REPORT
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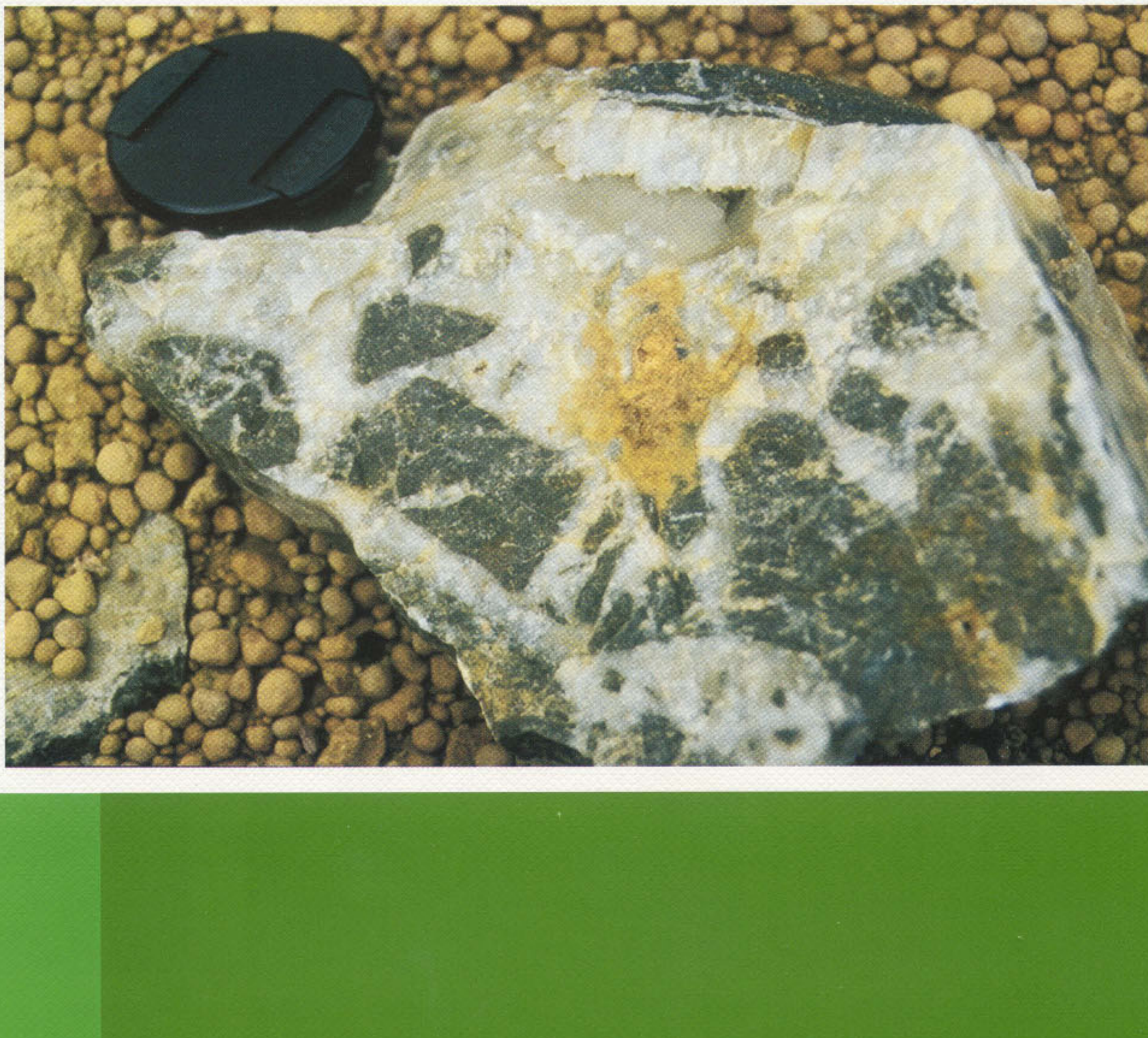
GOVERNMENT OF
WESTERN AUSTRALIA

MINERAL OCCURRENCES AND EXPLORATION POTENTIAL OF SOUTHWEST WESTERN AUSTRALIA

by L. Y. Hassan



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

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REPORT 65

MINERAL OCCURRENCES AND EXPLORATION POTENTIAL OF SOUTHWEST WESTERN AUSTRALIA

by
L. Y. Hassan

Perth 1998

MINISTER FOR MINES
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Copy editor: J. A. Mikucki

REFERENCE
The recommended reference for this publication is:
HASSAN, L. Y., 1998, Mineral occurrences and exploration potential of southwest Western Australia: Western Australia Geological Survey, Report 65, 38p.

National Library of Australia
Cataloguing-in-publication entry

Hassan, L. Y. (Lee Yvonne) 1951–.
Mineral occurrences and exploration potential of southwest Western Australia.

Bibliography.
ISBN 0 7309 6594 5

1. Geology, Structural — Western Australia.
2. Mines and mineral resources — Western Australia.
I. Geological Survey of Western Australia.
II. Title. (Series : Report (Geological Survey of Western Australia) ; 65).

553.409941

ISSN 0508–4741

Cover photograph:
Epithermal vein breccia, Hunter Venture gold mine, Donnybrook

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Abstract

Southwest Western Australia is the world's largest producer of bauxite, tantalite, and spodumene, and is also a significant producer of gold, coal, heavy minerals, tin, and silica sand. All known deposits, mineral occurrences, and geochemical anomalies have been entered into a Geographic Information System (GIS) database to highlight areas with potential for further discoveries.

Extensive bauxite deposits in the Darling Range area have formed by deep lateritic weathering of Precambrian basement. Land-access issues will restrict development of bauxite outside the State Agreement Act areas.

Primary gold mineralization at Boddington occurs in felsic rocks of the Archaean Saddleback greenstone belt. Lateritic and saprolitic gold has formed over and proximal to the primary deposit. There is potential for further primary and lateritic gold deposits in the Saddleback and Morangup greenstone belts, and also in slices of greenstone preserved along north-trending faults. There is also potential for gold mineralization in the Balingup, Jimperding, and Chittering Complexes, and along a major shear zone separating the Boddington Terrane from the Lake Grace Terrane. There are a number of epithermal gold and base-metal deposits in proximity to the Darling and Dunsborough Faults. These are interpreted to be rift-related deposits of Early Permian to Early Cretaceous age. There is potential for the discovery of further deposits of this type.

The Archaean Greenbushes tin–tantalum–lithium pegmatite was emplaced syntectonically and synmetamorphically into the Donnybrook–Greenbushes Shear Zone. This shear zone is considered highly prospective for further occurrences of Greenbushes-type pegmatite deposits.

The Collie, Wilga, and Boyup coal-bearing basins are grabens that preserve remnants of an originally more extensive Permian sequence. There is potential for the discovery of small basins beneath Cainozoic cover in the vicinity of northwest-trending faults. Coal is widespread in the Permian Sue Coal Measures of the Perth Basin, but, on the basis of current technology, only the coal within 600 m of the surface could be exploited.

Heavy minerals are being mined from Cainozoic and modern shorelines, and from Cretaceous fluviatile- and estuarine-facies rocks of the Leederville Formation. There is potential for further discoveries of both types of deposit.

Southwest Western Australia also has potential for PGE, nickel, chromium, vanadium, base metals, iron ore, diamonds, silica sand, kaolin, and other industrial minerals.

KEYWORDS: mineralization, greenstone, epithermal deposits, pegmatite, bauxite, gold, tin, tantalum, lithium, heavy minerals, kaolin, silica sands, coal, industrial minerals.

Introduction

Present study

Significant quantities of bauxite, coal, gold, heavy minerals, tin, tantalum, lithium, and silica sand are produced from southwest Western Australia (referred to as the Southwest in this Report). Nevertheless, the area is relatively underexplored, and receives only a small proportion of the total mineral exploration expenditure in Western Australia. This is in part due to difficulties in land access, but may also be due to a perceived lack of prospectivity. This study began as part of a joint project between the Geological Survey of Western Australia (GSWA) and the Bureau of Resource Sciences (BRS) involving a Geographic Information System (GIS)-based assessment of the known and potential mineralization of the Regional Forest Agreement (RFA) area (BRS and GSWA, 1998). The project was later extended by GSWA to include the entire area shown in Figure 1. The main purpose of this Report is to highlight areas within the Southwest that are prospective for minerals.

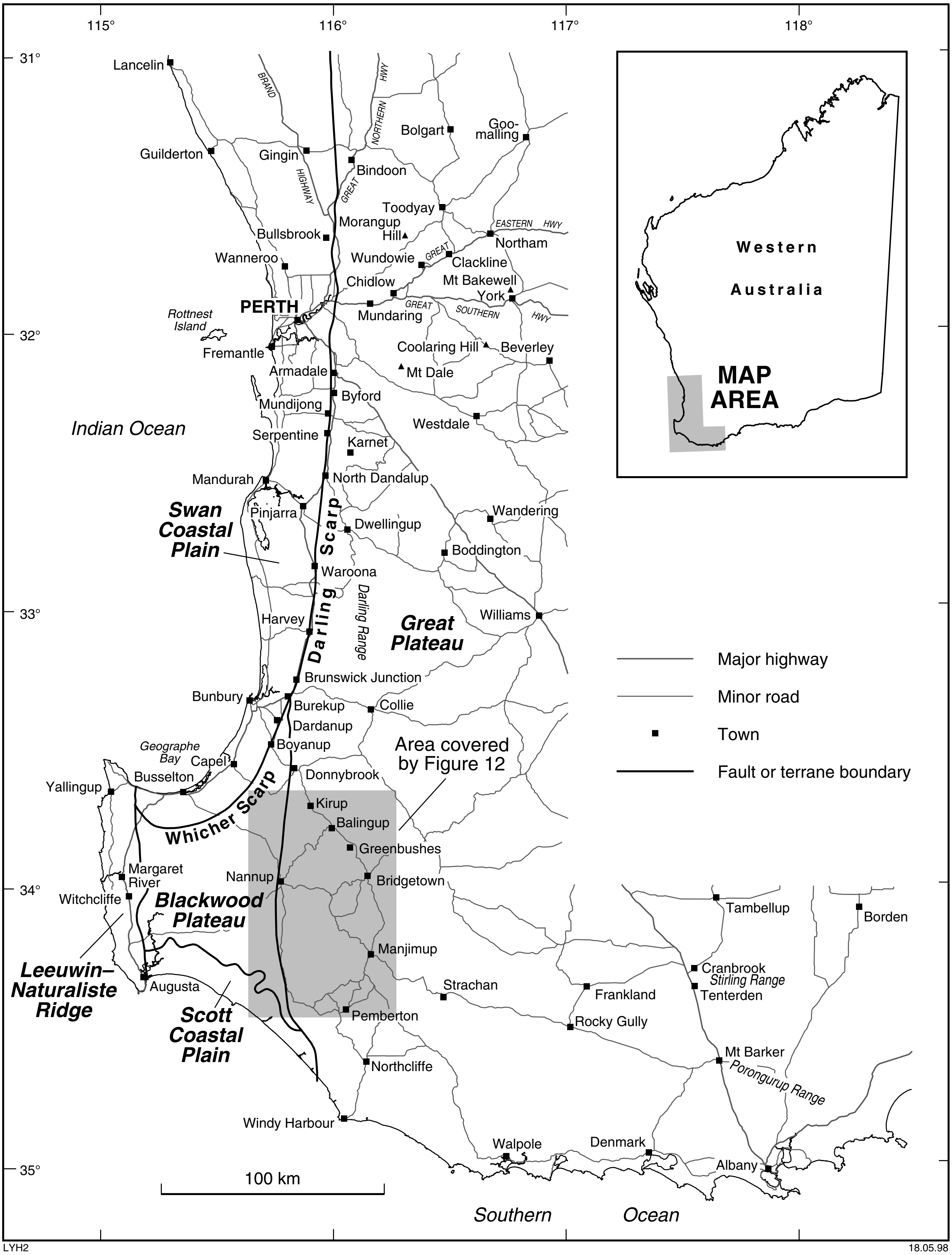

Figure 1. Topographic features of southwest Western Australia

The digital geological map accompanying this Report has four main layers (Precambrian, Permian, Triassic – lower Tertiary, and regolith), with linear features such as fold hinges, faults, lineaments, and dolerite dykes shown as separate themes. These layers have been combined to form an interpreted basement map with a simplified regolith overprint at 1:500 000 scale. Mineral occurrences are shown on this map (Plate 1).

Appendix 1 defines the terms used in the Mineral Occurrence database (WAMIN) and Appendix 2 gives a description of the digital datasets. The accompanying CD–ROM includes all the data used to compile the map and Report, and also includes files of geophysical, remote-sensing, and topographic data. The CD–ROM contains 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. Metadata statements on the geological, geophysical, and topographic datasets are also provided.

