma. The oldest exposed rocks north of the Woodroffe Thrust are c. 1600 Ma gneisses, equivalent to the banded quartzofeldspathic Olia Gneiss (Tyler et al., 1998). These consist of amphibolite-facies rocks of fine- to medium-grained, banded quartzofeldspathic gneiss and intrusions of porphyritic granite (Myers, 1990b).

Emplacement of voluminous mafic–ultramafic magmas of the Giles Complex as sills and lopoliths (>10 km thick in total) occurred at 1078 ± 3 Ma. Extrusion of the bimodal Tollu Group volcanic rocks was coeval with the intrusion of the Giles Complex. The volcanic rocks were erupted onto uplifted and eroded amphibolite-facies granitic gneisses, whereas the Giles Complex was emplaced into granulite-facies gneisses. Some dolerite dykes may represent feeders to the mafic–ultramafic intrusions. Penetrative simple-shear deformation (D_3) produced near-vertical high-strain zones and was followed by major uplift and erosion of more than 12 km of crust. Post-D_3 olivine dolerite dykes (Fig. 4) were emplaced at c. 1000 Ma. Quartz dolerite (Fig. 4) dykes were emplaced at c. 800 Ma. At least four phases of mylonite and ultramylonite zone formation (D_{4-7}) post-date the quartz dolerite dykes. The easterly trending D_6 ultramylonite–pseudotachylite zones are the largest, and were formed during major northward thrusting of the Musgrave Complex during the Petermann Ranges Orogeny (c. 550 Ma).

The c. 1080 Ma layered intrusions of the Giles Complex occupy an easterly trending belt about 200 × 40 km that forms prominent ranges of the Tomkinson, Blackstone, Murray, Cavenagh, Jamieson, and Hinckley ranges (Figs 2 and 4). At least 17 intrusions and/or faulted segments of intrusions, of several types, are recognized. They represent the most extensive mafic igneous activity recognized in exposed deep levels of the continental crust in Australia (Ballhaus and Berry, 1991; Glikson et al., 1996).

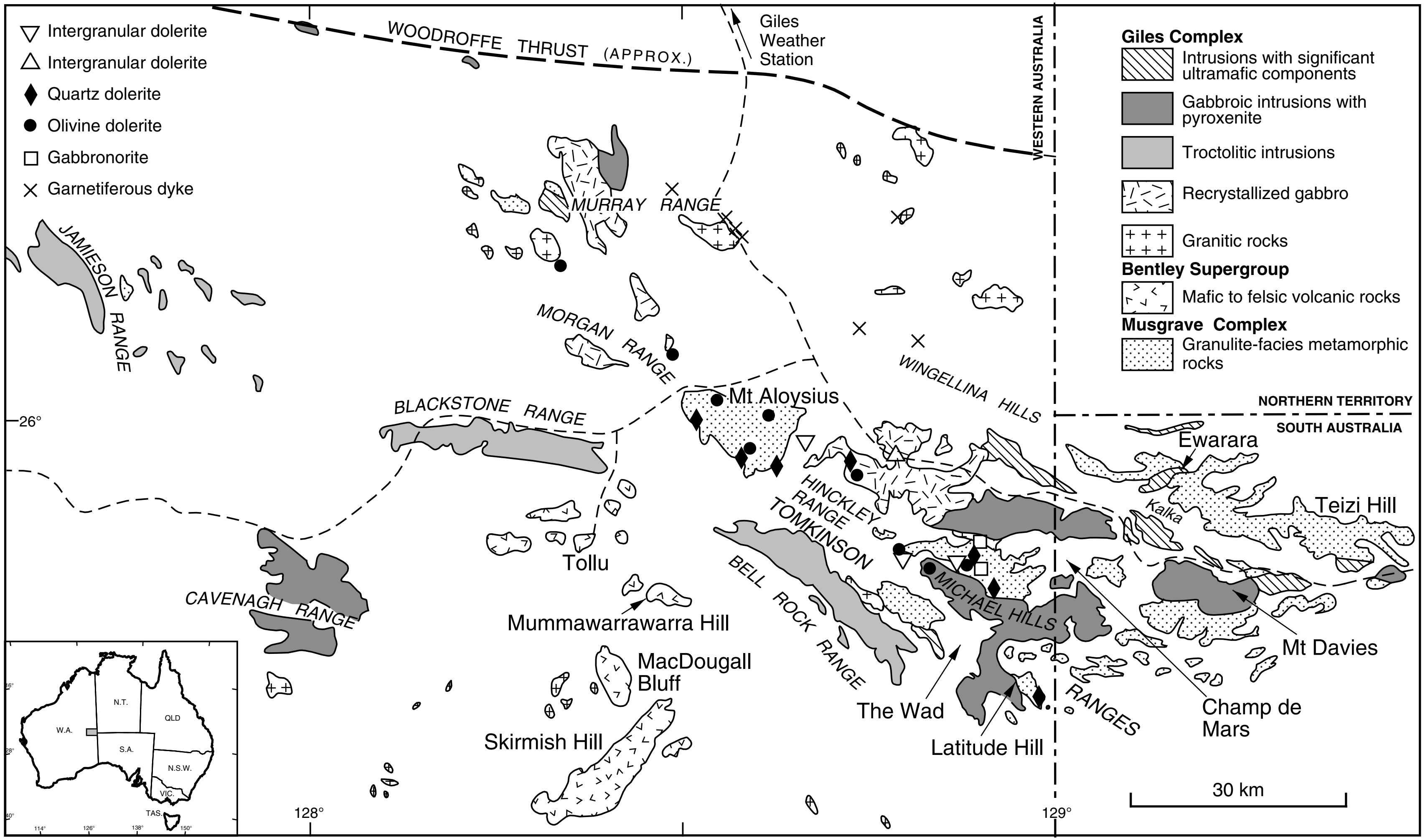

Figure 4. Geological map of the Musgrave Complex (western Musgrave Block), showing major Giles Complex intrusions and locations and chemical groupings of analysed mafic dykes (after Glikson et al., 1996)

The intrusions found in the Jamieson, Blackstone, Cavenagh, Bell Rock, and Hinckley ranges, all in Western Australia, are large (10–40 km along strike) clinopyroxene–orthopyroxene–plagioclase gabbro and olivine–clinopyroxene–plagioclase troctolite bodies, locally magnetite-rich, with little or no ultramafic component. At Michael Hills (in Western Australia), and Mount Davies and Kalka (in South Australia), there are large gabbroic bodies that have a significant ultramafic component. At Murray Range, The Wart, and Wingellina Hills (in Western Australia), there are medium-sized (<10 km) layered gabbro–pyroxenite intrusions. At Ewarara (in South Australia), there are small (<5 km) bodies of pyroxenite and minor metagabbro. Stratiform lenses of anorthosite are emplaced into felsic granulite near Teizi Hill (in South Australia). Similar bodies, such as those at Blackstone and Bell Rock ranges (in Western Australia), appear to be discrete sill-like bodies rather than tectonic slices of a single Bushveld-type lopolith (Glikson et al., 1996). The various intrusions in the Giles Complex cannot be related to a single parent magma, but probably crystallized from separate batches of variably fractionated parent melts (Ballhaus and Glikson, 1995; Glikson et al., 1995, 1996). Ballhaus and Glikson (1995) identified at least three discrete parental compositions: a near-primitive olivine(–clinopyroxene) saturated melt; a slightly fractionated olivine(–orthopyroxene)–clinopyroxene–plagioclase saturated melt; and a strongly fractionated fayalitic olivine–plagioclase(–magnetite) saturated melt.

Bentley Supergroup

The Mesoproterozoic (c. 1080 Ma) Bentley Supergroup includes all volcanic and minor sedimentary rocks of low-metamorphic grade in the Blackstone region that are younger than the granulites and related gneisses and schists but older than Neoproterozoic glacial rocks (Daniels, 1974). The Bentley Supergroup lies south of, and above, the Woodroffe Thrust, and consists of the Pussy Cat, Tollu, Cassidy, and Mission Groups. In addition, the Bentley Supergroup includes three large cauldron-subsidence complexes of felsic volcanic rocks and granite. These are called the Scamp Cauldron (containing the Scamp volcanic association), the Palgrave Cauldron (containing the Palgrave volcanic association), and the Skirmish Hill Cauldron (containing the Skirmish Hill volcanic association; Daniels, 1974; Sheraton and Sun, 1995). The Townsend Quartzite, previously assigned to the Bentley Supergroup (Daniels, 1974), is now considered to be a basal unit of the Officer Basin (Walter and Gorter, 1994).

To the north of the Woodroffe Thrust, the Mount Harris Basalt and the overlying Bloods Range ‘beds’ may be equivalent to the Cassidy Group. The Mount Harris Basalt may also be equivalent to the Wankari Volcanics dated in the Northern Territory at c. 1050 Ma (Scrimgeour et al., 1999).

Officer Basin

The Neoproterozoic Officer Basin occurs in the southern part of the Arunta–Musgrave, where it is exposed south of the Musgrave Complex, and it underlies the Phanerozoic Gunbarrel Basin (Fig. 1).

The western Officer Basin has been described by Lowry et al. (1972), Jackson and van de Graaff (1981), Phillips et al. (1985), Townson (1985), Iasky (1990), Hocking (1994), Hocking et al. (1994), Perincek (1996a,b), Grey (1983, 1998), Apak and Moors (2000, 2001), and Moors and Apak (2002). The South Australian portion of the basin has been reassessed by Gravestock and Hibburt (1991) and Preiss (1993). A summary of sedimentary successions within the Officer Basin is given in Figure 5. Perincek (1998) has given summaries of holes (BMR Talbot 1–5) drilled by the BMR on TALBOT and has reviewed data relating to the hydrocarbon prospectivity of the Officer Basin. Further discussions of the hydrocarbon prospectivity are given in Apak and Moors (2000, 2001) and Moors and Apak (2002). The subdivisions of the western Officer Basin (Middleton, et al., 1987; Iasky, 1990; Hocking 1994) are based on interpreted depth to basement from total magnetic intensity data. The thickness of the succession in the western Officer Basin is up to 6 km. The oldest rocks are those of the Townsend Quartzite and coeval units that are about 820 million years old and correlate directly with the basal portions of the Amadeus Basin succession (Hocking, 1994; Hocking et al., 1994). The Townsend Quartzite outcrops as a prominent broken ridge for a distance of approximately 110 km from Brown Range in the west (south of Warburton) to Hocking Range in the east.