Location, land access, and physiography

This Report covers part of the southwestern region of Western Australia (Fig. 1), including the PERTH*, PINJARRA, COLLIE, PEMBERTON – IRWIN INLET, BUSSELTON–AUGUSTA, and MOUNT BARKER – ALBANY 1:250 000 map sheets.

A network of bitumen roads joins the numerous towns in the Southwest (Fig. 1). A narrow-gauge railway links Perth and Bunbury, and there are ports at Fremantle, Bunbury, and Albany. Forestry tracks and private roads provide access to most other areas not accessible by bitumen roads.

State forest, conservation reserves, and private land occupy a large percentage of the area of the Southwest. Standard conditions have been developed to cover mineral exploration and mining in the different types of conservation reserves, proposed conservation reserves, State forests, and other environmentally sensitive areas. These guidelines have been published by the Department of Minerals and Energy (DME, 1995).

All new tenements and exploration licence renewals are subject to the legislation and procedures of the Commonwealth Native Title Act 1993, except where it is determined that the applications are over land where native title has been extinguished.

A fungal disease, known as 'dieback', that affects plant roots is widespread in the Southwest. All ground-disturbing activities in the area are required to have an effective management program to control the spread of this disease. Guidelines to minimize the spread of dieback during mineral exploration have been published by DME (Department of Mines, 1991).

* Capitalized names refer to standard map sheets.

The Darling Scarp is the main physiographic feature in the area. The scarp is the surface expression of the Darling Fault, and divides the Darling Plateau and Ravensthorpe Ramp to the east from the Swan Coastal Plain, the Blackwood Plateau, and the Scott Coastal Plain to the west. The Darling Plateau is an ancient erosion surface that forms part of the Great Plateau, as defined by Jutson (1934). The plateau is predominantly underlain by Precambrian rocks that were strongly lateritized during the Tertiary. The plateau has an average elevation of 300 m above sea level.

The Ravensthorpe Ramp is that part of the Great Plateau that slopes gradually to the southern coast. The Blackwood Plateau has a gently undulating surface ranging from 40 to 180 m above sea level. In the south, the Blackwood Plateau passes through a complex series of Cainozoic strand lines into the Scott Coastal Plain, a low-lying swampy region with remnants of dunes forming scattered hills and ridges. The Whicher Scarp is a complex marine erosional feature that marks the western edge of the Blackwood Plateau. The Leeuwin–Naturaliste Ridge is composed of Precambrian crystalline rocks capped by laterite, sand, and, in the vicinity of the coast, limestone. The Swan Coastal Plain extends west from the Darling and Whicher scarps to the Indian Ocean and ranges up to 60 m above sea level (Lowry, 1967; Wilde and Walker, 1982, 1984).

In the southwestern part of the area, the Stirling Ranges rise abruptly above the plain of the Great Plateau to a maximum height of 1047 m Australian Height Datum (AHD) at Bluff Knoll. A plain consisting of white sand and laterite, which overlies the late Eocene Plantagenet Group in the Bremer Basin, slopes gently south from the base of the Stirling Range to the coast. The Porongurup Range (up to 670 m AHD) and Mount Barrow (486 m AHD) are monadnocks of granite that were once islands in the Plantagenet sea (Muhling and Brakel, 1985).

Previous work

Geological mapping of the Southwest at a scale of 1:250 000, accompanied by Explanatory Notes, was completed by GSWA between 1967 and 1985, and includes: BUSSELTON–AUGUSTA (Lowry, 1967), PERTH (Wilde and Low, 1978), PINJARRA (Wilde and Low, 1980), COLLIE (Wilde and Walker, 1982), PEMBERTON – IRWIN INLET (Wilde and Walker, 1984), and MOUNT BARKER – ALBANY (Muhling and Brakel, 1985). The geology of ALBANY (1:1 000 000), which covers a large part of the area, was reinterpreted by Myers (1995) on the basis of the aeromagnetic data published by the Australian Geological Survey Organisation (AGSO). Part of the area has been covered by GSWA's 1:50 000 urban geology and environmental geology mapping. Wilde (1990), Wilde et al. (1996), and Partington et al. (1995) have published generalized interpretation maps of the region. More-detailed geological mapping of specific areas has been carried out by company geologists.

Aeromagnetic and gravity data at a scale of 1:250 000 have been published by AGSO and are also available in digital format. Whitaker (1992) interpreted these data for ALBANY (1:1 000 000). Detailed gravity surveys have been carried out over the Collie Basin and surrounding areas to assist in defining the Permian basins including the Wilga and Boyup Basins (Kevi, 1990, 1992). Various companies have carried out detailed aeromagnetic surveys to assist in geological interpretation (e.g. the definition of ultramafic units in the Balingup Complex).

Townsend (1994) described the mineral deposits on ALBANY (1:1 000 000). His study covered most of the main deposits in the southern part of the study area, but is mainly restricted to those deposits that are included in MINEDEX (DME's mine and mineral deposit database). Other studies have been restricted to particular commodities or deposits, and are cited in the appropriate sections of this Report.

Regional geology

The geological map (Plate 1) and the digital geological data accompanying this Report are based on the geological map of ALBANY (1:1 000 000), with detail added from the 1:250 000-scale geological maps. Additional information for the Precambrian has been taken from Myers (1989), Wilde (1990), Partington et al. (1995), Wilde et al. (1996), and various open-file company reports in WAMEX (DME's Western Australian Mineral Exploration database). Interpretation has also made use of aeromagnetic and Landsat TM images. The Permian and Cretaceous–Tertiary digital layers include additional detail from Iasky (1993) and Le Blanc Smith (1993). Various regolith units were combined to generally conform to the units currently used by GSWA in its geochemical and regional mapping programs (Morris et al., 1998).

The regional geology is summarized in Figure 2, which also shows the relationship of the main mineralizing events to geology. The main Precambrian geological subdivisions of the area are the Archaean Yilgarn Craton, the Proterozoic Albany–Fraser Orogen along the south coast, and the Proterozoic Pinjarra Orogen along the west coast (Fig. 3). The Phanerozoic Perth Basin is superimposed directly on the Pinjarra Orogen and is bounded to the east by the Darling Fault. Sedimentary rocks of the Phanerozoic Bremer Basin overlie part of the Albany–Fraser Orogen along the southern margin of the area. Phanerozoic sedimentary rocks of the Collie, Wilga, and Boyup Basins are preserved in grabens within the Yilgarn Craton (Myers, 1995; Plate 1). Most of the Precambrian and Phanerozoic rocks are covered by regolith (Plate 1).

Precambrian rocks

Yilgarn Craton

The Yilgarn Craton consists mainly of late Archaean granitoid rock with belts of greenstone. On the basis of field data acquired during regional mapping of the southwest Yilgarn Craton, Gee (1979) and Gee et al. (1981) identified an older granite–gneiss terrane (the Western Gneiss Terrane) characterized by the presence of metamorphic belts of schist and gneiss of sedimentary origin. This terrane passes eastward into three younger granite–greenstone terranes (the Murchison, Southern Cross, and Eastern Goldfields Provinces).

The belts of schist and gneiss were named the Jimperding, Chittering, and Balingup metamorphic belts by Wilde (1980) and Gee et al. (1981), and redefined as the Jimperding and Balingup Complexes by Myers (1990a). In this Report, the metamorphic belts are referred to as the Jimperding, Chittering, and Balingup Complexes.

From an interpretation of geophysical, geochronological, and geological data, Wilde et al. (1996) proposed a terrane-accretion model for the southwestern part of the Yilgarn Craton. Three terranes (the Balingup, Boddington, and Lake Grace Terranes, from west to east respectively), interpreted to be separated by major shear zones, were defined in the southwestern part of the Yilgarn Craton (Fig. 3). The Balingup Terrane includes the Balingup and Chittering Complexes. Part of the Jimperding Complex lies within the Boddington Terrane, and part within the Lake Grace Terrane. The Saddleback and Morangup greenstone belts are also within the Boddington Terrane. Granitoid rocks and migmatites occur within all three terranes.

Jimperding, Chittering, and Balingup Complexes

The dominant rock type within these metamorphic complexes is banded quartz–feldspar–biotite gneiss, locally containing garnet, cordierite, or hypersthene (*Anb*). Much of the gneiss is interpreted to have had a sedimentary protolith, although some may be orthogneiss or metamorphosed banded migmatite. There are also gneisses (*Ang*) that have clearly been derived from granitoid rocks. Other rock types include schists (*Al*) derived from pelitic and psammitic rocks, granofels (*Anf*) after greywacke, diopside–epidote–garnet–hornblende–plagioclase–microcline gneiss (*Anc*) after calcareous sedimentary rocks, metaquartzite (*Aq*), and banded iron-formation (BIF, *Aci*; Gee et al., 1981). Mafic and ultramafic rocks (*Ana*) intruded the sedimentary rocks prior to metamorphism (Cornelius et al., 1987). Amphibolite (*Aa*), and granulite consisting of interlayered mafic and felsic units (*Ahm*), are also present in the metamorphic complexes.

According to Gee et al. (1981), the presence of BIF, quartzite, psammitic rocks, and calc-silicate rocks after carbonate-rich sedimentary rocks in the Jimperding Complex and parts of the Balingup Complex suggests that these rocks represent a shallow shelf facies. In contrast, the granofels after greywacke in the Chittering Complex and portions of the Balingup Complex suggests that these rocks formed in a deeper water trough environment (Gee et al., 1981).

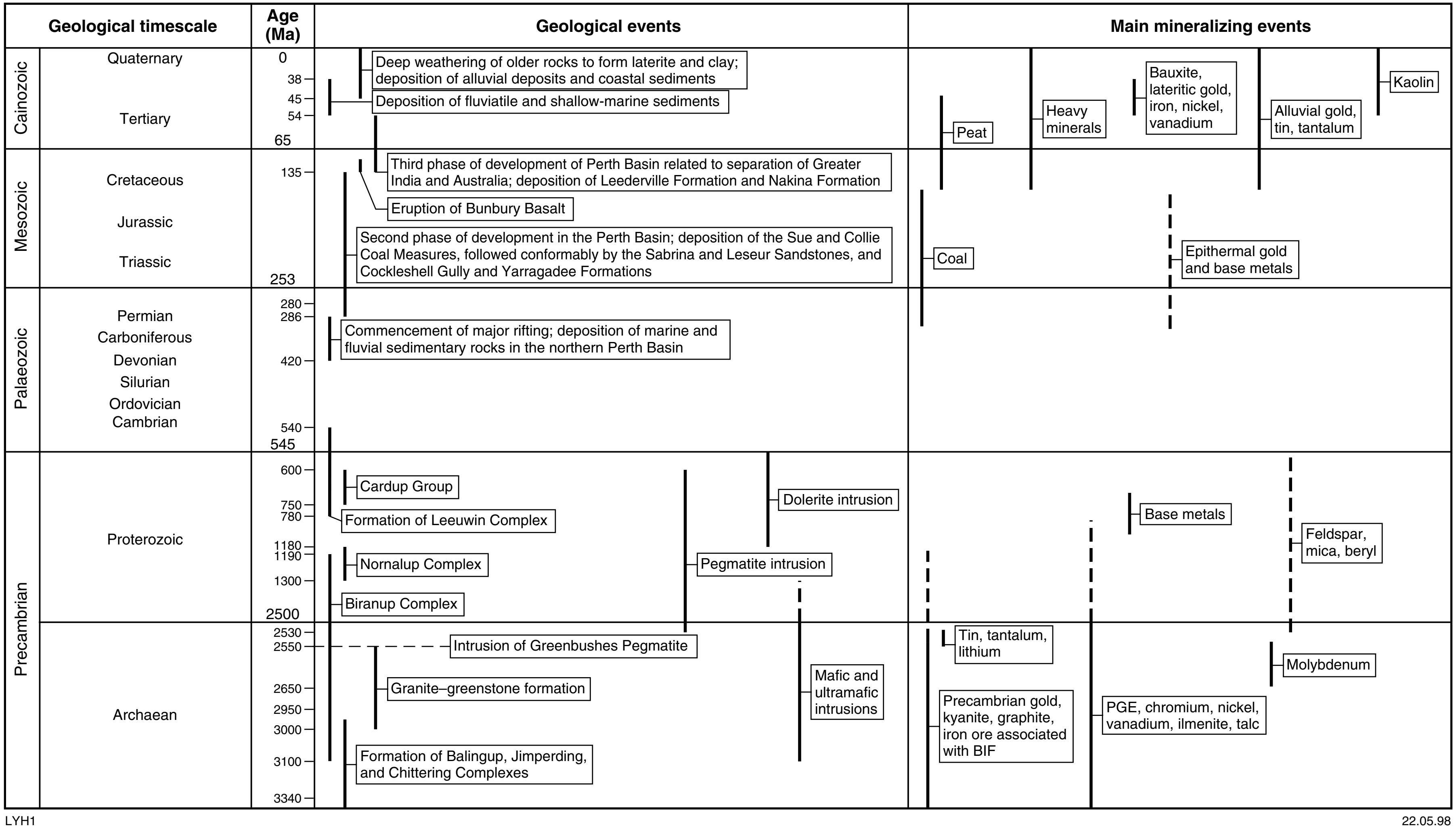

Figure 2. Summary of geological and mineralizing events in southwest Western Australia