The Officer Basin within the Arunta–Musgrave area is represented by the Yowalga and Waigen Sub-basins and the Neale Arch, which are all located south of the Musgrave Complex (Fig. 6). The Yowalga Sub-basin, the most westerly of the two sub-basins, is an asymmetric trough that contains up to 7 km of sedimentary rocks. The Waigen Sub-basin, the most easterly of the two sub-basins, is an asymmetric, deep trough that contains up to a 5 km-thick sequence of sedimentary rocks (Townson, 1985). The Neale Arch is a northeasterly trending, elongate, broad basement high extending from the Albany–Fraser Orogen to the Musgrave Complex. It is located between the Yowalga and Waigen Sub-basins, dividing the Officer Basin into a northwest-trending structural province in the west, and an east-trending structural province in the east. It is a distinct entity on total magnetic intensity maps and is covered by up to a 5 km-thick sequence of sedimentary rocks (Hocking, 1994). Apak and Moors (2000, 2001) showed from shallow seismic and well data that the Officer Basin sedimentary sequence dips and increases in thickness to the northeast. They were unable to recognize the subdivisions of the Officer Basin put forward by Iasky (1990) and suggested the presence of underlying Mesoproterozoic sedimentary rocks.

Redcliff Pound Group

The Neoproterozoic Redcliff Pound Group and its probable stratigraphic equivalents (Blake et al., 1979; Grey, 1979, 1990a) unconformably overlie the Arunta Orogen and the Birrindudu Group and are unconformably overlain by the Palaeozoic Lucas Formation. The Redcliff Pound Group consists of the laterally equivalent basal units of the Munyu, Muriel Range, and Lewis Range

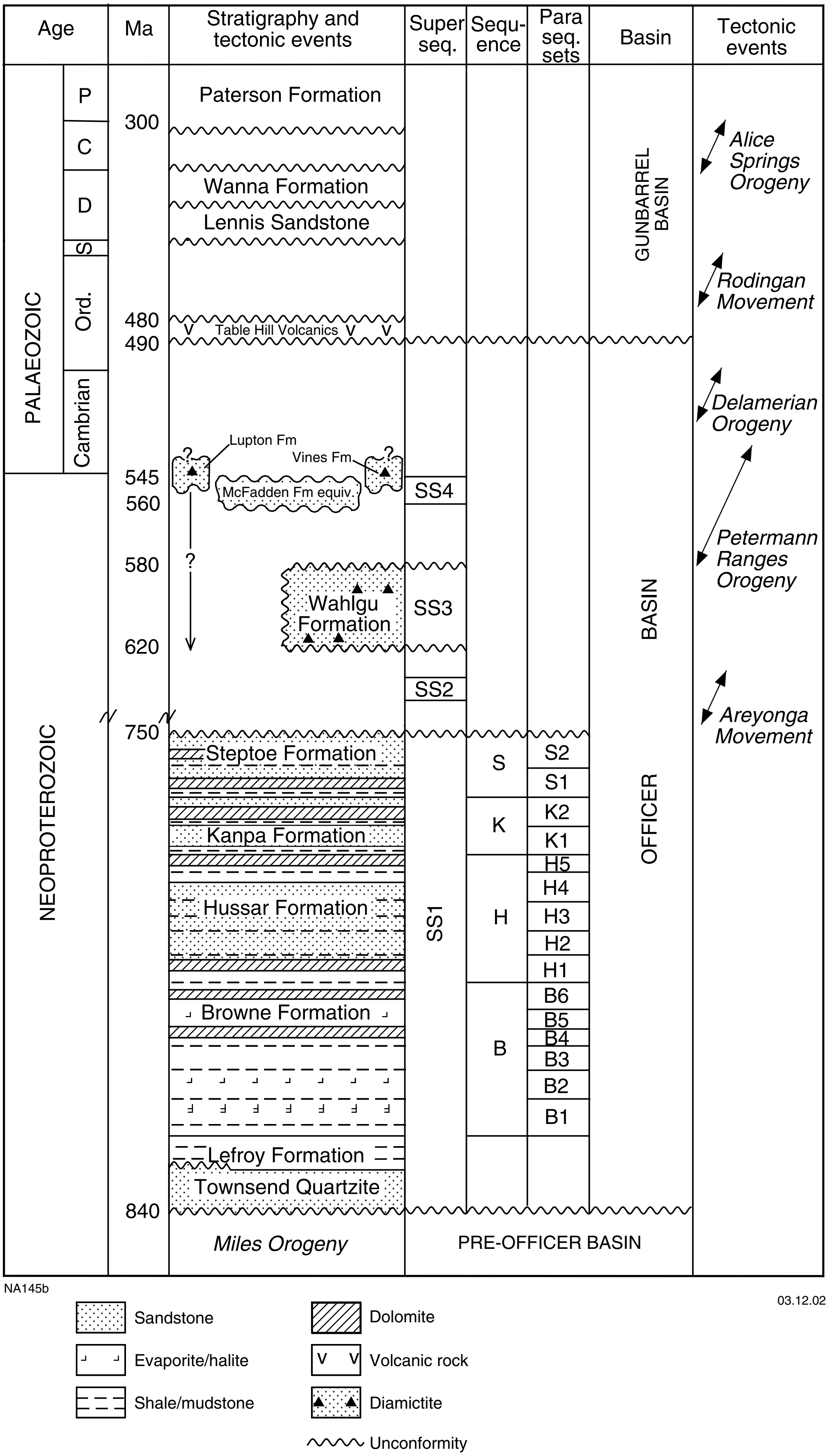

Figure 5. Generalized stratigraphy and tectonic events in the Officer Basin (after Moors and Apak, 2002)

Sandstones, which are conformably overlain by the Murraba Formation. The Erica Sandstone, unconformably overlying the Murraba Formation, is the youngest formation of the Redcliff Pound Group. The total thickness is probably greater than 2 km. The Redcliff Pound Group may be equivalent to Supersequence 1 of the Centralian Superbasin (Walter and Gorter, 1994; Tyler et al., 1998).

Amadeus Basin

The Amadeus Basin is a remnant of an intracratonic depression that had an east–west length of about 800 km, with a maximum cumulative thickness of about 14 km of latest Mesoproterozoic to Middle Palaeozoic sediments (Kennard et al., 1986). The basin has an area of about 170 000 km^2. Lindsay and Korsch (1991) suggested that the Amadeus Basin evolved in three main stages. Stage 1 began at about 900 Ma with an extensional and/or thermal event, followed by subsidence driven by thermal relaxation of the lithosphere. Stage 2 involved a less intense episode of extension, followed by subsidence at about 580 Ma. This was followed by Stage 3 with a major compressional event beginning at about 450 Ma, which resulted in the shortening of the basin by about 50–100 km and effectively concluded the sedimentation. Detailed studies of the Neoproterozoic and Early Palaeozoic sedimentary successions have led to the recognition of at least 19, and possibly 24, depositional sequences (Lindsay and Korsch, 1991). The onset of rifting may have actually occurred at c. 1050 Ma if the Dixon Range 'beds' are correlated with the Bloods Range 'beds' in the Musgrave Complex (Scrimgeour et al., 1999).

The regional geology of the Amadeus Basin was initially discussed by Forman (1966). The results of geological and geophysical studies carried out during 1983–91 are given in Korsch and Kennard (1991). Descriptions of the geology of the northern Amadeus Basin are also given in Kennard et al. (1986). Walter et al. (1995) and Walter and Veevers (2000) in their discussions on the Neoproterozoic of Australia referred to the geological units and evolution of the Amadeus Basin.

The Western Australian portion of the Amadeus Basin is about one tenth (about 17 000 km^2) of the total area of the basin and is referred to as the western Amadeus Basin (Grey, 1990b). The western Amadeus Basin is located on MACDONALD, RAWLINSON, WEBB, WILSON, RYAN, and COBB, and has a latest Mesoproterozoic to Neoproterozoic sequence of rocks, with the exception of a few small Ordovician and Silurian remnants and scattered, thin Permian–Carboniferous glacially influenced deposits (Hocking, 1994). The Permian cover extends eastwards from the Canning and Officer Basins. A description of the depositional sequences and stratigraphy in the western Amadeus Basin has been provided in Grey (1990b).

Gunbarrel Basin

The Phanerozoic Gunbarrel Basin consists of an undeformed, northward-thickening sequence of Palaeozoic and Mesozoic rocks that was previously included in the Officer

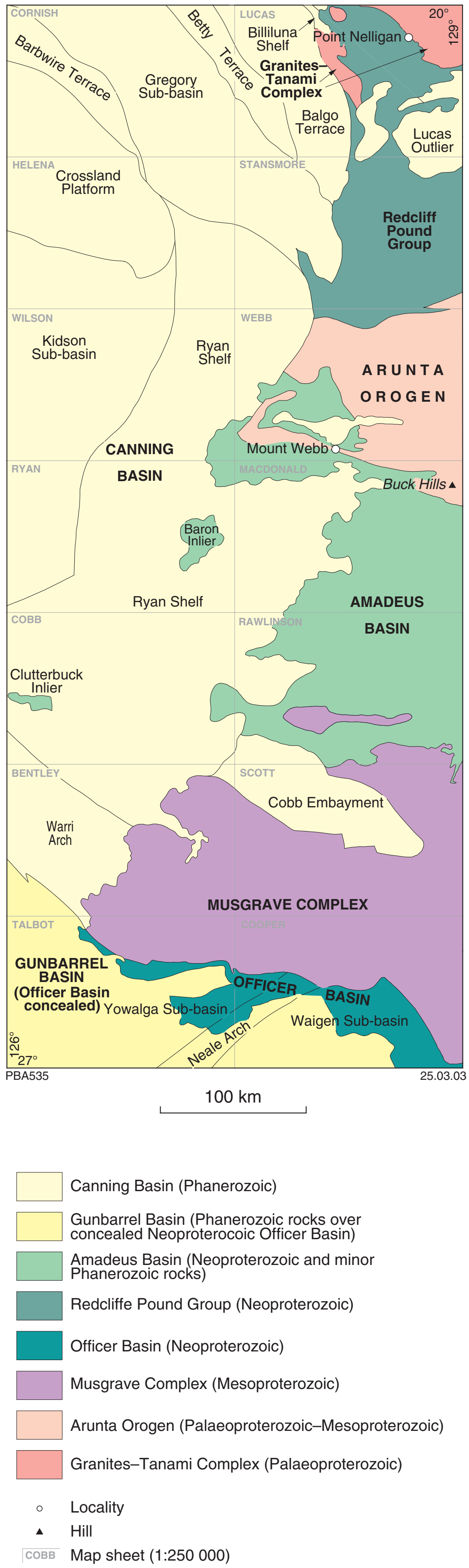

Figure 6. Sub-basins in the Canning Basin and other tectonic units of the Arunta–Musgrave area

Basin (Hocking, 1994; Hocking et al., 1994; Hocking and Preston, 1998; Apak and Moors, 2000, 2001). The Gunbarrel Basin onlaps the Yilgarn Craton and adjacent units, overlies the Officer Basin, and is onlapped by the Cainozoic sequence of the Eucla Basin. The Officer and Gunbarrel Basins have been differentiated because there is folding of the Neoproterozoic succession in the Officer Basin and above this the eruption of the Ordovician Table Hill Volcanics in the Gunbarrel Basin represents a significant and widespread magmatic event.