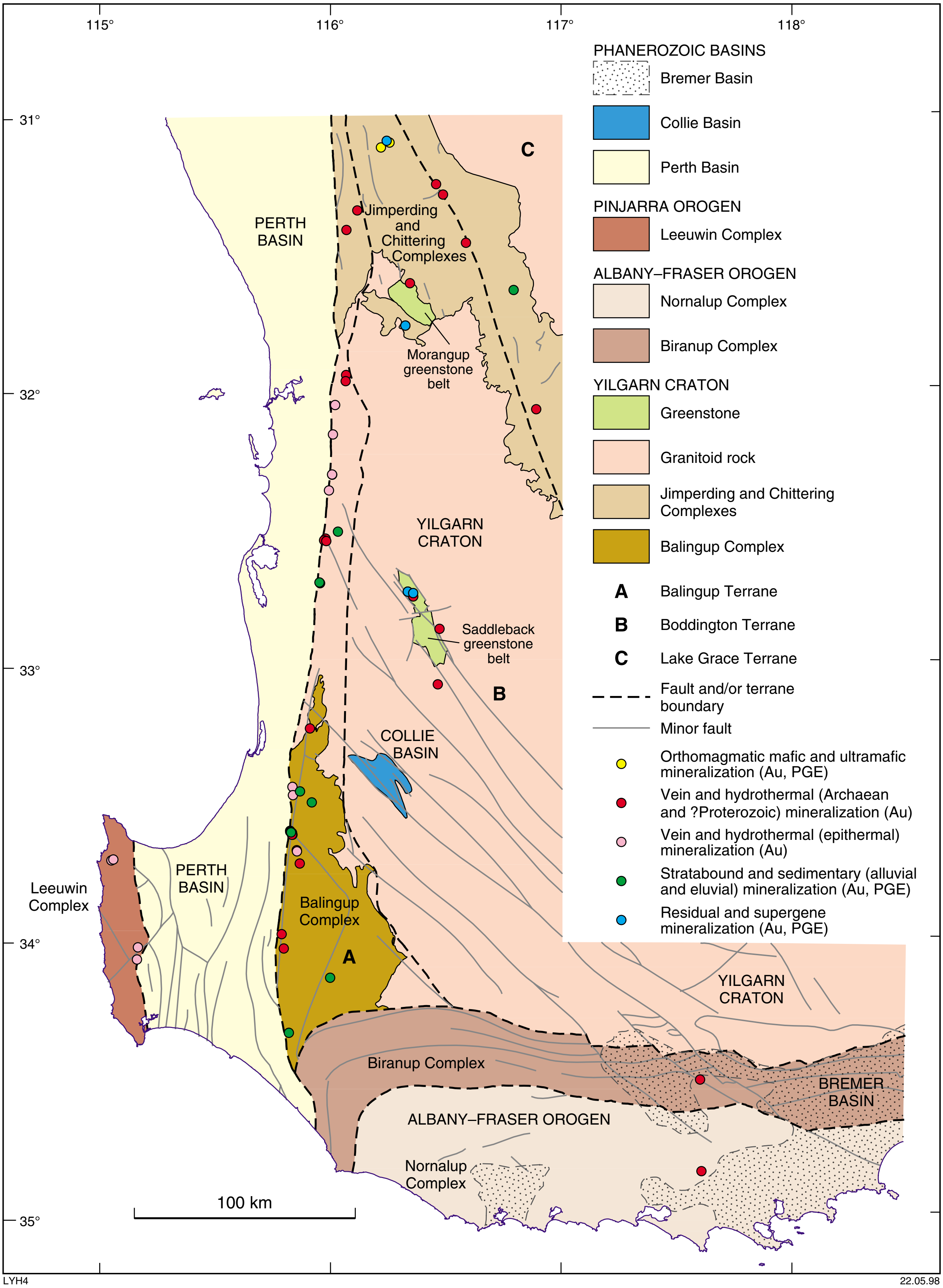

Figure 3. Tectonic sketch of southwest Western Australia showing the distribution of precious metals (Au, PGE)

Sm–Nd model ages indicate that sedimentary rocks in the Balingup Complex were deposited between 3070 and 2830 Ma and those in the Chittering Complex after 2890 Ma (Wilde et al., 1996). Data from detrital zircons in quartzites within the Jimperding Complex suggest an age of deposition between 3100 and 3000 Ma, whereas detrital zircons as old as c. 3735 Ma indicate derivation from substantially older crust (Wilde et al., 1996).

The metamorphic grade in the Jimperding Complex increases progressively from lower amphibolite facies in the east to granulite facies in the west. The presence of andalusite and iron-rich cordierite indicates low-pressure conditions. In contrast, the presence of kyanite, sillimanite, and staurolite in the Chittering and Balingup Complexes indicates moderate-pressure, Barrovian-style metamorphism (Wilde et al., 1996). Metamorphism in the Balingup Complex has been dated by Rb–Sr techniques at c. 2838 Ma near Bridgetown (Wilde et al., 1996). Sensitive high-resolution ion-microprobe mass spectrometer (SHRIMP) dating and conventional U–Pb dating of accessory minerals from the Jimperding Complex at Katrine near Toodyay indicates that metamorphism took place between 2670 and 2635 Ma (Bosch et al., 1996).

The metasedimentary rocks of the Jimperding Complex within the Boddington Terrane form part of a major flat-lying nappe that has been tightly refolded, whereas in the Lake Grace Terrane the metasedimentary rocks of the complex form north-plunging upright folds. Either the Jimperding Complex was originally composed of two separate sequences, or the metasedimentary sequence was originally confined to the Lake Grace Terrane, with the flat-lying nappes being thrust onto the Boddington Terrane during accretion (Wilde et al., 1996).

Saddleback and Morangup greenstone belts

All rocks in the greenstone belts have been metamorphosed but the prefix 'meta' or 'metamorphosed' has been omitted for simplicity. Three formations have been recognized within the Saddleback greenstone belt (Wilde, 1976; 1990). The Hotham Formation forms the base of the greenstone sequence and consists of siltstone and thin pyroclastic horizons, with minor quartz–mica schist and greywacke (*As*). The overlying Wells Formation consists of felsic tuff, pyroclastic breccia and agglomerate, felsic lavas, and subvolcanic dioritic intrusions (*Afv*). The Marradong Formation, which forms the top of the sequence, consists predominantly of tholeiitic basalt with minor intercalations of sedimentary rock and dacite (*Ab*).

The Morangup greenstone belt is poorly exposed, and is interpreted by Wilde and Pidgeon (1990) to consist predominantly of basalt with minor andesite and sedimentary rocks.

The Saddleback greenstone belt has been dated at 2671 to 2654 Ma by Wilde and Pidgeon (1986), but more recent dating indicates that mafic and felsic volcanism occurred between 2714 and 2696 Ma, and again at c. 2675 Ma (Allibone et al., 1996). Two suites of ultramafic dykes were emplaced: one at 2696 to 2675 Ma and the other at 2675 to 2611 Ma (Allibone et al., 1996). The Morangup belt is interpreted by Wilde et al. (1996) to be similar in age to the Saddleback belt.

Both greenstone belts contain predominantly greenschist-facies assemblages, but in the Saddleback greenstone belt the grade increases to lower amphibolite facies in the southwest, near the contact with an intrusive granitoid rock (Wilde, 1990).

Four phases of ductile deformation have been recognized along three generations of discrete shear zones. The youngest of these is interpreted to have taken place between 2675 and 2611 Ma (Allibone et al., 1996).

Granitoid rocks

Granitoid rocks within the southwestern part of the Yilgarn Craton have been informally referred to as the Darling Range batholith in the western part (Wilde and Low, 1978) and the Wheat Belt granitoid rocks to the east of a line joining Meckering and Quairading (Wilson, 1958). Wilde et al. (1996) recognized that there are granitoid rocks of different ages and characteristics within the different terranes.

Granitoid rocks in the Balingup Terrane are younger than those in most other parts of the Yilgarn Craton. SHRIMP U–Pb dating of zircons from the Logue Brook granitoid, east of Bunbury, indicates a crystallization date of 2612 ± 5 Ma (Compston et al., 1986). Whole-rock Pb-isotope analysis of the Cowan Brook Dam granitoid gave an age of 2588 ± 93 Ma, and the zircon U–Pb age of the Millstream Dam granitoid is 2577 ± 4 Ma (Partington et al., 1995). All of these granitoids have undergone ductile deformation to form orthogneisses (*Ang*). The Greenbushes Pegmatite (*Apf*) has been dated at 2527 Ma using SHRIMP techniques (Partington et al., 1995). The Gibralter Quartz Monzonite (*Agz*) was emplaced along the eastern margin of the Balingup Terrane at 2740 Ma (Wilde et al., 1996).

Granitoid rocks in the Boddington Terrane include relatively undeformed equigranular granite (*Age*), porphyritic granite (*Agp*), undeformed to moderately deformed granite and granodiorite (*Agg*), diorite (*Agd*), syenite (*Ags*), and moderately to strongly deformed granite and granodiorite (*Agn*). Myers (1995) considered that the deformed granitoid rocks pre-dated the undeformed granitoid rocks, but Wilde et al. (1996) have shown that deformed and undeformed granitoid rocks have similar ages. Conventional U–Pb dating of zircons from granitoid rocks intruding the Jimperding metamorphic belt at Toodyay gave an age of 2677 to 2642 Ma (Nieuwland and Compston, 1981). An adamellite intruding the Saddleback greenstone belt gave an age of 2640 ± 26 Ma (Wilde and Pidgeon, 1986). These dates led Wilde et al. (1996) to suggest that granitoid rocks within the Boddington Terrane developed within a short time span between 2677 and 2640 Ma. However, a late-stage granitoid rock cutting all other Archaean rocks in the Saddleback greenstone belt has been dated at 2611 Ma (Allibone et al., 1996).

The granitoid rocks of the Wheat Belt batholith within the Lake Grace Terrane (*Agc*) are characterized by the presence of hypersthene and are interpreted to be charnockites of igneous origin (Wilde et al., 1996).

Migmatite and mylonite

Migmatite (*Am*), formed by intense deformation of gneissic rocks and granitoid rocks, occurs along the margins of the metamorphic complexes (Wilde et al., 1996). Mylonite and gneiss (*An*), derived from Archaean and Proterozoic deformation of Archaean rocks, occur adjacent to the Darling Fault (Wilde and Low, 1980).

Albany–Fraser Orogen

The Albany–Fraser Orogen trends in an easterly direction along much of the south coast of the Southwest. At the western end, the trend of the orogen turns abruptly southward and is partly truncated by the Darling Fault. The main components of the Albany–Fraser Orogen are the Biranup Complex, the Nornalup Complex, and the northern foreland (Myers, 1995).

Biranup Complex

The Biranup Complex forms the northern part of the Albany–Fraser Orogen. The complex consists mainly of granitic orthogneiss (*Æng*), compositionally layered gneiss (*Ænb*) of possible sedimentary origin, and migmatite (*Æm*). The complex also contains minor quartz–mica schist (*Æl*) of sedimentary origin, quartzite (*Æq*), BIF (*Æci*), and metamorphosed mafic and ultramafic rocks (*Æa*). The gneisses and metasedimentary rocks have been intruded by equigranular granite (*Æge*) and diorite (*Ægd*). Zircons from samples of granitic orthogneiss from near Groper Bluff (just to the east of the mapped area) have U–Pb SHRIMP ages of c. 3100 and c. 1190 Ma (Black et al., 1992), indicating that the Biranup Complex contains both Archaean and Proterozoic components. The rocks were intensely deformed and recrystallized during metamorphism up to granulite facies during the Proterozoic. The rocks form a number of steeply dipping tectonic slices separated by zones of intense deformation (Myers, 1995).