In Western Australia, the Gunbarrel Basin succession is up to 1.5 km thick, and contains Cambrian volcanics overlain by ?Devonian, Upper Carboniferous – Lower Permian, and Cretaceous siliciclastic rocks (Jackson and van de Graaff, 1981; Iasky, 1990; Hocking, 1994). Cambrian and Ordovician siliciclastic rocks are present in South Australia. The Kingston Shelf contains a sequence of Phanerozoic sedimentary rocks that is less than 1 km thick and overlies Precambrian rocks of the Yilgarn Craton and Albany–Fraser Orogen. The Sherriff Shelf overlies sedimentary rocks of the Officer Basin and contains a 1.5 km-thick sequence of sedimentary and volcanic rocks (Hocking, 1994).

Canning Basin

The Phanerozoic Canning Basin is the largest (approximately 550 000 km^2) sedimentary basin in Western Australia and contains Ordovician, Silurian – Lower Devonian, Devonian – Lower Carboniferous, Upper Carboniferous – Permian, Triassic, Jurassic, and Lower Cretaceous sequences. The Mesozoic sequences are essentially veneers that extend outwards from the main Mesozoic depocentres in the Roebuck Basin, forming the western portion of the Canning Basin that is located offshore to the northwest (Hocking, 1994).

Only about 25% of the Canning Basin occurs within the Arunta–Musgrave study area of this Record. The subdivisions of the Canning Basin present in the Arunta–Musgrave area are the Ryan Shelf, Kidson Sub-basin, Gregory Sub-basin, Crossland Platform, Cobb Embayment, Warri Arch, Barbwire Terrace, Betty Terrace, Balgo Terrace, and Billiluna Shelf (Fig. 6). Descriptions of these subdivisions have been provided in Hocking (1994) and Hocking et al. (1994).

Regolith

Regolith is the unconsolidated to indurated rock layer on bedrock and consists of a variety of transported or residual materials that are the products of weathering, mass wasting, erosion, and transport (Hocking and Cockbain, 1990; Hocking et al., 2001). A digital dataset of the regolith layer (1:500 000) of the Arunta–Musgrave is included on the CD-ROM that accompanies this Record. This digital map was compiled from the 1:250 000 map sheets of CORNISH, LUCAS, HELENA, STANSMORE, WILSON, WEBB, RYAN, MACDONALD, COBB, RAWLINSON, BENTLEY, SCOTT, TALBOT, and COOPER, The various regolith units identified from the 14 map sheets are lacustrine (*L*), alluvium/fluvial (*A*), colluvium (*C*), sandplain (*S*), duricrust (*Rf*), calcrete (*Rk*), and exposed rock (*X*). Included in the lacustrine units are inland lakes, dune and playa terrain, saline and freshwater playas and claypans, and minor eolian deposits directly associated with the lake system. Grouped under alluvium/fluvial units are alluvial deposits in channels and floodplains. The colluvium unit includes proximal mass-wasting deposits grading into sheetwash with a significant to perceptible slope. Also classified under colluvium are sand, silt, and clay in alluvial and eolian depressions. Sandplains include sand of mixed origin, which includes residual, sheetwash, and eolian sands. Included in duricrust are pisolitic and ferruginous pisoliths. Grouped under calcrete are surficial sand and gravel cemented into a hard mass by calcium carbonate. Exposed rock includes fresh rock, weathered rock, subcrop, and bouldery lag.

Mineralization

Most (71) of the 89 mineral occurrences known to date in the Arunta–Musgrave are within the Musgrave Complex (Fig. 7; Table 1). Only one mineral occurrence is known in the Arunta Orogen and none in the Granites–Tanami Complex, although recent exploration to the east and north (in the Northern Territory, South Australia, and Western Australia) shows that the Granites–Tanami Complex and the Arunta Orogen are highly prospective for metallic minerals, particularly gold.

No significant mineral occurrences are yet known in the sedimentary basins in the Arunta–Musgrave, but of the remaining 16 mineral occurrences known, ten are in the Canning Basin, five in the Amadeus Basin, and one in the Gunbarrel Basin.

The following discussion is a brief overview of the mineralization patterns of the tectonic units in the study area.

Musgrave Complex

The first significant mineralization was discovered in 1955 by Southwestern Mining (a subsidiary of INCO) at Wingellina in the Giles Complex. The company located large deposits of lateritic nickel and undertook a number of assessment programs between 1955 and 1970, including drilling and bulk sampling from costeans and shafts. The mineralization is developed in ochre in the regolith, resulting from the deep weathering of sheared pyroxenites and dunites in the Hinckley Range Gabbro. The ochre is enriched in cobalt and manganese (Sprigg and Rochow, 1975; Marston, 1984; Glikson et al., 1996).

An early resource estimate for the nickel laterite deposits was reported by Nickel Mines of Australia NL (a joint venture partner with INCO at Wingellina) as 56 Mt averaging 1.24% Ni (for 0.697 Mt contained nickel) and 0.09% Co (Sprigg and Rochow, 1975).

Nickeliferous ochre deposits in the Giles Complex also occur to the east of Wingellina in South Australia (Heirn, 1975).

Minor chromite and chrysoprase are also present in the

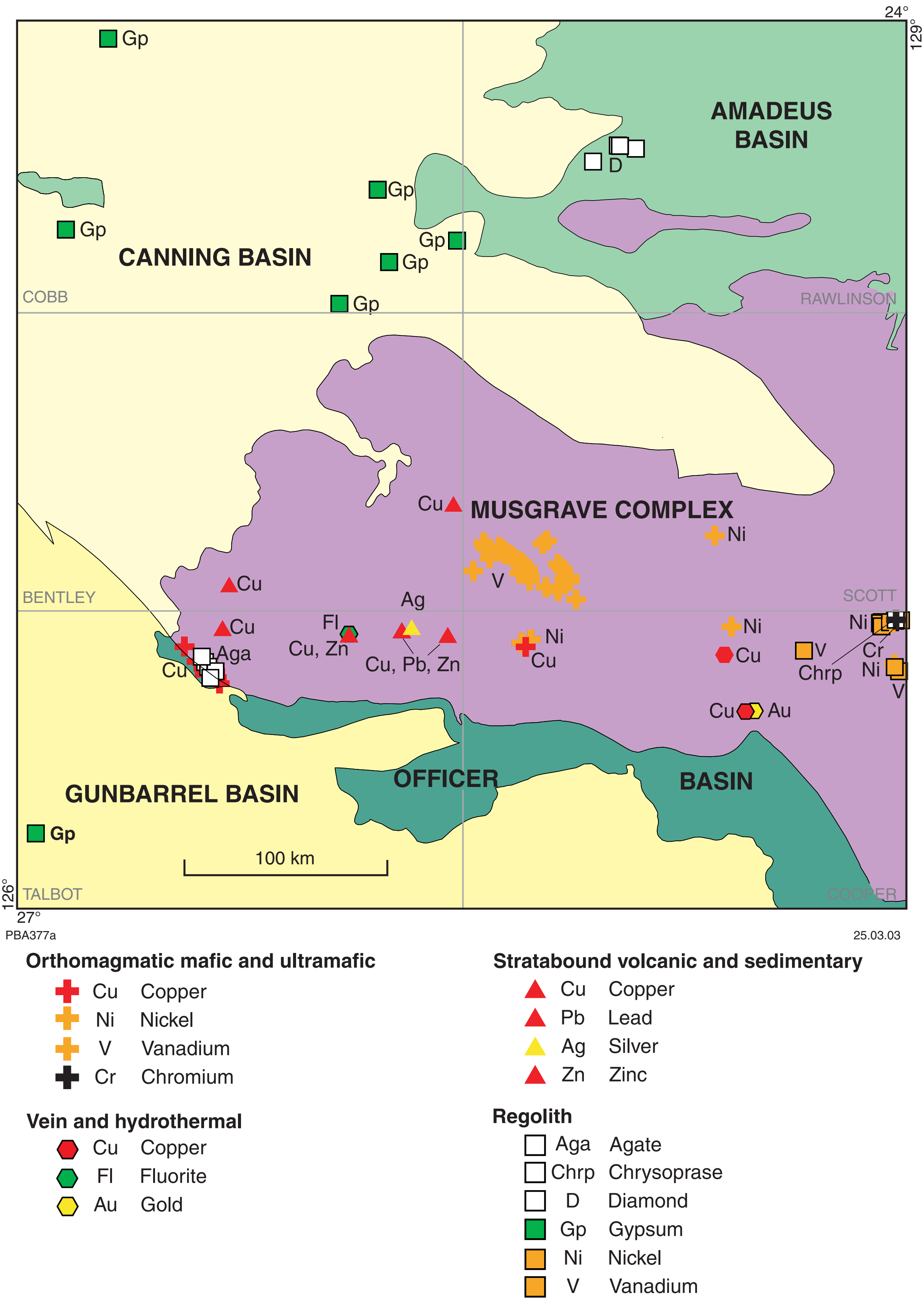

Figure 7. Mineral occurrences in the Musgrave Complex and adjacent tectonic units

Table 1. Mineral occurrences in the Arunta–Musgrave area

*Number**	*Commodity*	*Latitude (S)*	*Longitude (E)*	*Deposit name*
BASE METAL				
Orthomagmatic mafic and ultramafic — undivided				
10483	Cu	26°07'12"	126°33'59"	Warburton 1 (Cu)
10484	Cu	26°10'13"	126°36'27"	Warburton 2 (Cu)
10488	Cu	26°11'55"	126°38'32"	Warburton 3 (Cu)
10485	Cu	26°12'44"	126°38'06"	Warburton 4 (Cu)
10489	Cu, Aga	26°12'12"	126°40'10"	Warburton 5 (Cu)
10493	Cu	26°13'24"	126°40'26"	Warburton 6 (Cu)
10494	Cu	26°14'38"	126°41'02"	Warburton 7 (Cu)
Stratabound volcanic and sedimentary — undivided				
10437	Cu	26°03'30"	126°41'38"	Pussy Cat Hill
10497	Cu	25°54'45"	126°42'55"	Scamp Hill
10498	Zn, Pb, Cu	26°04'55"	127°26'55"	Mount Eliza
10499	Cu, Pb, Ag, Zn	26°03'57"	127°17'40"	Mount Palgrave
10514	Cu	25°38'30"	127°28'02"	Domeyer Hill
Disseminated and stockwork in plutonic intrusions				
10621	Cu, Au, Ag	22°48'55"	127°45'05"	Mount Webb (location approximate)
Vein and hydrothermal — undivided				
10436	Cu	26°08'55"	128°22'35"	Tollu
10495	Cu, trace of Au	26°20'15"	128°28'35"	Skirmish Hill
13020	Au, Cu	26°12'29"	128°05'44"	Voyager 2 SE
INDUSTRIAL MINERAL				
Sedimentary — undivided				
10515	Phos	20°08'35"	127°55'05"	Balgo Community
Regolith — residual and supergene				
10434	Chrp, Co	26°01'50"	128°56'58"	Wingellina (chrysoprase)
Stratabound volcanic and sedimentary — undivided				
10512	Fl, Cu, Zn	26°04'45"	127°07'05"	Mount Elvire
Undivided				
1521	Gp	20°09'11"	127°31'05"	Lake Gregory
3852	Gp	20°13'06"	127°30'56"	Gregory Salt Lake
3871	Gp	24°45'36"	127°28'43"	Christopher Lake
3872	Gp	24°04'55"	126°18'35"	Lake Cobb
3873	Gp	20°56'09"	128°57'35"	Lake Dennis
3874	Gp	24°49'55"	127°15'05"	Lake Farnham
3875	Gp	24°35'20"	127°12'47"	Lake Farnham North
3876	Gp	20°56'09"	128°50'05"	Lake Lucas
3877	Gp	23°29'55"	128°57'35"	Lake MacDonald
3878	Gp	24°43'21"	126°10'05"	Lake Newell
3879	Gp	24°58'17"	127°05'05"	Van Der Linden Lakes
10491	Aga	26°09'18"	126°37'26"	Warburton 8 (agate)
10486	Aga	26°10'22"	126°38'02"	Warburton 9 (agate)
10487	Aga	26°11'19"	126°38'43"	Warburton 10 (agate)
10492	Aga	26°13'33"	126°39'07"	Warburton 11 (agate)
10513	Gp	26°44'52"	126°04'00"	Baker Lake
STEEL INDUSTRY METAL				
Orthomagmatic mafic and ultramafic — layered mafic intrusions				
10447	Ni	26°03'10"	128°24'03"	Blackstone Range
10517	Ni, Cu	26°06'26"	127°41'49"	West Musgrave, Babel
10518	Ni, Cu	26°05'43"	127°43'38"	West Musgrave, Nebo
Orthomagmatic mafic and ultramafic — undivided				
10428	V	25°57'45"	127°52'42"	Finlay Range
10445	Ni	26°10'46"	128°56'45"	Michael Range
10506	V	25°56'04"	127°49'05"	Mount Elliott 1
10510	V	25°55'13"	127°46'41"	Mount Elliott 2
10508	V	25°52'26"	127°41'21"	Jamieson Range Zone 4
10509	V	25°51'26"	127°49'51"	Jamieson Range, Turkey Hill

Table 1. (continued)

*Number**	*Commodity*	*Latitude (S)*	*Longitude (E)*	*Deposit name*
10446	V	25°52'00"	127°32'04"	Pine Tree Rock
10659	Cr, Co, Ni, Chrp	26°01'45"	128°56'51"	Wingellina
10481	V	25°46'16"	127°34'08"	Jamieson Range 1
10480	V	25°47'01"	127°34'25"	Jamieson Range 2
10479	V	25°47'30"	127°34'50"	Jamieson Range 3
10478	V	25°49'25"	127°35'22"	Jamieson Range 4
10477	V	25°47'10"	127°37'17"	Jamieson Range 5
10476	V	25°47'27"	127°37'25"	Jamieson Range 6
10475	V	25°47'42"	127°38'00"	Jamieson Range 7
10473	V	25°47'48"	127°37'51"	Jamieson Range 8
10474	V	25°47'46"	127°38'06"	Jamieson Range 9
10472	V	25°48'12"	127°38'12"	Jamieson Range 10
10471	V	25°48'26"	127°38'26"	Jamieson Range 11
10470	V	25°48'38"	127°38'42"	Jamieson Range 12
10469	V	25°48'44"	127°39'26"	Jamieson Range 13
10467	V	25°49'15"	127°40'04"	Jamieson Range 14
10466	V	25°49'46"	127°40'38"	Jamieson Range 15
10465	V	25°50'09"	127°41'30"	Jamieson Range 16
10464	V	25°50'35"	127°41'55"	Jamieson Range 17
10463	V	25°50'58"	127°42'20"	Jamieson Range 18
10462	V	25°51'32"	127°42'59"	Jamieson Range 19
10461	V	25°51'39"	127°43'05"	Jamieson Range 20
10460	V	25°53'00"	127°43'24"	Jamieson Range 21
10458	V	25°53'54"	127°43'22"	Jamieson Range 22
10457	V	25°53'22"	127°50'24"	Jamieson Range 23
10456	V	25°53'25"	127°50'54"	Jamieson Range 24
10455	V	25°53'50"	127°50'56"	Jamieson Range 25
10454	V	25°53'58"	127°51'26"	Jamieson Range 26
10453	V	25°53'58"	127°51'27"	Jamieson Range 27
10452	V	25°53'14"	127°51'28"	Jamieson Range 28
10451	V	25°50'37"	127°49'06"	Jamieson Range 29
10448	V	25°46'31"	127°46'00"	Jamieson Range 30
8310	V	25°45'53"	127°46'52"	Jamieson Range 31
Regolith — residual and supergene				
10426	Ni, Co, Cr, Chrp	26°02'00"	128°58'04"	Wingellina (INCO) No. 1
10429	Ni, Co, Cr, Chrp	26°02'04"	128°56'49"	Wingellina (INCO) No. 2
10430	Ni, Co, Cr, Chrp	26°02'22"	128°54'12"	Wingellina (INCO) No. 3
10432	Ni, Co, Cr, Chrp	26°02'33"	128°53'52"	Wingellina (INCO) No. 4
10433	Ni, Co, Cr, Chrp	26°03'11"	128°54'08"	Wingellina (INCO) No. 5
10435	Ni, Co	26°02'20"	128°55'48"	Wingellina (INCO) Shaft 1
10519	Ni, Co, Cr, Chrp	26°02'23"	128°56'22"	Wingellina (Acclaim)
10438	V	26°08'07"	128°38'33"	Northwest Bell Rock Range
10439	V	26°12'13"	128°57'38"	Central Michael Hills 1
10440	V	26°11'24"	128°56'48"	Central Michael Hills 2
PRECIOUS MINERAL				
Regolith — alluvial placers				
10500	Dmd	24°29'40"	127°56'05"	Mount Destruction W
10503	Dmd	24°27'03"	128°04'41"	Mount Destruction NNE
10504	Dmd	24°26'26"	128°01'01"	Mount Destruction 1 NNW
10505	Dmd	24°26'30"	128°01'31"	Mount Destruction 2 NNW

NOTE:

Ag	silver	Fl	fluorite
Aga	agate	Gp	gypsum
Chrp	chrysoprase	Ni	nickel
Co	cobalt	Pb	lead
Cr	chromium	Phos	phosphate
Cu	copper	V	vanadium
Dmd	diamond	Zn	zinc

* **KEY TO OPERATING STATUS:** Plain numbers — mineral deposit; italic numbers — mineral occurrence or prospect

nickeliferous deposits at Wingellina (Daniels, 1974). There are rare occurrences of chromite elsewhere in the Giles Complex and these include a 1.5 cm-thick layer of chromitite at Mount Davies in the Giles Complex in South Australia (Coats, 1956) and chromite grains in pegmatoid pyroxenite in the Wigellina intrusion (Ballhaus and Glikson, 1989).

The lateritic nickel deposits at Wingellina are currently being reassessed by Acclaim Exploration, and the company recently announced estimated measured, indicated, and inferred resources of 227 Mt at 1% nickel for 2.3 Mt of contained nickel. Drilling by Acclaim Exploration has established that the nickel–cobalt oxide mineralization at Wingellina extends to depths of 200 m, well below the level of holes drilled by INCO between 1958 and 1971. New interpretation of the regional geology has shifted the focus of sulfide nickel exploration to the basement gneiss, where targets have been identified for further testing. Acclaim considers that the basal contact intersected by drilling has further enhanced the prospectivity of the Wingellina layered intrusion for nickel sulfide mineralization (Acclaim Exploration NL, 2002).

Significant nickel sulfide mineralization has recently been discovered by WMC Ltd at the Nebo and Babel deposits, in layered mafic rocks in the Giles Complex of the west Musgrave area, about 125 km to the west of Wingellina (WMC Ltd, 2002). The two deposits are 4 km apart and were located in 2000 within areas of gabbronorite, leucogabbronorite, olivine dolerite, and other mafic rocks.

Nebo was identified as an electromagnetic anomaly interpreted as a south-dipping sheet-like body at least 1400 m long. Drilling to test the anomaly intersected 62 m averaging 1.14% Ni, 0.87% Cu, 0.04% Co, and 0.4 g/t platinum group metals and gold. This intersection includes 26.5 m averaging 2.45% Ni, 1.78% Cu, 0.09% Co, and 0.74 g/t precious elements. The mineralized body was intersected 50 m beneath the surface.

Babel was identified as overlapping electromagnetic anomalies, and drilling intersected disseminated sulfides over 148.9 m (from 51 m beneath the surface) averaging 0.3% Ni, 0.42% Cu, 0.01% Co, and 0.29 g/t precious metals. Further drilling at Babel in the latter part of 2001 gave an intersection of 21 m (true thickness) at 0.8% Ni, 1.4% Cu, and 0.34 g/t Pt and Pd (WMC Ltd., 2001).