Nornalup Complex

The Nornalup Complex forms the southern part of the Albany–Fraser Orogen. The complex consists of granitic orthogneiss (*Ᵽng*), layered quartz–feldspar–biotite (–hornblende–garnet) gneiss (*Ᵽns*) of uncertain protolith, heterogeneous compositionally layered gneiss (*Ᵽnb*) of possible sedimentary origin, migmatite (*Ᵽm*), mafic rocks (*Ᵽa*), quartzite (*Ᵽq*), and BIF (*Ᵽci*). These rocks have all been intruded by large plutons consisting of equigranular granite (*Ᵽge*) and porphyritic granite (*Ᵽgp*). The gneisses have been strongly deformed and metamorphosed at amphibolite or granulite facies but are commonly much less intensely deformed than the rocks of the Biranup Complex. The granitoid rocks were intruded at c. 1180 Ma (Myers, 1995).

Northern foreland

The northern foreland is a belt, approximately 100 km wide, along the southern margin of the Yilgarn Craton that has been intruded by dolerite dykes of the Gnowangerup dyke swarm. The dykes are subvertical and trend subparallel to the orogen boundary. Metasedimentary rocks (quartzite, phyllite, and slate) of the Stirling Range Formation (*Ᵽbq* and *Ᵽbs*) have been thrust northwards over the Archaean Basement (Myers, 1995).

A Rb–Sr whole rock isochron of c. 1150 Ma was obtained from phyllite of the Stirling Range Formation by Turek and Stephenson (1966), but fossils of possible Ediacaran age (590–570 Ma) from the Stirling Range Formation have been described by Cruse et al. (1993), raising doubts about the true age of the formation.

Pinjarra Orogen

The Pinjarra Orogen extends along the western coast and is bounded to the east by the Darling Fault. The orogen is largely covered by sedimentary rocks of the Perth Basin but is exposed as the Leeuwin Complex west of the Dunsborough Fault, and in a narrow belt of metasedimentary rocks known as the Cardup Group along the edge of the Darling Fault. A belt of sheared rock to the east of the Darling Fault (Darling Fault Zone) and the Boyagin Dyke Swarm, are probably related to the Pinjarra Orogen (Myers, 1995).

Cardup Group

Deformed shale, sandstone, and minor conglomerate (*ᵽC*) outcrop in a narrow belt along the eastern edge of the Darling Fault. The rocks have been metamorphosed to greenschist facies and have been intruded by dolerite dykes. According to Playford et al. (1976), the Cardup Formation formed between 750 and 560 Ma.

Leeuwin Complex

The Leeuwin Complex consists mainly of deformed granitoid rock and granitic gneiss (*Ᵽlg*), with minor anorthosite (*Ᵽla*) and mafic granulite (*Ᵽlb*). The age of the complex is poorly constrained, with dates between c. 1480 and c. 560 Ma being recorded (Myers, 1990b). Nelson (1996) reported SHRIMP U–Pb ages between 760 and 540 Ma for zircons from gneisses of the Leeuwin Complex.

Phanerozoic rocks

Perth Basin

The Perth Basin developed over the Pinjarra Orogen as a result of major rifting that was initiated during the Silurian, at about 420 Ma, and continued intermittently until the Early Cretaceous at about 136 Ma. Marine and fluvial sedimentary rocks accumulated in the northern part of the Perth Basin from the Silurian to Carboniferous, during the first phase of development (Myers, 1995).

A second phase of basin development was related to movement on interior faults in the basin during the Early Permian. Sedimentation extended into the southern part of the Perth Basin, and was mainly fluvial and lacustrine. The Permian Sue Coal Measures (*Pcm*) were deposited during this phase, followed conformably by the Triassic Sabina and Leseur Sandstones, and the Jurassic sandstones and siltstones of the Cockleshell Gully and Yarragadee Formations (*Js*; Iasky, 1993; Myers, 1995). Claystone intersected in a drillhole at Donnybrook contains palynomorphs of earliest Permian age, indicating that Permian sedimentary rocks were also deposited to the east of the Darling Fault (Backhouse, 1985; Backhouse and Wilson, 1989).

At the beginning of the Cretaceous, there was a third phase of basin development related to the rifting and separation of Greater India and Australia during the breakup of Gondwana (Iasky, 1993). The Bunbury Basalt (*Kbb*) was erupted at this stage (about 136 Ma) as lava flows within valleys incised into the Jurassic sedimentary rocks. The basalt and older sedimentary rocks were subsequently buried by Cretaceous sedimentary rocks (*Ks*) of the Leederville Formation. These range from lacustrine–fluviatile rocks with thin peaty coal seams to higher energy estuarine–fluviatile rocks. The Donnybrook Sandstone, which contains miospores of Early Cretaceous age similar to those in the Leederville Formation, was deposited over Permian sedimentary rocks to the east of the Darling Fault near Donnybrook (Backhouse and Wilson, 1989).

Collie, Wilga, and Boyup Basins

Fluvioglacial rocks (*Ps*; unit does not outcrop on the map area but is included as a layer in the digital data) and coal measures (*Pcm*) of Permian age are preserved in grabens in the Collie, Wilga, and Boyup Basins. These rocks may be relicts of an extensive Permian sequence that extended across the Yilgarn Craton. Fluviatile rocks of the Nakina Formation (*Ks*) overlie the Permian sedimentary rocks in the Collie Basin. Palynomorphs in the Nakina Formation suggest a correlation with the Cretaceous Leederville Formation in the Perth Basin (Backhouse and Wilson, 1989).

Bremer Basin

The Bremer Basin forms a veneer over the Albany–Fraser Orogen and the southern part of the Yilgarn Craton in the southeastern part of the area. Although initial deposition in the basin occurred in the Jurassic, the only onshore deposition was of sandstone, siltstone, and spongolite of the Plantagenet Group during the Eocene (Hocking, 1990).

Regolith

A veneer of unconsolidated or partly consolidated sediments covers much of the Southwest. This regolith includes weathering products, drainage-related sediments, and coastal sediments.

Laterite is a residual product formed by intense weathering of the underlying basement. In the Darling Range area, warm temperature, high rainfall, moderate relief, good drainage, and dense vegetation were conducive to the formation of bauxite. Other weathering products include lateritic gravel, residual and transported sand, and clay.

Drainage-related sediments include sand, silt, clay, and conglomerates deposited in creeks, swamps, lakes, and estuaries. Colluvium is present on slopes.

Coastal sediments include cemented, windblown calcareous sand formed during periods of low sea level at the peaks of Pleistocene glaciation, and modern and fossil beach and dune sand deposits.

Exploration and mining

This section describes the history of exploration and mining of various commodities in the Southwest, in the chronological order of the first discovery of each commodity.

The first mine in Western Australia was established in 1847 on a lead–silver–zinc-bearing quartz reef at Mundijong near the Darling Scarp south of Perth. The reef was worked sporadically until 1927. There has been no reported exploration for further occurrences of lead–zinc. Billiton Australia explored for base metals in the northern part of the area during the 1980s, and intersected subeconomic copper mineralization at the Southern Brook prospect, northeast of Northam (Shaw, 1984).

Gold was discovered at Kendenup, north of Mount Barker, in 1853 but development of the prospect in the mid-1870s proved unsuccessful. The first payable gold discovery in the Southwest was at Donnybrook in 1897. Proclamation of the Donnybrook Goldfield occurred in 1899 after 16.1 kg of gold had been produced. Although several hundred metres of underground development took place on this epithermal vein gold deposit, virtually no ore was stoped and the company went into liquidation in 1904. West Coast Holdings diamond drilltested a number of the old Donnybrook workings in the 1980s but, although quite broad widths of mineralization were intersected, no economic orebody was found. Geochemical investigations over the Mount Saddleback greenstone belt by GSWA during the late 1970s defined a base-metal and gold anomaly northwest of Boddington (Davy, 1979). Further exploration by Reynolds Australia and Alcoa of Australia led to the discovery of a large tonnage, low-grade, laterite-hosted gold deposit that straddled State Agreement bauxite leases held by Worsley Alumina and Alcoa of Australia. Two separate gold mines (Boddington and Hedges) were developed by Worsley Alumina and the Boddington Gold Mine (BGM) group of companies, and by Hedges Gold, in 1987 and 1988 respectively. Subsequent drilling beneath the laterite at Boddington located primary Archaean gold mineralization that could be mined by openpit and underground mining operations (Townsend, 1994). The discovery of lateritic gold at Boddington led to a spate of exploration for this type of mineralization in the Southwest but, to date, no other deposits of this type have been found in the area.

The Collie coalfield was discovered in 1883. Production commenced in 1898, when the railway between Perth and Collie was completed, and continues to the present day. The two producing companies are Griffin Coal Mining Company and Western Collieries (Le Blanc Smith, 1993). The coal-bearing Wilga and Boyup Basins were discovered in 1918 (Townsend, 1994). Coal in the Sue Coal Measures on the Vasse Shelf was discovered in 1966 in Sue No. 1 Well at a depth of more than 1000 m. Systematic hydrogeological drilling by GSWA in 1966–67 indicated that coal occurred at depths of less than 300 m, and exploration drilling by CRA outlined the limits of the coal body (Townsend, 1994).

Alluvial tin was discovered at Greenbushes in 1898 and the Greenbushes Pegmatite was discovered shortly afterwards (Blockley, 1980). Although tin was initially the only product mined, the Greenbushes Pegmatite is currently the world's largest tantalite and spodumene producer. Exploration for further Greenbushes-type pegmatites was carried out by Greenbushes Limited and Pancontinental Mining during the 1980s using stream-sediment sampling and multielement analysis of laterite samples collected on a very widely spaced grid. Although anomalies were defined, and some pegmatites were tested by drilling at Smithfield, no other large pegmatites have been discovered.

The first production of iron ore in the State was between 1899 and 1907, from lateritized BIF at Clackline (Wilde and Low, 1978). Subsequently, minor lateritic iron occurrences (Scott River Iron, Brookton One, and Cheyne Iron) have been investigated, but no economic iron deposits have been discovered.

The occurrence of bauxite within the Southwest was first recorded in 1902 on the Darling Range. In 1919, GSWA mapped the extent of laterite in the Darling Range near Perth that might contain economic bauxite. The Electrolytic Zinc Company of Australia explored the Darling Range bauxite deposits in 1918, but at that time it was thought that the bauxite was restricted to the lateritic caprock and the deposits were regarded as being of subeconomic grade. No further exploration took place until 1957, when Western Mining Corporation began to explore for bauxite in the Darling Range. Following regional exploration, a joint-venture company, Western Aluminium NL, was formed to explore temporary reserves over a large portion of the Southwest. The most prospective areas were drilled at 60 m intervals, and the less prospective areas at 100 m intervals. By late 1961 the company had delineated reserves of 37 Mt of bauxite at an average grade of 33% available $A1_2O_3$. Commercial mining commenced in 1963 after construction of a refinery at Kwinana. Subsequently, bauxite mining commenced at Huntly – Del Park in 1972, Mount Saddleback in 1983, and Willowdale in 1984. The ore from these mines is treated at refineries at Pinjarra, Worsley, and Wagerup respectively (Hickman et al., 1992).

The first production of heavy minerals in the State occurred in 1949 at Cheyne Bay on the south coast. Significant heavy-mineral production from the Perth Basin commenced in 1956 on the Capel shoreline near Bunbury. The Waroona and Yoganup shoreline deposits were also drilltested in 1956 (Baxter, 1977). A significant discovery of heavy minerals at Beenup on the Scott Coastal Plain was announced in 1988. This deposit started production in 1995. Other recent discoveries of heavy minerals in the Southwest include Jangardup and Jangardup South on the Scott Coastal Plain, and Metricup in the Leeuwin area. Exploration techniques used in heavy-mineral exploration include aeromagnetic and ground magnetic surveys, aerial photograph interpretation to detect ancient strandlines and embayments in old coastlines, and drilling.

Layered mafic–ultramafic rocks near Northam and in the Balingup Complex in the southern part of the area have been explored for nickel, chromium, and platinum-group element (PGE) minerals since the 1960s. Aeromagnetic surveys, stream-sediment sampling, and drilltesting of selected anomalies are the main exploration techniques that have been used. Only subeconomic occurrences have been reported.

Gwalia Consolidated commenced mining of silica sand suitable for container glass from Kemerton in 1996.

CRA has been actively exploring for kaolin in the southwestern part of the area since the early 1990s.

Petroleum exploration in the southern Perth Basin commenced in 1902 with the drilling of three shallow wells (Warren River 1, 2, and 3) but these were barren. In 1968, gas was intersected in Whicher 1 in the Whicher Range. Amity Oil and Penzoil Exploration are currently investigating the gas field using hydraulic fracture stimulation technology to determine if the gas can be extracted economically. As petroleum is beyond the scope of this study, it is not considered further in this Report.