WMC undertook diamond drilling in 2002 to test for high-grade and massive orebodies in and around the Babel and Nebo prospects, and also at another prospect known as Gerar that is located 10 km north of Babel. One drillhole at Babel intersected 41.6 m averaging 0.81% Ni and 1.37% Cu, from about 34 m beneath the surface (WMC Ltd, 2002, 2003).

About 30 km north of Nebo and Babel drilling by WMC has intersected anomalous concentrations of titanium, vanadium, and precious metals within bands of magnetite (WMC Ltd, 2000).

West Musgrave Mining Ltd is also exploring for nickel sulfides and platinum group elements in layered mafic intrusions in the west Musgrave area and has identified numerous geophysical targets in areas east of the Nebo and Babel prospects. The company reported that it had also located copper–gold mineralization in a quartz vein in Tollu Group volcanic rocks about 8 km southeast of Voyager 2 in the company's Cavenagh Range project area. The mineralized quartz vein is up to 2 m wide and can be traced for approximately 300 m. Samples returned maximum values of 5.3 g/t Au and 6.34% Cu. Reconnaissance drilling by West Musgrave Mining has tested geophysical and geochemical targets at the Voyager 1, Voyager 2, and Rosetta prospects. Three holes were drilled at Voyager 1, six holes at Voyager 2, and two holes at Rosetta. The holes varied in depth from 40 to 195 m. Results included an intersection of 28 m at 0.10% Cu and 0.10 g/t Pt–Pd–Au from 64 m depth and an intersection of 14 m at 0.05% Cu and 0.27 g/t Pt–Pd–Au from 82 m depth. The company considers the results to be encouraging, given the broad-spaced reconnaissance nature of the drilling and the absence of previous exploration in the region. West Musgrave Mining has recently entered a joint venture with BHP Billiton to explore its west Musgrave areas (West Musgrave Mining Ltd, 2002a,b,c,d).

ReLode Ltd has large tenement holdings to the east and northwest of Warburton and has identified two nickel–sulfide targets 40 km south of Wingellina at Bell Rock Range, based on interpretations of gravity and magnetic data. The company has also identified two other priority areas at Round Hill and Morgan Range. The Round Hill area has potential for copper–gold mineralization and Morgan Range (within the Giles Complex) is being tested for nickel sulfide mineralization (ReLode Ltd, 2002).

Other important mineral commodities in the Musgrave Complex are vanadium and copper (Daniels, 1974; Baxter, 1978; Glikson et al., 1996; Tyler et al., 1998). The most significant vanadium occurrences are associated with the titaniferous magnetite bands in ultramafic and mafic rocks of the Jameson Range Gabbro of the Giles Complex. Vanadium was also found in regolith samples collected by South Western Mining Ltd (INCO subsidiary) from the Michael Hills and Bell Rock Range areas (Laine, 1968).

The copper mineralization in the area is mainly of two types. One type is related to the felsic volcanic rocks found at Tollu, Pussy Cat Hill, Mount Elvire, Scamp Hill, Mount Palgrave, Mount Eliza, and Domeyer Hill; and the other type is related to the basaltic rocks in the Warburton area. In association with copper, there are small occurrences of fluorite, lead, zinc, silver, agate, and gold, all in the Musgrave Complex, associated with felsic volcanic rocks (Daniels, 1974; Baxter, 1978; Glikson et al., 1996; Tyler et al., 1998).

In the vicinity of the Wingellina nickel deposit, chrysoprase has been produced intermittently from a deposit north of the no. 2 laterite nickel orebodies. The chrysoprase occurs in discontinuous layers within the regolith developed over the Hinckley Range Gabbro.

Ballhaus and Glikson (1995) suggested that any sulfide – platinum group element (PGE) mineralization of the Giles Complex in the Musgrave Complex may be restricted to single cumulative sequences. They also suggested that prospects for the Giles Complex for magmatic chromite–sulfide–PGE mineralization are considerably limited, as the intrusions have important differences from economically important complexes such as the Bushveld, Great Dyke, and Stillwater Intrusions. In their view, the Giles Complex intrusions cooled faster than the above layered intrusions, thus leaving less chance for the efficient accumulation of elements such as PGEs. Chromite layers are also lacking, probably because the melt became depleted in Cr at an early stage owing to high-pressure clinopyroxene fractionation (Ballhaus and Glikson, 1995; Glikson et al., 1996). However, Tyler et al. (1998) suggested that the large size and inadequate knowledge of the Giles Complex makes it a prime target for both magmatic and hydrothermal mineral deposits; a suggestion vindicated by the WMC discovery in 2000 (WMC Ltd, 2002).

Arunta Orogen

Recent work in the Arunta Orogen in Western Australia and in the Northern Territory by Geoscience Australia and the Northern Territory Geological Survey indicate that the mafic–ultramafic intrusions in the western and central Arunta Province have some potential for Ni–Cu–Co sulfide deposits, and that the eastern Arunta Province could be prospective for PGE mineralization (Wyborn et al., 1998; Hoatson, 2001; Geoscience Australia, 2002). Wyborn et al. (1998) stated that the primary and alteration geochemistry of the felsic rocks of the Mount Webb region in Western Australia resemble those of Proterozoic Cu–Au mineralized areas elsewhere in Australia. There is evidence of extensive magmatic alteration (sodic–calcic and sericitic) at some localities, particularly within felsic varieties of granite.

At the time of writing this Record, only one mineral occurrence has been recorded in the Arunta Orogen. This is a copper, silver, and gold occurrence in the Mount Webb area, found by Aurora Gold Ltd in 1997. Samples from this locality returned results of 9.1% Cu, 3 ppm Ag, and 0.38 ppm Au over a true width of 4 m, and 0.3% Cu and 8 ppm Ag over a true width of 10 m (Aurora Gold Ltd, 1997). An aircore-drilling program by Aurora Gold in this locality (along three adjacent 800 m-spaced grid lines) returned highest values of 0.21 ppm Au, 896 ppm Cu, and 1.6 ppm Ag.

Granites–Tanami Complex

In the Arunta–Musgrave, no mineral occurrences have been identified in the Granites–Tanami Complex, although there is potential for mineralization similar to that in the Northern Territory, where the complex represents one of Australia's most important new gold provinces. Within Western Australia, to the north of the study area, gold mineralization occurs in the Granites–Tanami Complex on BILLILUNA (Hassan, 2000; Geological Survey of Western Australia, 2002) and exploration for gold is currently in progress in the Granites–Tanami Complex in the study area.

In the Northern Territory, there are more than 50 gold occurrences, including three established goldfields — Dead Bullock Soak, The Granites, and Tanami (Blake et al., 1979; Mayer, 1990; Nicholson, 1990; Smith et al., 1998; Tunks and Marsh, 1998; Wygralak et al., 2001; Wygralak and Mernagh, 2001; Dean, 2001). The region has produced 121 t of gold, with another known resource of 190 t of gold remaining. The Dead Bullock Soak goldfield is the largest in the Tanami region, with a total resource of 23.6 Mt at 5.6 ppm gold (Wygralak and Mernagh, 2001). Stratabound mineralization is hosted in carbonaceous siltstone, iron-rich rocks, and chert of the Dead Bullock Formation that have been metamorphosed to greenschist facies. Gold mineralization is also known in BIF and chert. Unlike other goldfields in the Tanami region, in the Dead Bullock Soak goldfield there is no close spatial association between gold mineralization and granitoids (Wygralak et al., 2001; Wygralak and Mernagh, 2001). The Granites goldfield has a total resource of 1.9 Mt at 3.8 ppm gold and contains stratabound mineralization within intensely folded, amphibolite-facies iron-rich rocks of the Dead Bullock Formation (Wygralak and Mernagh, 2001). The ore is hosted in amphibole–garnet–magnetite schist with up to 15% sulfides. Unlike the Dead Bullock Soak goldfield, there is a close spatial association of mineralization and granite. The Inningarra and The Granites granite suites (1815 ± 4 and 1795 ± 5 Ma respectively) occur in close proximity to the mineralization (Wygralak et al., 2001). The Tanami goldfield has a total resource of 7.2 Mt at 3.2 ppm gold, and consists of weakly deformed basalt and medium-grained clastic sediments of the Mount Charles Formation that contain quartz veins (Wygralak and Mernagh, 2001; Wygralak et al., 2001). Petrographic and geochemical studies of the granitic rocks in the Tanami region indicate a magmatic component to the mineralizing fluids (Dean, 2001). Dean (2001) suggested that felsic intrusive rocks provided magmatic fluids and the thermal environment to drive hydrothermal systems, and that the younger intrusive rocks of the area may have been important in this respect.

Amadeus Basin

There are no significant mineral occurrences in the study area, but there have been some encouraging results from diamond exploration. In four localities in the area north of Mount Destruction, seven microdiamonds were recovered from three loam samples. In addition, one microdiamond and possibly one grain of pyrope were recovered from a composite sample (5 m) of a drillhole on a magnetic anomaly north of Mount Destruction. The drillhole has possibly intersected weathered kimberlite. One occurrence of gypsum is also known in a lake deposit in regolith overlying the basin.

Canning Basin

Mineralization in the Canning Basin in the Arunta–Musgrave is limited to 11 gypsum occurrences, and a minor phosphate occurrence in the Permian Noonkanbah Formation on LUCAS. The gypsum deposits are in the lake deposits of the regolith.

The Canning Basin is currently being explored for many minerals including base metals, diamond, gold, and petroleum. Most of the known deposits and exploration activities are around the Lennard Shelf area, outside the Arunta–Musgrave. The prospectivity of the Canning Basin (mainly the Fitzroy Trough – Lennard Shelf area) for base metals has been discussed in Rasmussen et al. (1997). Vearncombe et al. (1995) have discussed the regional- and prospect-scale fault controls on Mississippi Valley-type Zn–Pb mineralization in the Canning Basin. The prospectivity for petroleum in the Canning Basin has been discussed in Apak and Carlsen (1997), Havord et al. (1997), Crostella, (1998), and Apak and Backhouse (1999).

Officer, Gunbarrel, and Murraba Basins

At present, only one gypsum occurrence is known in the Gunbarrel Basin. There is no known mineralization in the study area within the Officer Basin or within the Redcliffe Pound Group of the Murraba Basin.

The western Officer Basin has been explored for various minerals including petroleum and evaporite minerals. Mineral potential of the western Officer Basin has been discussed in Jackson (1979). The petroleum potential of the western Officer Basin has been discussed in Ghori (1998a,b), Carlson et al. (1999), and Apak and Moors (2000, 2001). The exploration activities for evaporite minerals at the Woolnough Hills and Madley diapirs in the Officer Basin in Western Australia have been discussed in Wells and Kennewell (1974).

Conclusions

The Arunta–Musgrave area is a large and remote underexplored region of Western Australia. The most prospective parts are the Musgrave Complex (nickel, cobalt, copper, vanadium, chromium, platinum, zinc, and silver) and the Granites–Tanami Complex (gold), based on results from past and current exploration, and analogies with known areas of mineralization in adjacent parts of these tectonic units in the Northern Territory and South Australia. The Arunta Orogen (gold and base metals) is also considered to be prospective, based on recent mineral-exploration results that have been obtained in the Northern Territory. Diamond potential has been highlighted by preliminary surveys in the Amadeus Basin.

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Appendix 1

Description of digital datasets on CD-ROM

There are two main parts of this study — this Record and a CD-ROM containing digital datasets for use with database or GIS software. The CD-ROM includes all the data used to compile the Record, and also includes files of exploration and mining activity, geophysical, remote-sensing, and topographic data. The CD-ROM also includes the files necessary for viewing the data in the ArcView GIS environment, and a self-loading version of the ArcExplorer software package modified to suit this particular dataset.

Mineral occurrences (WAMIN)

The mineral occurrence dataset (from WAMIN, the Western Australian mineral occurrence database) as used in this Record is described in Appendix 2. The dataset on the CD-ROM includes textual and numeric information on:

- location of the occurrences (latitude and longitude, geological province, location method, and accuracy)
- commodities and commodity group
- mineralization classification and morphology
- order of magnitude of resource tonnage and estimated grade
- mineralogy of ore and gangue
- details of host rocks
- both published and unpublished references.

EXACT

The EXACT dataset (from EXACT, Geological Survey of Western Australia's spatial index of exploration activities) as used in this Record is described in Appendix 2. The dataset on the CD-ROM contains spatial and textual information (derived from the Western Australian mineral exploration (WAMEX*) database open-file reports) defining the locations and descriptions of exploration activities in the area. EXACT for the Arunta–Musgrave area was compiled between 1996 and 1998, and contains information on types of mineral exploration activity such as statistics relating to:

- report numbers
- sample types and numbers
- elements assayed
- metres of drilling and number of holes
- scales of presentation of the data.

Positional data were taken from hardcopy maps of various scales, from company reports (in WAMEX), or located from coordinate and/or geographical information (from topographic maps or Landsat images), and then digitized. Table 2.5 (Appendix 2) lists the exploration activity types.

The activity data are linked to more general data concerning the individual open-file reports (commonly defined in WAMEX by accession A-numbers) and individual exploration projects (commonly defined in WAMEX by open-file Item numbers). This information includes the company or companies involved in the project, the commodities explored for, the timing of the project, names of localities in the project, and a summary (annotation) of the project, including the exploration concept, activities, and a synopsis of the results.

WAMEX

All relevant open-file company mineral-exploration reports for the area, indexed in the Department of Industry and Resources (DoIR) WAMEX database were referred to for this study. Information extracted from these reports was used to analyse the historical trends in exploration activity and target commodities.

MINEDEX

The MINEDEX database (Townsend et al., 1996, 2000) has current information on all mines, process plants, and deposits, excluding petroleum and gas, for Western Australia. Mineral resources included in MINEDEX must conform with the Joint Ore Reserves Committee (JORC) (1999) code to be included in the database. The database contains information relevant to WAMIN under the following general headings:

- commodity group and minerals
- corporate ownership and percentage holding
- site type and stage of development
- location data (a centroid) including map, shire, mining district, and centre
- current mineral-resource estimates
- mineralization type
- tectonic unit
- tenement details.

MINEDEX contains all the relevant resource information and WAMIN uses the unique MINEDEX site number as a cross-reference for this information. WAMIN may contain pre-resource global estimates that do not conform to the JORC (1999) code, and are not included in MINEDEX.

TENGRAPH

The TENGRAPH database (DoIR's electronic tenement-graphics system) shows the position of mining tenements relative to other land information. TENGRAPH provides

* WAMEX, MINEDEX, and TENGRAPH are available on the DoIR website

information on the type and status of the tenement and the name(s) and address(es) of the tenement holders (Department of Minerals and Energy, 1994). It should be borne in mind that the tenement situation is constantly changing and that current tenement plans should be consulted before making any landuse-based decisions or applying for tenements.

Interpreted bedrock geology and regolith

The interpreted bedrock geology and regolith incorporates an interpretation of the study area, at 1:500 000 scale, based on a compilation of Geological Survey of Western Australia (GSWA) mapping. The full details of the solid geology and regolith are on the CD-ROM and in Appendix 3.

Geophysics

The aeromagnetic data covering the area are presented in the form of a total magnetic intensity (TMI) colour image. The data used to create the image were flown in 1995 for the National Geoscience Mapping Accord (between Geoscience Australia (formerly Australian Geological Survey Organisation) and GSWA), mostly at a line spacing of 400 m, and gridded to a cell size of 800 m for the colour image. More-detailed data, gridded to a cell size of 100 m, may be obtained from Geoscience Australia or GSWA.

Measurements of the background radiation using an airborne crystal usually took place concurrently with the Geoscience Australia aeromagnetic surveys over the area. The colour image on the CD-ROM shows the comparative K–Th–U ratios as red–green–blue (RGB). The data are relatively disparate in nature as variations in the crystal size and flying height were not tightly constrained over the area.

A regional gravity survey by Geoscience Australia, at a nominal station spacing of 11 km, is presented in the digital dataset as an image showing the Bouguer anomaly, gridded to a cell size of 5 km.

Landsat

Landsat TM imagery has been acquired for all the 1:250 000-scale map sheets in the Arunta–Musgrave study. The raw data are available commercially through the Remote Sensing Services section of the Department of Land Administration (DOLA). Images are included in the digital package that preserve the original 25 m pixel size, but these cannot be reverse-engineered back to any bands or band ratios of the original 6-band dataset.

Both image datasets comprise a patchwork of 1:250 000-scale map tiles. The simplest of the two uses a decorrelation stretch of the first principal component of bands 1, 2, 3, 4, 5, and 7, written out as an 8-bit dataset that can be viewed as a monochrome image. The second, more complex, image can be viewed in colour, and was created using a decorrelation stretch of bands 4, 5, and 7.

Cultural features

Selected roads and tracks are given as a single dataset, and range from sealed highways through shire roads to major station tracks. The digital data in this file were captured by digitizing from Landsat imagery.

Place names for the area, in a separate file, are given for major hills, stations, and communities. More-comprehensive topographical and cultural data, including drainage, can be obtained from the Australian Land Information Group (AUSLIG).

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Appendix 2

WAMIN and EXACT databases

WAMIN database (mineral occurrences)

The WAMIN (Western Australian mineral occurrence) database of the Geological Survey of Western Australia (GSWA) contains geoscience attribute information on mineral occurrences in Western Australia. The database includes textual and numeric information on the location of the occurrences, location accuracy, mineral commodities, mineralization-style classification, order of magnitude of resource tonnage and estimated grade, ore and gangue mineralogy, details of host rocks, and both published and unpublished references. Each of the occurrences in WAMIN is identified by a unique 'deposit number'.

The WAMIN database uses a number of authority tables to constrain the essential elements of a mineral occurrence, such as the operating status, the commodity group, and the style of mineralization. In addition, there are parameters that dictate whether the presence of a mineral or an analysed element is sufficiently high to rank occurrence status; this Record only deals with mineral occurrences. These and other attributes were extracted either from open-file mineral exploration reports in WAMEX (Western Australian mineral exploration database) or from the published literature.

Operating status

The database includes mineralization sites (referred to as deposits) ranging from small, but mineralogically significant, mineral occurrences up to operating mines. The classification includes all MINEDEX sites with established resources. MINEDEX is the Department of Industry and Resources (DoIR) mines and mineral deposits information database (Townsend et al., 1996, 2000). All occurrences in the WAMIN database are assigned a unique, system-generated number (deposit number). The system used to describe the operating status is:

- Mineral occurrence — any economic mineral exceeding an agreed concentration and size found in bedrock or regolith.
- Prospect — any working or exploration activity area that has found subeconomic mineral occurrences, and from which there is no recorded production.
- Mineral deposit — economic minerals for which there is an established resource figure.
- Abandoned mine — workings that are no longer operating, or are not on a care-and-maintenance basis, and for which there is recorded production, or where field evidence suggests that the workings were for more than prospecting purposes.
- Operating mine — workings that are operating, including on a care-and-maintenance basis, or that are in development leading to production.

The names of the occurrences, and any synonyms that may have been used, are derived from the published literature and from open-file reports (in WAMEX). Names that appear in the MINEDEX database have been used where possible, although there may be differences created because MINEDEX uses site names based on overall production and resources, whereas WAMIN may show names of individual occurrences at a MINEDEX site.

Commodity group

The WAMIN database includes a broad grouping that is based on the potential end-use or typical end-use of the principal commodities comprising a mineral occurrence, as listed in Table 2.1.

The commodity groupings are based on those published by the Mining Journal Limited (1998) with modifications, as shown in Table 2.2, to suit the range of minerals and end-uses for the mineral output of Western Australia.

Mineralization style

There are a number of detailed schemes for classifying mineral occurrences into groups representing different styles of mineralization, with the scheme of Cox and Singer (1986) probably being the most widely used. The application of this scheme in Western Australia would necessitate modifications to an already complex scheme, along the lines of those adopted by the Geological Survey of British Columbia (Lefebure and Ray, 1995; Lefebure and Hoy, 1996).