Mineralization

The mineral occurrences on Plate 1 are firstly grouped by commodity (distinguished by colour), and secondly by mineralization style (distinguished by symbol). However, for ease of description, the following section groups occurrences first by mineralization style and then by commodity. Associated commodities are given in parentheses. To assist in placing the occurrences in their tectonic framework, some of the commodities have been plotted separately on a tectonic sketch. These include precious metals (Fig. 3), speciality metals (Fig. 4), steel-industry metals (Fig. 5), and bauxite (Fig. 6).

Pegmatitic mineralization

Speciality metal — lithium, tin, tantalum, REE

The Greenbushes rare-metal pegmatite is the world's largest producer of tantalum and spodumene. Most

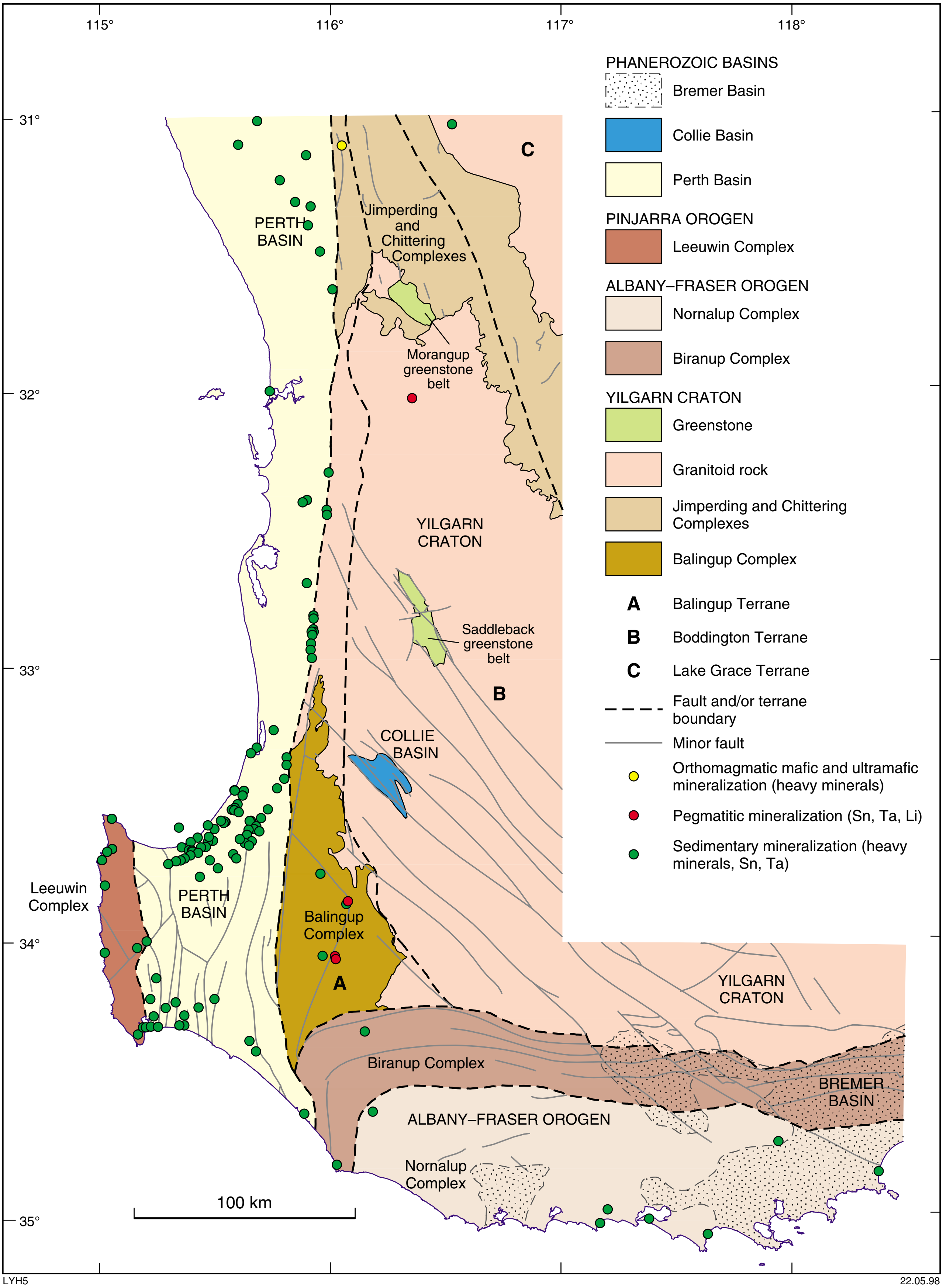

Figure 4. Tectonic sketch of southwest Western Australia showing the distribution of speciality metals (heavy minerals, Sn, Ta, Li)

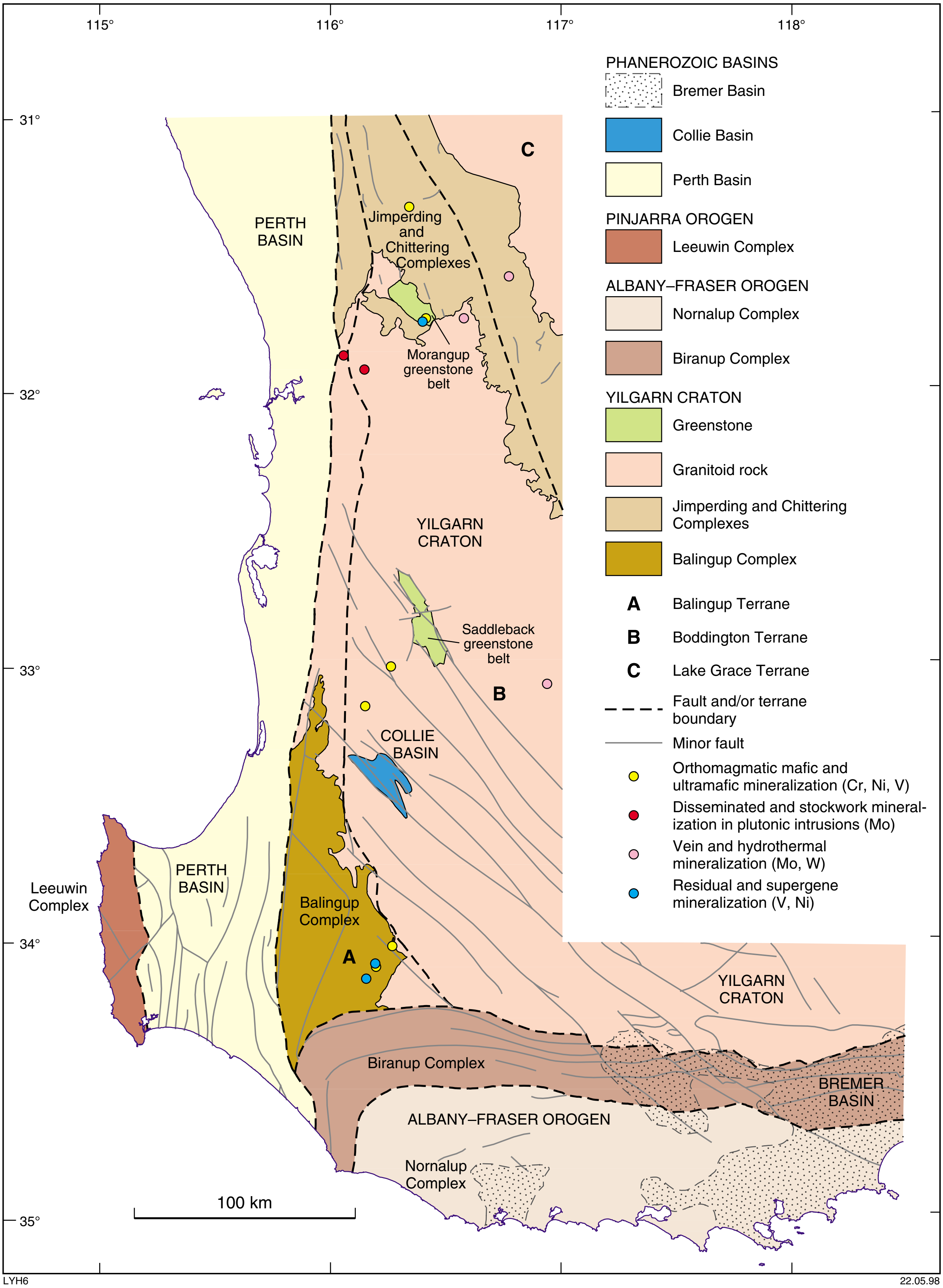

Figure 5. Tectonic sketch of southwest Western Australia showing the distribution of steel-industry metals (Cr, Mo, Ni, V, W)

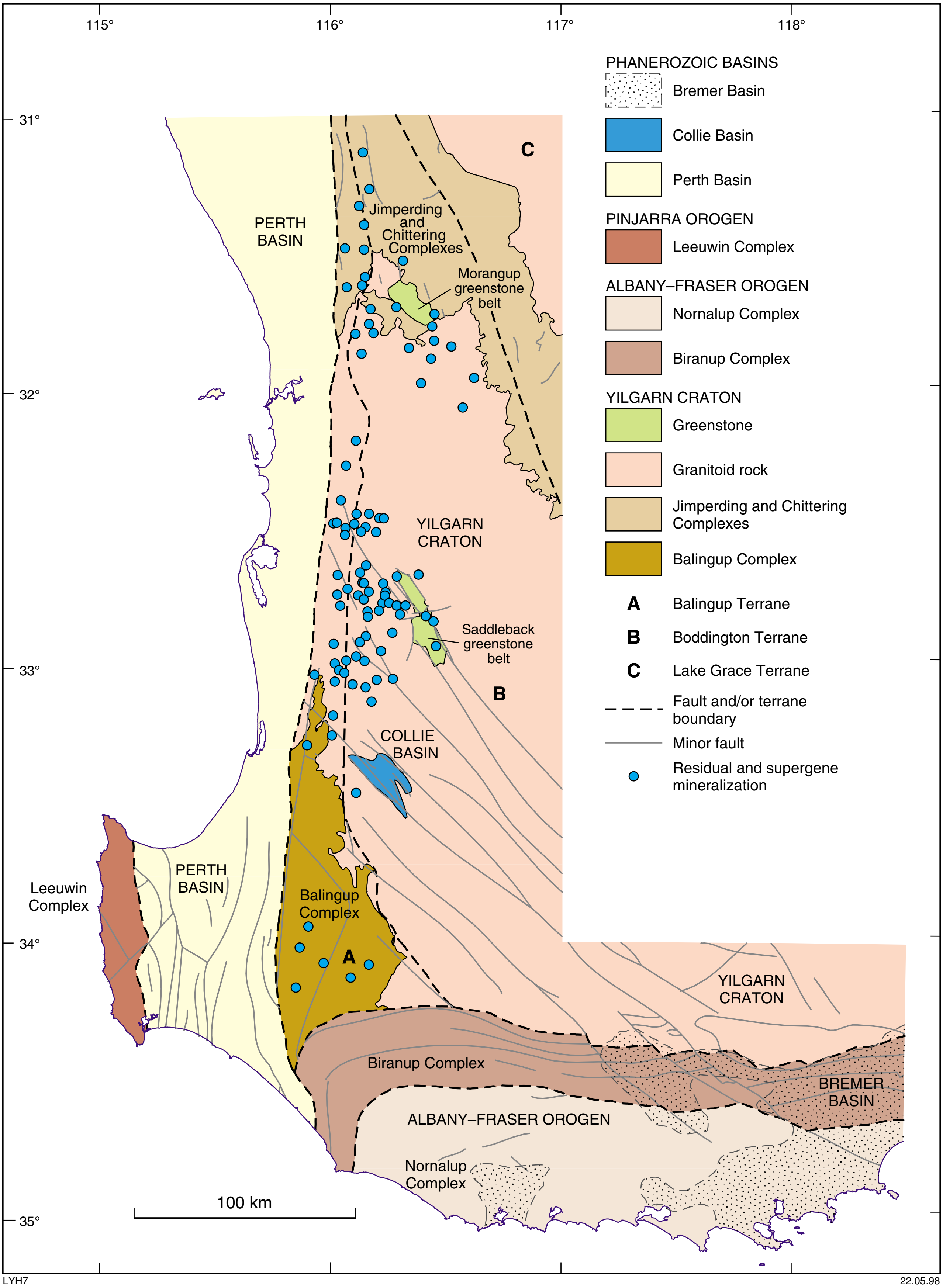

Figure 6. Tectonic sketch of southwest Western Australia showing the distribution of bauxite

production has come from weathered pegmatite and alluvial deposits, but openpit mining of the fresh pegmatite commenced in 1992 when the emphasis changed from tin to tantalum production. Spodumene is being mined from a separate openpit. A new lithium carbonate plant has recently been commissioned and is expected to produce 5000 t per annum of lithium carbonate powder. Production between 1889 and the end of 1996 was 22 400 t of tin, 5300 t of tantalite, and 560 000 t of spodumene. Total demonstrated resources at the end of 1995 were 33.0 Mt at 0.29 kg/t Ta_2O_5, 13.88 Mt at 3.83% Li_2O, and 5.7 Mt at 0.25 kg/t SnO_2, with additional inferred resources of 7.9 Mt at 0.31 kg/t Ta_2O_5.

The Greenbushes Pegmatite consists of one main pegmatite body and several smaller pegmatite bodies that have intruded the Balingup Complex over a strike length of 7 km, along the regional Donnybrook–Bridgetown Shear zone. The main pegmatite is approximately 3.3 km long and up to 250 m wide, and has been drilled to a vertical depth of 500 m, with no decrease in thickness (Hatcher and Clynick, 1990). The pegmatite occurs at, or close to, the contact between mafic–ultramafic rocks and laminated metasedimentary rocks (granofels). The pegmatite has distinct Li-rich, K-rich, and Na-rich zones, but unlike other zoned pegmatites in which the Li-rich zone occurs in the central part of the pegmatite, the Na-rich zone is centrally disposed and the Li-rich zone forms a carapace to the pegmatite. Tin–tantalum mineralization is disseminated throughout the Na-rich zone.

Granitoid rocks of the Darling Range batholith outcrop 10 km north of Greenbushes to the east of a major lineament. Blockley (1980) reported that the petrography and chemistry are different to those of typical tin granites. There are also a number of smaller granitoid intrusions aligned parallel to the Donnybrook–Bridgetown Shear zone (Partington et al., 1995). Recent age-dating of pegmatites and granitoid rocks in the area suggests that the intrusion of pegmatites post-dates intrusion of the granitoid rocks by at least 85 to 50 Ma. In addition, a regional gravity survey discounts the possibility of a body of granitoid rock large enough to be parental to these pegmatites (Partington et al., 1995).

Unlike most other rare-metal pegmatites, intrusion and crystallization of the Greenbushes Pegmatite was synchronous with deformation and the pegmatite was emplaced under medium- to high-temperature and medium-pressure metamorphic conditions (Bettenay et al., 1985; Partington et al., 1995). According to Partington et al. (1995), the most important control on the intrusion of the pegmatite was the Donnybrook–Bridgetown Shear zone. Bettenay et al. (1985) suggested that the Greenbushes Pegmatite formed directly by partial melting of Li-rich source rock. They proposed the term 'magmatic disseminated' for this syntectonic–synmetamorphic type of rare-metal pegmatite.

A small swarm of tin- and tantalum-bearing pegmatites occurs at Smithfield (approximately 30 km south of Greenbushes), close to the Donnybrook–Bridgetown Shear zone, and is probably also of the magmatic disseminated type.

A small pegmatite containing minor rare-earth minerals, manganocolumbite, and beryl has been recorded near Mount Dale (Simpson, 1948) but there are no documented details of the geological setting.

Industrial mineral — beryl, feldspar, mica

The Ferndale pegmatite has been dated at 680 Ma (Partington et al., 1986). Recorded production is 10.91 t of beryl. The pegmatite is also reported to contain a large tonnage of feldspar suitable for the ceramics industry (Matheson, 1944a). Four groups of pegmatites of Proterozoic age in the Mullalyup district have been worked for sheet mica. Total recorded production up to the end of 1942 was 3683.2 kg of mica. Beryl crystals up to 0.5 kg have been found, but there is no recorded production (Matheson, 1944a; Townsend, 1994). Beryl has also been reported from the Kirup and Katterup pegmatites and sheet mica from the Bussel Brook pegmatite (Simpson, 1948, 1952).

Orthomagmatic mafic and ultramafic mineralization

Undivided

Precious metal — PGE

Significant PGE and copper mineralization has been recorded from the Yarawindah prospect near New Norcia. Values of up to 1 m at 2.68 g/t Pt and 0.36 g/t Pd have been recorded, as well as grades of up to 2.4% Cu and 1.5% Ni. Reynolds Australia Metals (Cornelius, 1989) estimated a resource of 31 000 t at 0.5 g/t PGE per vertical metre in the primary zone but concluded that this was subeconomic. The mineralization is in a 4 km-long ultramafic–mafic complex that consists of olivine gabbronorite as well as serpentinite after peridotite and pyroxenite. On the basis of plots of Pt/(Pt + Pd) and Cu/(Cu + Ni) ratios, Harrison (1986) concluded that the parent magma had tholeiitic affinities. However, on the basis of chondrite-normalized PGE patterns, Cornelius et al. (1987) concluded that the complex was originally a komatiitic-like sill. Cornelius (1989) inferred that PGE mineralization had been redistributed during regional metamorphism.

Steel-industry metal — chromium, nickel, vanadium

The distribution of all steel-industry metal occurrences, including those of orthomagmatic mafic and ultramafic type, is shown on the tectonic sketch (Fig. 5). Primary and supergene occurrences of chromium and nickel are related to ultramafic rocks in the Balingup Complex. These include chromium and nickel at Yornup South, chromium at Yornup Northeast, and nickel at Palgarup. Planet Management and Research obtained best intersections of 0.83% Ni at Palgarup (Apthorpe, 1971a), whereas at Yornup South they obtained drill intersections of commonly less than 0.3% Ni (Apthorpe, 1971b). The best chromium intersections were 5 m at 5.3% Cr obtained by Western Mining Corporation (1980) at Yornup South, and 2 m at 7.4% Cr obtained by West Coast Holdings at Yornup Northeast (Chadwick, 1986). Hunter Resources obtained BLEG (bulk-leach extractable gold or other element) soil anomalies of up to 3.1 ppb Pd and 3.9 ppb Pt in the Yornup area (Cameron, 1990). The ultramafic–mafic complex at Yornup consists of olivine gabbronorite, harzburgite, lherzolite, and dunite that have been extensively serpentinized. Harrison (1986) concluded that the Yornup and Palgarup host rocks were remnants of a large layered tholeiitic intrusion that he termed the Donnelly River Complex. However, Cornelius et al. (1987) concluded that the complex was originally a komatiitic sill.

Vanadium-rich titaniferous magnetite is present in a lateritized gabbro at Coates Siding. The gabbro is zoned from leucogabbro at the base through magnetite gabbro in the centre to gabbro at the top. The magnetite gabbro contains 20 to 40% magnetite and ilmenite, concentrated in lenticular layers. The ilmenite:magnetite ratio varies considerably but is commonly about 4:1. The vanadium is concentrated in the magnetite, but small amounts also occur in ilmenite. The magnetite gabbro contains between 0.3 and 0.7 per cent V_2O_5. The gabbro has been subjected to intense weathering and lateritization. Both the kaolinized gabbro and the ferricrete contain vanadium resources, with the ferricrete containing the highest grades (0.88 per cent V_2O_5; Baxter, 1978). The measured and indicated resource for the primary deposit is 39 Mt at 0.51% V_2O_5, and the indicated resource for the lateritized deposit is 1.5 Mt at 0.6% V_2O_5 (Baxter, 1978). The deposit was mined in 1980 and 1981, but mining was suspended because of falling metal prices and difficulties with the processing plant. Recent aeromagnetic interpretation suggests that the Coates gabbro is part of a very extensive north-northwesterly trending dyke (I. Chalmers, 1997, pers. comm.).

East of the Bindoon Army training area, the Army Reserve prospect contains vanadium-rich layers of titaniferous magnetite in a basic complex consisting of leucogabbro, magnetite gabbro, and anorthosite. A resource potential of 90 000 t per vertical metre, at a grade of 0.3% V_2O_5, or 20 000 t per vertical metre at a grade of 0.45% V_2O_5, has been estimated (Harrison, 1986).

The Tallanalla vanadium occurrence occurs within a poorly exposed gabbro containing magnetite bands in the central part of the area.

Speciality metal — ilmenite

At the Wannamal–Mogumber occurrence, large segregations of ilmenite–hematite intergrowth occur within a mafic dyke cutting gneiss of the Chittering Complex. The ilmenite can be can be traced over a distance of 1.6 km (Simpson, 1952).

Industrial mineral — talc, vermiculite, asbestos

Talc deposits at Glen Lynn, Bolgart, Meaneys Bridge, Beverley, Goomalling, Hamersley Siding, Manjimup, Wagerup, Wellington Mill, Wongamine, Mount Hardy, and Mount Bakewell have formed by metamorphism of ultramafic intrusions. Vermiculite and asbestos at Goomalling have also formed by metamorphism of an ultramafic unit.

Disseminated and stockwork mineralization in plutonic intrusions

Precious metal — gold (copper)

The Boddington primary gold deposit was described by Roth et al. (1990) as having many features in common with porphyry copper deposits. More recent work by Allibone et al. (1996) suggests that it belongs to the vein and hydrothermal category.

Steel-industry metal — molybdenum

At Swan View, molybdenite occurs as scattered flakes and foliated masses within granite in a pit about 3 m long and 2 m deep. Disseminated pyrite is also present in the granite (Talbot, 1915; Simpson, 1952). Talbot (1915) stated that there was no sign of any lode or reef, suggesting that the molybdenite is primary.

Vein and hydrothermal mineralization

Undivided

Precious metal — gold (barium, copper, molybdenum, lead, zinc, tungsten)

Vein and hydrothermal gold occurrences in the Southwest are essentially of two types: mesothermal gold deposits of Archaean and possible Proterozoic age, and epithermal gold deposits of Lower Permian to Lower Cretaceous age. These are shown separately in Figure 3.

Archaean (and ?Proterozoic) gold

The Boddington mine in the Saddleback greenstone belt is the second largest gold producer in Australia. Most production to date has come from lateritic and saprolitic ore, but there are large resources of primary ore. Published resources for the primary Wandoo orebody at Boddington are 302 Mt containing 0.92 g/t Au and 0.1% Cu.

The primary mineralization is mainly confined to quartz veins and fractures within diorite intrusions, and within structurally favourable sites in the surrounding felsic volcanic rocks. Gold is typically associated with chalcopyrite, pyrite, and pyrrhotite. Molybdenite, sphalerite, scheelite, arsenopyrite, cubanite, native bismuth, and galena are accessory phases. The presence of exsolved cubanite in chalcopyrite indicates a temperature of formation of greater than 250–300°C. This is supported by fluid-inclusion studies that indicate a minimum trapping temperature of 300°C, and saline (up to 40 wt% NaCl equivalent) fluids (Roth et al., 1990). Roth et al. (1990) concluded that Boddington had a close similarity to Phanerozoic porphyry-gold systems.

However, Allibone et al. (1996) have shown that the mineralized veins crosscut the foliation associated with the youngest ductile-shearing event. Allibone et al. (1996) concluded that the potassic alteration described by Roth et al. (1990) is a regional metamorphic assemblage, that the phyllic alteration is a sericitic assemblage localized within shear zones, and that the mineralization is not of porphyry-copper type.

There are several small gold workings in quartz veins, quartz reefs, and shear zones in schists, gneisses, quartzites, and BIF of the Balingup, Jimperding, and Chittering Complexes. Of these, only Jimperding has a recorded production of primary gold (10.17 kg). Three of these deposits (Wongamine, Blackboy Hill, and Bolgart) lie on or close to the major shear zone between the Boddington Terrane and the Lake Grace Terrane (Plate 1).

The Kendenup quartz reef was discovered in 1853. The quartz reef cuts granitic gneiss, medium-grained pyritic leucogranofels, and pyritic amphibolite of the Biranup Complex, and is close to a major northwest-trending fault. Five tonnes of ore sent to Victoria for treatment in the early 1870s yielded 0.13 kg of gold. However, production from a stamp mill erected in 1875 failed because of low gold recoveries due to the high pyrite content of the ore (Hassell, 1972; Townsend, 1994).

Gold was mined from a quartz reef in felsic gneiss and amphibolite of the Nornalup Complex at Redmond (Bluegum Creek) in 1898. The reef was reputed to assay about 10 g/t Au with high silver and copper values. The mineralization could be either Proterozoic in age, or Archaean gold mobilized during the Proterozoic.

Permian to Cretaceous epithermal gold

In the Donnybrook area, total recorded production of gold between 1897 and 1904 was 26.1 kg from 1613 t of ore. The main producers were Hunters Venture, Mount Cara, Cammilleri's, Queen of the South, Empress Helena, Arc of Gold, Brookmans, The Wild Wave, and Bullington. There are a number of gold-bearing silicified shear zones, breccia zones, quartz stringers, and quartz veins in close proximity to the Darling Fault to the south of Donnybrook.