Table 2.1. WAMIN authority table for commodity groups

Commodity group	*Typical commodities*
Precious mineral	Diamond, semi-precious gemstones
Precious metal	Ag, Au, PGE
Steel-industry metal	Co, Cr, Mn, Mo, Nb, Ni, V, W
Speciality metal	Li, REE, Sn, Ta, Ti, Zr
Base metal	Cu, Pb, Zn, Sb
Iron	Fe
Aluminium	Al (bauxite)
Energy mineral	Coal, U
Industrial mineral	Asbestos, barite, kaolin, talc
Construction material	Clay, dimension stone, limestone

Table 2.2. Modifications made to the Mining Journal Limited (1998) commodity classification

Commodity group (Mining Journal Limited, 1998)	*Commodities*	*Changes made for WAMIN commodity group*
Precious metals and minerals	Au, Ag, PGE, diamonds, other gemstones	Diamond and other gemstones in precious minerals group; Au, Ag, and PGE in precious metals group
Steel-industry metals	Iron ore, steel, ferro-alloys, Ni, Co, Mn, Cr, Mo, W, Nb, V	Fe in iron group
Speciality metals	Ti, Mg, Be, REE, Zr, Hf, Li, Ta, Rh, Bi, In, Cd, Sb, Hg	Sn added from major metals; Sb into the base metals group
Major metals	Cu, Al, Zn, Pb, Sn	Cu, Pb, and Zn into the base metals group; Al (bauxite) into aluminium group; Sn in speciality metals
Energy minerals	Coal, U	No change
Industrial minerals	Asbestos, sillimanite minerals, phosphate rock, salt, gypsum, soda ash, potash, boron, sulfur, graphite, barite, fluorspar, vermiculite, perlite, magnesite/magnesia, industrial diamonds, kaolin	No change

GSWA has adopted the principles of ore deposit classification from Evans (1987) with some modifications based on Edwards and Atkinson (1986). This scheme works on the premise that 'If a classification is to be of any value it must be capable of including all known ore deposits so that it will provide a framework and a terminology for discussion and so be of use to the mining geologist, the prospector and the exploration geologist'. The system below is based on an environmental–rock association classification, with elements of genesis and morphology where they serve to make the system simpler and easier to apply and understand (Table 2.3).

Mineral occurrence determination limits

Any surface expression of mineralization (gossan or identified economic mineral) is an occurrence. Subsurface or placer mineralization is included as an occurrence where it meets the criteria given in Table 2.4.

Professional judgement is used if shorter intercepts or surface occurrences at higher grade (or vice versa) are involved. Any diamonds or gemstones would be mineral occurrences, including diamondiferous kimberlite or lamproite.

EXACT database (exploration activities)

The EXACT* database is a GIS-based spatial index, for exploration activities in WAMEX, that has been developed by GSWA to improve access to information in open-file mineral exploration reports (Ferguson, 1995). A major limitation to data retrieval in WAMEX, in its current form, is the difficulty in selecting reports that cover a specific area and, further, in precisely locating various individual exploration activities described within a selected report.

In the current WAMEX database, when spatial parameters are used to make data searches, the results of searches are constrained to very large areas. The smallest search polygon that can be effectively used to locate reports in WAMEX is the area of a 1:100 000-scale sheet. Even though a query may be entered as a single point (latitude/longitude coordinates), the resulting search will produce all reports for the 1:100 000-scale sheet in which that single point is located. Hence, for example, it is not possible to restrict report selection to small areas of prospective ground of particular interest to the user. As a consequence these WAMEX searches are time consuming, and they have become more time consuming as the number of open-file reports has increased with continuing releases of data.

The EXACT spatial index overcomes this problem and allows easy access to data on specific areas of previous exploration activity. It also provides a spatial representation of the intensity of past exploration, thereby highlighting prospective areas that may have been lightly or inadequately tested by various earlier exploration methods.

The spatial index consists of an attribute database, developed in Microsoft Access, that is linked to ArcView for spatial representation. On the CD-ROM, the dataset includes tabulated textual and numeric information that has been retrieved from open-file mineral exploration reports and attached to individual exploration activities. The areas of exploration activity are digitized (as polygons, lines, or points) using the computer-assisted

* The EXACT database is a GIS-based spatial index of **EX**ploration **ACT**ivities. This term supersedes the acronym SPINDEX (Spatial Index) used in Cooper et al. (1998), Ferguson (1998), and Hassan (1998).

Table 2.3. WAMIN authority table for mineralization styles and groups

Mineralization style	*Typical commodities*
Carbonatite and alkaline igneous intrusions	Nb, Zr, REE, P
Kimberlite and lamproite intrusions	Diamond
Disseminated and stockwork in plutonic intrusions	Cu, Mo, Au
Greisen	Sn
Pegmatitic	Sn, Ta, Nb, Li
Skarn	W, Mo, Cu, Pb, Zn, Sn
Orthomagmatic mafic and ultramafic — komatiitic or dunitic	Ni, Cu, Co, PGE
Orthomagmatic mafic and ultramafic — layered mafic intrusions	Ni, Cu, Co, V, Ti, PGE, Cr
Orthomagmatic mafic and ultramafic — undivided	Ni, Cu, Co, V, Ti, PGE, Cr
Vein and hydrothermal — undivided	Au, Ag, Cu, Pb, Zn, Ni, U, Sn, F
Vein and hydrothermal — unconformity	U
Stratabound volcanic and sedimentary — volcanic-hosted sulfide	Cu, Zn, Pb, Ag, Au
Stratabound volcanic and sedimentary — sedimentary-hosted sulfide	Pb, Zn, Cu, Ag
Stratabound volcanic and sedimentary — volcanic oxide	Fe, P, Cu
Stratabound volcanic and sedimentary — undivided	Pb, Zn, Cu, Ag, Au, Fe
Stratabound sedimentary — carbonate-hosted	Pb, Zn, Ag, Cd
Stratabound sedimentary — clastic-hosted	Pb, Zn, Cu, Au, Ag, Ba, Cd, U
Stratabound sedimentary — undivided	Pb, Ba, Cu, Au
Sedimentary — banded iron-formation (supergene-enriched)	Fe
Sedimentary — banded iron-formation (taconite)	Fe
Sedimentary — undivided	Mn
Sedimentary — basin	Coal, bitumen
Regolith — alluvial to beach placers	Au, Fe pisolites, Ti, Zr, REE, diamond, Sn
Regolith — calcrete	U, V
Regolith — residual and supergene	Al, Au, Ni, Co, Mn, V, Fe scree
Regolith — residual to eluvial placers	Au, Sn, Ti, Zr, REE, diamond
Undivided	Various

drafting (CAD) system Microstation, converted into ArcInfo, and then transferred into ArcView to enable an interactive display of EXACT. The positional data are digitized from hardcopy maps and plans in mineral exploration reports, using various published sources (geological maps, topographic maps, and TENGRAPH — DoIR's electronic tenement-graphics system) for geo-reference purposes. The types of exploration activity detailed are essentially those used in WAMEX, with some rationalization, and these are listed in Table 2.5. In the table, the 25 activities are grouped as follows:
- geological activities (and remote sensing activities)
- geophysical activities
- geochemical activities
- mineralogical activities
- drilling activities
- mineral resources
- hydrogeological activities.

The above groups relate to those specified in the statutory guidelines for mineral exploration reports (Department of Minerals and Energy, 1995).

For each separate exploration activity the following statistics have been compiled:
- description of activity
- sample types and numbers
- elements analysed (asterisk symbol (*) against elements for a rough guide to anomalism)
- metres of drilling and number of holes
- scales of presentation of data in reports.

The activity data are also linked in the dataset to the following related information taken from WAMEX:
- A-numbers (WAMEX accession numbers for individual reports)
- I-numbers (WAMEX item numbers for single or groups of reports on microfiche)
- company or companies that submitted reports
- period of exploration (years)
- mineral commodities sought
- summaries (annotations) of exploration projects included in individual item numbers.

In ArcView, the exploration activities are included as spatial **themes**, which are displayed as polygons, lines, or points on the interactive on-screen map known as the **view**. The **table of contents** (i.e. map legend) provided alongside the **view** allows access to the **themes**, so that any **theme** or combination of **themes** may be displayed. Details (taken from attribute tables) of any

Table 2.4. Suggested minimum intersections for mineral occurrences in drillholes or trenches

Element	*Intersection length (m)*	*Grade*
Hard rock and lateritic deposits		
Gold	>5	>1 ppm
Silver	>10	>1 ppm
Platinum	>0.5	>1 ppm
Lead	>5	>0.5%
Zinc	>5	>2%
Copper	>5	>0.5%
Nickel	>5	>0.5%
Cobalt	>5	>0.1%
Chromium	>0.2	>5% Cr_2O_3
Vanadium	>5	>0.1%
Tin	>5	>0.02%
Iron	>5	>40% Fe
Manganese	>5	>25%
Uranium	>5	>1000 ppm U
Diamonds	na	any diamonds
Tantalum	>5	>200 ppm
Tungsten	>5	>1000 ppm (0.1%)
Placer deposits		
Gold	na	>300 mg/m^3 in bulk sample
Diamonds	na	any diamonds
Heavy minerals	>5	>2% ilmenite

NOTE: na not applicable

theme can be accessed on screen, and **queries** can be carried out either as spatial queries through a **view** or as textual queries direct from the attribute tables. Further details (with examples) of displays, queries, charts, and view layouts are provided by Ferguson (1995).

Table 2.5 Types of exploration activity detailed in the EXACT database

Activity type	*Description*
Geological	
GEOL	Geological mapping
AMS	Airborne multispectral scanning
LSAT	Landsat TM data
Geophysical	
AEM	Airborne electromagnetic surveys
AGRA	Airborne gravity surveys
AMAG	Airborne magnetic surveys
ARAD	Airborne radiometric surveys
MAG	Magnetic surveys
EM	Electromagnetic surveys (includes TEM, SIROTEM)
GEOP	Other geophysical surveys (includes IP, resistivity)
GRAV	Gravity surveys
RAD	Radiometric surveys (includes downhole logging)
SEIS	Seismic surveys
Geochemical	
SOIL	Soil surveys
SSED	Stream-sediment surveys
REGO	Regolith surveys (includes laterite, pisolite, ironstone, and lag)
NGRD	Non-gridded geochemical surveys (includes chip, channel, dump, and gossan)
ACH	Airborne geochemistry
Mineralogical	
HM	Heavy mineral surveys
Drilling	
DIAM	Diamond drilling
ROT	Rotary drilling (predominantly percussion drilling)
RAB	RAB drilling (includes other shallow geochemical drilling such as auger)
RC	RC drilling
Mineral resources	
MRE	Mineral resource estimate
Hydrogeological	
HYDR	Groundwater surveys

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Appendix 3

Rock units of the Arunta–Musgrave area

Palaeoproterozoic

ⱣPmtG	Undifferentiated, metamorphosed (very low to low grade) feldspathic wacke, sandstone, siltstone, and mudstone; minor quartzite, banded chert, basalt, dolerite, gabbro, and felsic porphyry; includes Killi Killi Formation
ⱣPg_ls	LEWIS GRANITE: muscovite and biotite monzogranite, locally porphyritic; minor biotite granodiorite
ⱣPmtA	Undifferentiated metasedimentary rock
ⱣPgA	Granitic rock
ⱣPf_p	POLLOCK HILL FORMATION: dacite, rhyodacite, and volcaniclastic sedimentary rock
ⱣPg_we	MOUNT WEBB GRANITE: monzogranite; syenogranite, granodiorite, and tonalite

Mesoproterozoic

ⱣMBI	BIRRINDUDU GROUP: sandstone, siltstone, shale, conglomerate, stromatolitic chert, limestone, and glauconitic sandstone
ⱣMmtM	Quartzite and quartz–mica schist
ⱣMmnM	Granulite and gneiss
ⱣMmgM	Granite, porphyritic granite, and gneissic and migmatitic granitic rock
ⱣMf_k	SKIRMISH HILL VOLCANIC ASSOCIATION: rhyolitic volcanic and volcaniclastic rock; minor basalt; metamorphosed
ⱣMf_c	SCAMP VOLCANIC ASSOCIATION: rhyolitic volcanic and volcaniclastic rock; metamorphosed
ⱣMf_p	PALGRAVE VOLCANIC ASSOCIATION: rhyolitic volcanic and volcaniclastic rock
ⱣMTO	TOLLU GROUP / PUSSY CAT GROUP: rhyolite, dacite, ignimbrite, basalt, volcaniclastic sedimentary rock, sandstone, and conglomerate
ⱣMgM	Hypabyssal granite, associated with Bentley Supergroup volcanic rock
ⱣMaI	GILES COMPLEX: layered mafic–ultramafic intrusions
ⱣM_h	MOUNT HARRIS BASALT: metamorphosed basalt, basaltic tuff, conglomerate, and quartzite
ⱣM_l	BLOODS RANGE BEDS: metamorphosed sandstone and siltstone, and felsic and mafic schist derived from volcanic rock
ⱣMCA	CASSIDY GROUP: rhyolite and basalt; minor sandstone and siltstone
ⱣMMI	MISSION GROUP: conglomerate, sandstone, shale, and basalt; minor tuff, dolomite, and quartzite
ⱣM_d	DIXON RANGE BEDS: sandstone, siltstone, and conglomerate

Neoproterozoic

ⱣNRD	REDCLIFFE POUND GROUP: quartz sandstone and greywacke; minor conglomerate, siltstone, shale, limestone, dolomite, chert, and glauconitic sandstone
ⱣN_i	HIDDEN BASIN BEDS: sandstone, shale, and siltstone
ⱣN_d	DEAN QUARTZITE and HEAVITREE QUARTZITE: quartz sandstone, sandstone, and conglomerate; kyanite schist locally
ⱣN_s	BITTER SPRINGS FORMATION and PINYINNA BEDS: dolomite, stromatolitic dolomite, siltstone, sandstone, and basalt
ⱣN_b	BOORD FORMATION and CARNEGIE FORMATION: siltstone, dolomite, diamictite, sandstone, and conglomerate
ⱣN_f	SIR FREDERICK CONGLOMERATE and ELLIS SANDSTONE: conglomerate, sandstone, quartz wacke, and siltstone

ⱣN_m	MAURICE SANDSTONE: very fine to medium-grained quartzose sandstone; cross-bedded; minor laminited, micaceous siltstone
ⱣNs	Sandstone and siltstone
ⱣN_l	CLUTTERBUCK FORMATION: feldspathic sandstone, siltstone, and conglomerate
ⱣNBt	TOWNSEND QUARTZITE and LEFROY FORMATION: laminated to very thick bedded, well-sorted, medium- to coarse-grained quartz arenite and feldspathic arenite; minor conglomerate and shale beds; medium- to large-scale cross-bedding
ⱣN_u	LUPTON FORMATION: massive pebble to boulder conglomerate (tillite) and medium- to thick-bedded sandstone; minor siltstone
ⱣN_p	PUNKERRI SANDSTONE: quartz sandstone, feldspathic sandstone, and siltstone; minor conglomerate
od	Dolerite dykes, sills, and plugs; fine- to medium-grained dolerite

Palaeozoic

O_t	TABLE HILL VOLCANICS: flow-banded, fine-grained tholeiitic basalt, amygdaloidal and vesicular; minor sandstone interbeds; subaerial
O_l	LENNIS SANDSTONE: feldspathic sandstone and siltstone
Ok	Limestone, dolomite, shale, and sandstone
Ss	Sandstone; minor conglomerate
D_w	WANNA FORMATION: cross-bedded quartz arenite; minor claystone
D_l	LUCAS FORMATION: sandstone, calcareous sandstone, siltstone, and mudstone; minor limestone and dolomite
D_k	KNOBBY SANDSTONE: sandstone, siltstone, and conglomerate
CPG	GRANT GROUP: sandstone, siltstone, mudstone, and conglomerate
P_a	PATERSON FORMATION: diamictite, sandstone, siltstone, and shale
P_p	POOLE SANDSTONE: sandstone and siltstone
P_n	NOONKANBAH FORMATION: mudstone and sandstone
PL	LIVERINGA GROUP: sandstone, mudstone, and conglomerate

Mesozoic

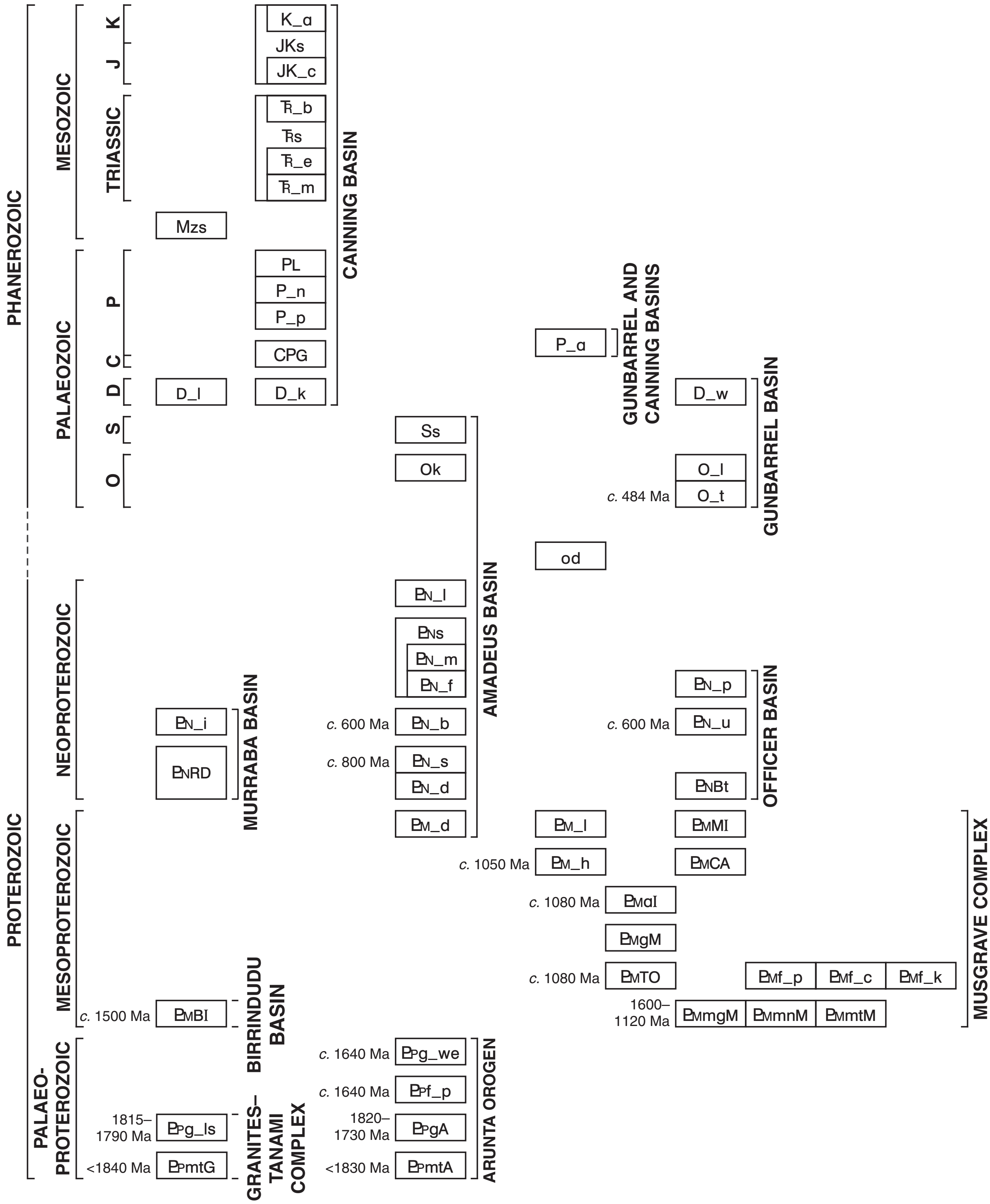
Mzs	Unassigned sandstone and conglomerate
TR_m	MILLYIT SANDSTONE: sandstone
TR_e	ERSKINE SANDSTONE: sandstone
TRs	Sandstone, siltstone, shale, and conglomerate; includes Blina Shale, Erskine Sandstone, and Millyit Sandstone
TR_b	BLINA SHALE: mudstone
JK_c	CALLAWA FORMATION: sandstone and conglomerate; includes equivalent units Melligo Sandstone, Broome Sandstone, and Cronin Sandstone
JKs	Unassigned sandstone and conglomerate;
K_a	ANKETELL FORMATION: sandstone and siltstone; minor conglomerate; includes equivalent units Samuel Formation, Parda Formation, Frezier Sandstone, and Emeriau Sandstone

Cainozoic (regolith)

C	Proximal mass-wasting deposits grading into sheetwash with a significant to perceptable slope; includes sand, silt, and clay in depressions deposited by alluvial and eolian processes
A	Alluvium in channels and on floodplains
L	Inland lakes, dunes and playa terrain; includes saline and freshwater playas and claypans, and minor eolian deposits directly associated with lake systems
S	Sandplain dominated by red quartz sand; may be of mixed origin, including residual, sheetwash, and eolian sand
Rf	Ferruginous duricrust, locally pisolitic
Rk	Calcrete, dominantly residual
X	Rock and weathered rock; includes bouldery lag

Appendix 4

Stratigraphic correlations of the rocks of the Arunta–Musgrave area [(a)]



PBA539 30.05.03

NOTE: (a) see Appendix 3 for details of geocodes