Gold has been mined from mudstone and fluvioglacial sandstones of Early Permian age (Backhouse and Wilson, 1989), and from the underlying schists, gneisses, and amphibolites of the Balingup Complex. The mineralization has a number of distinctive epithermal features including platy textures with silica replacing original carbonate or sulfate minerals (Fig. 7), breccias recemented by silica (Fig. 8), multiple thin quartz veins (stockwork), and pyritic silica and chert breccias (Beyschlag and Krusch, 1900; Morant, 1988). Alteration includes silicification, and propylitic and argillic alteration (Ward, 1986). Alunite is associated with the highest grade mineralization, and pyrite and hematite are locally associated with silicification in the sandstones (Morant, 1988).

Mineralization was previously thought to be Cretaceous in age and related to the 136 Ma Bunbury Basalt. However, pebbles of mineralized Donnybrook Sandstone have been found in palaeovalleys beneath the Bunbury Basalt, indicating that mineralization preceded the eruption of the basalt. Furthermore, the Bunbury Basalt and Leederville Formation, which unconformably overlie the Donnybrook Sandstone, show no sign of hydrothermal alteration, whereas the Donnybrook Sandstone is pervasively silicified. For these reasons, Morant (1988) concluded that the mineralization was of Permian age, but may have been a prelude to basaltic volcanism. Chalmers (1997, pers. comm.) suggested that high heat flow associated with major rifting and the Gondwana breakup was responsible for the epithermal fluids.

The Mitchell gold occurrence, south of Donnybrook, is hosted by Archaean felsic gneiss. There are multiple quartz veins, some of which display epithermal quartz–carbonate textures (R. Rogerson, 1997, pers. comm.). An old shaft was sunk on an epithermal vein in Archaean schist and amphibolite at the Ironstone Road occurrence to the north of Donnybrook. A nearby breccia was considered by Page (1987) to be a hydrothermal vent breccia.

Gold of probable epithermal origin is also reputed to have been produced from Serpentine, Mundijong (Woodward, 1908), Armadale, and Gosnells (Montgomery, 1910) on the Darling Scarp to the south of Perth. At the Gosnells occurrence there is a 53 m-long adit into a massive quartz vein cutting granodiorite. The quartz vein is about 3 m wide, but a stockwork of quartz veins and stringers extends for about 15 m on either side of the veins. The host granodiorite has undergone intense argillic alteration and some silicification in the vicinity of the quartz vein, and contains boxworks after disseminated sulfides. Assays up to 110 g/t Au were obtained on samples reputed to have come from the adit, but Montgomery (1910) obtained only traces of gold in samples that he collected. A sample of quartz and a sample of altered granodiorite collected during this study from the surface contained only 5 ppb and 2 ppb Au respectively. However, the extent of alteration is large and the possibility of localized concentrations of gold cannot be ruled out.

Several small gold occurrences in the Leeuwin Complex close to the Dunsborough Fault (e.g. Petterd and Cross Reef, Happy Jack Reef, and Boodgidup Brook) also have epithermal textures and have been interpreted as rift-related epithermal deposits (I. Chalmers, 1997, pers. comm.). No production has been officially recorded from these mines.

LYH 12 27.05.98

Figure 7. Platy textures (silica replacing carbonate and sulfate minerals), indicative of an epithermal origin, Hunter Venture mine, Donnybrook

LYH 17 27.05.98

Figure 8. Epithermal vein breccia, Hunter Venture gold mine, Donnybrook

Base metal — copper, lead, zinc (silver, gold, barium, fluorite)

The Mundijong lead–zinc–silver mine, which was established in 1846, was the first mine in Western Australia. A few tonnes of galena were shipped to London in 1870. The main shaft and several costeans have now been filled in, but the dump remains. The mineralized quartz vein extends over a length of 200 m near the contact between sheared granite and a fine-grained mafic rock. Mica schist and a porphyritic quartz gabbro are also present on the dump. Sedimentary rocks of the Cardup Group outcrop to the northwest of the workings, but according to Esson (1927) the reef did not intersect the sedimentary rocks. The main ore minerals are galena and sphalerite, with accessory copper and silver minerals. Minor barite and fluorite are present in the quartz vein. The laminated nature of the reef (Esson, 1927) suggests an epithermal origin. According to Woodward (1908), the best mineralization was on a steeply dipping ore shoot. Lead was rich near the surface but the zinc content increased with depth. Assays up to 12.64% Pb, 43.75% Zn, and 106 g/t Ag have been recorded (Simpson and Gibson, 1907). Difficulties in separating the lead from the zinc, coupled with flooding of the mine, led to its closure in 1927. Another quartz vein is exposed in a small adit in a railway cutting near Mundijong. This vein is clearly epithermal as it is laminated with well-developed drusy quartz crystals. The core of the vein contains disseminated galena and some fine-grained fluorite. Gold is reputed to have been found in the vicinity (Woodward, 1908), but a sample assayed in this study contained only 4 ppb Au; it did, however, contain 8.4 ppm Ag.

Drilling by Billiton Australia intersected irregular pods of base-metal mineralization at the Southern Brook prospect, to the northeast of Northam, in 1984. The best intersection was 2 m at 3.25% Cu in a rotary air-blast drillhole. The best diamond drillhole intersection was 1 m at 0.71% Cu and 2.2 g/t Au from 152 m. The mineralization is hosted by charnockite, garnet–biotite–feldspar–quartz gneiss, and amphibolite. According to Shaw (1984), metasedimentary rocks with intercalated mafic rocks were subjected to granulite facies metamorphism, then retrograde metamorphism and granite intrusion. Shaw (1984) interpreted the mineralization to be introduced at a late stage during a metasomatic event related to the retrograde metamorphism and granite intrusion.

Steel-industry metal — molybdenum, tungsten

Numerous pieces of wolframite were discovered in a ploughed field at Grass Valley (Blatchford, 1918). Gneiss and quartzite of the Jimperding Complex outcrop nearby. Blatchford (1918) suggested that the wolframite was pegmatitic in origin. Wilde and Low (1978) noted tourmaline-bearing quartz in the vicinity, suggesting that the wolframite belongs to the vein and hydrothermal category.

Traces of molybdenite are present in a shear zone at the Williams occurrence (Wilde and Walker, 1982) and in joints in granite at Mokine (Simpson, 1952). At Spencers Brook, molybdenite occurs in four or five parallel quartz veins up to 10 cm wide. These quartz veins crosscut the foliation of the enclosing granite (Simpson, 1952). The Swan View molybdenite occurrence is possibly of vein and hydrothermal type, but has tentatively been assigned to the disseminated and stockwork in plutonic intrusions category.

Industrial mineral — barite

Three barite veins were discovered in sandstones of the Stirling Range Formation at Cranbrook in 1897. The largest vein is 0.25–0.75 m wide. A total of 2487 t of barite was produced between 1953 and 1975. According to Noldart (1956), the major proportion of the veins consisted of ‘a coarse-grained, translucent crested or lamellar variety of barite’ with the remainder containing fine-grained opaque barite. Noldart (1956) concluded that the veins were mesothermal. On the basis of the textures that he described the veins could also be interpreted as epithermal.

Barite has been mined from a vein in slate at Cardup, on the Darling Scarp to the south of Perth. The vein varies from 30 to 120 cm wide. The barite in the purer sections of the vein has a coarsely lamellar texture and is 99.19% $BaSO_4$ (Simpson, 1948).

Barite veins are also present in slate and sandstone near Gosnells. Simpson (1948) reports that in one vein a later generation of quartz has formed a layer of small crystals over the barite, indicating an epithermal origin for the mineralization.

Stratiform sedimentary and volcanic mineralization

Undivided

Precious metal — gold (copper, molybdenum)

The old Mine Hill gold deposit contains gold in association with chalcopyrite and molybdenite in quartz veins parallel to the schistosity in a quartz–muscovite schist in the Balingup Complex. Page (1987) considered that the schist was possibly a metamorphosed felsic tuff and that the deposit may have been volcanogenic in origin. However, R. Rogerson (1997, pers. comm.) could find no evidence of a volcanogenic origin and concluded that the deposit falls into the vein and hydrothermal category.

Stratabound mineralization

Undivided

Precious metal — gold

At the Yanmah prospect in the Balingup metamorphic belt, a drillhole intersected gold mineralization (2 m at

2.75 ppm Au) with associated high arsenic values at the contact between a light coloured and a dark coloured biotite–garnet schist. The gold could be metasedimentary in origin or may be structurally controlled.

Precious mineral — opal

A piece of clear fire opal 30 cm long was found in the Pallinup Siltstone near Twow Swamp by Fred Simpson whilst clearing his land (D. Townsend, 1997, pers. comm.).

Industrial mineral — graphite, kyanite, sillimanite, limestone

Graphite has been reported from schist near fault zones in metasedimentary rocks of the Biranup Complex at the Kendenup, Martigallup, Shaws, and Furniss occurrences (Blatchford, 1922a,b).

Metamorphic segregations of primary kyanite have been worked from kyanite schist in the Balingup Complex at Manjimup Brook (Lord, 1950). Large quantities of kyanite at Wattle Flat, and of sillimanite at Goyamin Pool, occur in schists of the Chittering Complex. These would require crushing and special beneficiation to be utilized (Wilde and Low, 1978). At Clackline, 2 t of sillimanite was produced in 1948 from schist of the Jimperding Complex (Wilde and Low, 1978).

Sedimentary mineralization

Basin

Energy mineral — coal

The Collie Coalfield is the only commercial producer of coal in the State. The coal occurs in a fault-bounded basin approximately 226 km^2 in area. Approximately 60 significant coal seams, ranging from a few centimetres to 15 m in thickness, have been recognized over a stratigraphic thickness of about 1000 m. The stratigraphic succession is described in detail in Le Blanc Smith (1993).

The coal rank varies from bituminous to sub-bituminous and has a specific energy of 18–22 MJ/kg, a moisture content of approximately 25%, an ash content of 3–10%, and contains 0.29–0.49% S (Le Blanc Smith, 1993).

Although previously mined from both opencut and underground mines, all coal is now produced from opencut mines. Most of the coal is used to produce the State's electricity. Production between 1898 and the end of 1996 was 133 Mt. Resources in the Collie Basin total approximately 2400 Mt (Le Blanc Smith, 1993).

Like the Collie Basin, the Wilga and Boyup Basins are remnants of a formerly more extensive Permian sequence preserved in grabens. They contain coal resources of 264 and 90 Mt respectively (Townsend, 1994).

The Vasse coal deposit is situated on the Vasse Shelf, a step-faulted block between the Leeuwin Complex and the Busselton Fault. Estimated resources of coal on the Vasse Shelf for seams over 1.3 m thick and within 600 m of the surface are 600 Mt (Le Blanc Smith, 1990).

Undivided

Base metal — lead

Highly anomalous lead values (up to 0.19% Pb over 2 m) have been reported from shaly coal in the Permian coal basin (Davy and Wilson, 1989). Although not quite meeting the normal criteria for a mineral occurrence, it was considered sufficiently important to be included in this study.

Industrial mineral — clay, diatomaceous earth, glauconite, graphite, gypsum, kaolin, limestone, peat, phosphorous, silica, spongolite

Silica sand

Very high quality silica sands are present within well-sorted Pleistocene sands along the south coast, and the Scott Coastal Plain. Westralian Sands located a number of silica-sand deposits suitable for glass manufacture within a 40 km radius of Albany. Washed sands from these deposits contain greater than 99% SiO_2. Two of the deposits, in the Narrikup area, have a total resource of 4 Mt (Monks, 1993).

Gwalia Consolidated commenced mining of high-grade silica sand at Kemerton in 1996. They are currently producing sand at a rate of 300 000 – 350 000 t per annum with a target of about 1 Mt per annum. The indicated resource is 200 Mt containing 1–3% alumina. The high alumina content enables the sand to be marketed as container glass (Quinn, 1997).

Numerous silica-sand deposits in the Perth metropolitan area are also being quarried for use in glass-making, steel and cast-iron work, and as a construction material. Only those deposits with resources in MINEDEX are shown on Plate 1.

Kaolin

Kaolin has been mined for use as a filler material from the Mount Kokeby deposit. Total recorded production between 1941 and 1983 was 8046 t. The kaolin occurs in lacustrine deposits interbedded with sand, sandstone, and blue clay (Lipple, 1977; Abeysinghe, in prep.). Ceramic-quality kaolin, of probable lacustrine origin, has been mined from four separate layers, up to 2 m thick, in a flooded claypan 17 km west of Goomalling (Wilde and Low, 1978; Abeysinghe, in prep.).

Other clays

Ceramic and brick clays have been quarried extensively from alluvial deposits in the Swan and Helena River Valleys. Only those deposits with resources in MINEDEX are shown on Plate 1.

Graphite

Microcrystalline graphite occurs in schist of the Balingup Complex at the Donnelly River deposit (Ellis, 1953). About 400 t of ore has been mined since 1904. The graphite has potential for use in foundries, refractory bricks, conductive coatings, batteries, pencils, or speciality paint (Townsend, 1994).

Gypsum

There is an estimated resource of 6000 t of seed gypsum at 93% purity, and 3150 t of kopi at 85% purity in a small dune on the edge of a salt lake near Pootenup (Jones, 1994). Other gypsum occurrences associated with inland salt lakes include those at North Kambellup, Cookernup Siding, and Youngs Siding.

Diatomaceous earth

A number of lakes and swamps overlying the Bassendean Sand on the Swan Coastal Plain contain diatomaceous material (Wilde and Low, 1978). At Lake Gnangara and Yeal Swamp, some of this material is sufficiently pure to be mined for use in swimming-pool filters.

Peat

Peat suitable for garden use has been produced from Cowerup Swamp, 1 km north of Lake Muir, and from a swamp on the southwestern margin of Lake Muir. Resources in Cowerup Swamp have been estimated at 450 000 t (Knight, 1980). Peat has also been reported from Lake Surprise and from Neaves Rd – Melaleuca Park on the Swan Coastal Plain. The sedimentary rocks of the Bremer Basin and the Cretaceous sedimentary rocks west of the Darling Fault also host peat deposits.

Glauconite

Glauconite occurs in the Upper Cretaceous Molecap and Poison Hill Greensands, and in the Lower Cretaceous Osborne Formation. About 32 500 t of greensand were mined from Molecap Hill between 1932 and 1960; this yielded 6570 t of glauconite concentrate that was shipped to England for water-softening purposes (Wilde and Low, 1978).

Phosphorous

A thin bed of phosphatic nodules near the top of the Molecap Greensand was quarried at Molecap Hill, but the bed was too thin to be profitable (Wilde and Low, 1978).

Limesand and limestone

Limesand and limestone on the Swan Coastal Plain is used for road making, building material, and as a source of industrial and builder's lime. A significant resource of limestone also occurs at Point D'Entrecasteaux. Only those deposits with resources in MINEDEX are shown on Plate 1.

Spongolite

Opencut mining of spongolite from the Plantagenet Group commenced in 1997 at Woogenellup, 17 km northeast of Mount Barker. The spongolite has a potentially wide range of industrial and household applications including absorbent material to soak up oil, chemical, and acid spills; pet litter; potting mixes; odour absorbent, lightweight building materials; and fire-resistant building materials.

Construction materials — sandstone

The Cretaceous Donnybrook Sandstone has been quarried for building purposes since about 1900. This building stone is a fine- to medium-grained, feldspathic sandstone varying in colour from white through pale yellow and pink to red, depending on the iron oxide content (Townsend, 1994).

Quartzites in the Jimperding Complex have been mined for building and facing stone. The best quality facing stone has smooth partings devoid of crenulations. Green chrome mica is concentrated on some of the fissile planes. The main quarry is situated 9 km south-southwest of Toodyay (Wilde and Low, 1978).

Banded iron-formation

Iron — Fe

Lateritized BIF at Clackline in the Jimperding Complex was the source of the first iron-ore production in the State. Recorded production between 1899 and 1907 was 18 545 t, although larger quantities may have been mined (Wilde and Low, 1978).

Alluvial to beach placers

Speciality metal — heavy minerals, tin, tantalum, niobium

Heavy minerals

The Southwest is one of the world's largest heavy-mineral producers. To the end of 1996, production from the area was approximately 26 Mt of heavy-mineral concentrates and synthetic rutile. Measured and indicated resources of contained heavy minerals in the area at the end of 1992 were 67 Mt (Townsend, 1994).

Most of the heavy-mineral production from the Southwest has come from fossil and modern strandlines: the Capel, Waroona, Yoganup, Happy Valley, and Quindalup shorelines on the Swan Coastal Plain, and the Warren or Scott, Donnelly, Milyeaanup, and Quindalup shorelines on the Scott Coastal Plain. Descriptions of the deposits on these shorelines are given in Baxter (1977).

A typical heavy-mineral strandline deposit at Waroona is shown in Figure 9.

Another significant heavy-mineral deposit in the Southwest is the Beenup deposit. This is a large, low-grade deposit associated with estuarine and fluviatile sedimentary rocks in the Cretaceous Leederville Formation on the Scott Coastal Plain. The overlying Tertiary sedimentary rocks also contain heavy minerals (BHP–Utah Minerals International, 1995). The Beenup project, which commenced production in 1996, is expected to produce 600 000 t per annum of ilmenite and 20 000 t per annum of zircon.

Tin, tantalum, and niobium

Alluvial tin was discovered at Greenbushes in 1898. Cassiterite occurs in both Holocene alluvial deposits, and in sandstone and conglomerate of probable fluvial origin in the Greenbushes Formation. The Greenbushes Formation unconformably overlies the Archaean rocks of the Balingup Complex, and is overlain by laterite. The Greenbushes Formation has been correlated with the Nakina Formation, but no fossils have been found, and it could be any age between Early Cretaceous and Late Tertiary (Blockley, 1980). The tin in both the Holocene alluvial deposits and the Greenbushes Formation has been derived from the Greenbushes Pegmatite.

At Willow Springs, tin, tantalum, and niobium are present in conglomerates of the Greenbushes Formation. The source of the tin is uncertain, as no pegmatites have yet been discovered in the vicinity.

Cassiterite has been found in Holocene alluvium at Smithfield and Native Dog Gully where it is associated with small pegmatite intrusions.

Precious metal — gold, PGE

Small quantities of alluvial gold have been reported from Donnybrook, Waterfall Gully, North Dandalup, Marinup Brook, and Wellington Mill. On the basis of the gold morphology, Honman (1916) concluded that someone put the gold in the creek at North Dandalup.

Two samples of concentrates, said to be from a tributary of the Donnelly River at Nannup South, assayed 7790 and 9360 g/t Pt and 9711 and 1765 g/t Os + Ir respectively, but Simpson (1914) doubted that they came from the area.

Residual to eluvial placers

Precious metal — gold

The small gold workings at Grass Valley are on an eluvial deposit derived from an Archaean vein deposit.

Speciality metal — heavy minerals, tin, tantalum

Tin and tantalum

Some of the tin and tantalum production included in the Greenbushes Alluvial Group is probably eluvial in origin,

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Figure 9. Typical heavy-mineral strandline deposit at Waroona

but no records have been kept to distinguish alluvial from eluvial production.

Heavy minerals

A residual heavy-mineral deposit has been reported from Witchcliffe, but details are unavailable.

Industrial mineral — kyanite

Boulders of eluvial kyanite derived from schist of the Balingup Complex have been worked at Manjimup Brook, Donnelly River, and Ross Swamp.

Residual and supergene mineralization

Alumina — bauxite

The Darling Range area in the Southwest is the world's leading bauxite producer. The distribution of bauxite occurrences is shown on Figure 6. The four currently operating mines are Jarrahdale, Huntly (Del Park – Huntly), Willowdale, and Saddleback. All bauxite is mined by openpit methods. Following crushing, the ore is transported to the Kwinana, Pinjarra, Wagerup, and Worsley refineries respectively.

Since production began in 1963, and up to the end of 1996, 136.8 Mt of alumina has been produced from 440 Mt of bauxite. Gallium is also produced as a byproduct. Known reserves of bauxite are 1052 Mt, with additional resources of 1107 Mt in the measured and indicated categories, and 653 Mt in the inferred category (Table 1). The average grade of these resources is greater than 27.5% available Al_2O_3. Some of these resources are no longer available for mining because they lie within current conservation reserves or areas of urban development.

At Jarrahdale, most of the bauxite is developed on Archaean rocks, chiefly even-grained, porphyritic granite, with minor amounts on migmatite gneiss, dolerite, and gabbro. The bauxite deposits average 4 m in thickness and are best developed on hill slopes. Available alumina grades average 33% (Hickman et al., 1992).

The lateritic bauxite deposits at the Huntly (Del Park – Huntly) mine are developed on similar bedrock types to those at Jarrahdale. The bauxite deposits are up to 13 m in thickness, and average 4 to 5 m.

At Willowdale, most of the bauxite has developed over porphyritic granite, but in the western part of the area thick bauxite has developed over gneissic rocks of the Darling Scarp zone. In contrast, bauxite deposits at the Saddleback mine have formed on mafic volcanic rocks of the Saddleback greenstone belt. Average bauxite ore thickness is 6 to 7 m, and locally exceeds 20 m. Average Al_2O_3 is about 35% (Hickman et al., 1992).

In addition to the above mines, there are many large and potentially economic, unmined deposits in the Darling Range (Table 1), some of which are constrained by other landuses. Most of these were formed on granite bedrock, but others (e.g. Manjimup and Wannamal) have developed over metasedimentary rocks and gneisses in the metamorphic complexes.

Precious metal — gold, PGE

Gold

The Boddington mine in the Saddleback greenstone belt is the second largest gold producer in Australia. Lateritic gold mineralization has been mined by openpit methods at the Boddington mine by Worsley Alumina and the BGM group of companies since 1987, and at the adjacent Hedges mine by Hedges Gold since 1988. Combined production between 1987 and the end of 1995 for the Boddington and Hedges mines was 131.4 t Au from 73 Mt of ore. Total demonstrated resources of lateritic gold for Boddington at the end of 1995 were 182.9 Mt at 1.08 g/t, with additional inferred resources of 74.1 Mt at 1.0 g/t. Demonstrated resources for Hedges at the end of 1995 were 4.53 Mt at 1.25 g/t.

The Boddington–Hedges lateritic gold deposit has developed over, and proximal to, primary gold–copper mineralization in felsic volcanic rocks and felsic intrusions of the Saddleback greenstone belt. At Boddington, three subhorizontal mineralized zones separated by barren or weakly mineralized clay have been recognized. There is a continuous upper horizon (average thickness 5 m, to a maximum of 20 m) that occurs mainly in the ferruginous zone. Below this is a second discontinuous horizon of similar thickness that occurs in the clay zone. A third discontinuous zone, less than 5 m thick, occurs in saprolite at the base of the clay zone (Monti, 1987). At Boddington, gold is homogeneously distributed in the laterite but erratically distributed in saprolite (Symons et al., 1990).

PGE

There has been supergene enrichment in PGE at Yarawindah Brook (Cornelius, 1989) over primary mineralization in a layered ultramafic intrusion. There is an inferred resource of 2.9 Mt at 0.79 g/t (Pt + Pd) at a cutoff of 0.5 g/t or 0.505 Mt at 1.44 g/t (Pt + Pd). At present, the deposit is not economic.

Steel-industry metal — nickel, vanadium

Supergene concentration of nickel in ultramafic rocks has taken place at Yornup South and Palgarup, but the occurrences are not economic.

Lateritic vanadium ore overlies the primary vanadium ore at Coates. Reserves in the lateritic zone are estimated at between 1.5 and 1.2 Mt, averaging 0.88% V_2O_5 and 5.7% SiO_2 (Baxter, 1978).

Iron — Fe

Scott River iron, Brookton One, and Cheyne Iron are occurrences of lateritic iron ore. None are economic at the present time.

Table 1. Bauxite — past production, reserves, and resources for southwest Western Australia

Deposit	*Past production (Mt)*	*Resources (Mt)*		*Reserves (Mt)*
		Measured and indicated	*Inferred*	
Bombala		28		
Brigadoon–Bells		12	4.7	
Brookton Hwy – Bannister Group		145		
Cameron		16		
Churchman		11		
Clarke Hill		30		
Clinton		36		
Collie–Balingup general			1.3	
Del Park – Huntly	190			233
Dingo Knob		17		
Dwellingup–Waroona general			220	
Gidgeganup		2.9	2.5	
Hoffman		22		
Holmes		43		
Holyoake		41		
Howse		70		
Inglehope		51		
Jarrahdale (Alcoa)	130			140
Julimar West		5.5	1.7	
Kalamunda–Dale general			69	
Karnet		27		
Little Jimperding Hill – Bindoon		30	8.4	
Lower Chittering		32	1.4	
Manjimup Bauxite			26	
Mount Solus		32		
Mount Wells		16		
Mundaring–Wundowie general			63	
Mungalup		8		
Munnapin Brook – Julimar East		4.9	1.2	
Myarra		33		
Nanga		17		
O'Neil		13		
Pindalup		28		
Plavins		74		
Red Hill – South Bindoon		8.3	2.5	
Saddleback – Tunnel Road	56			
Saddleback Group				390
Smiths Mill Hill		13		
Spion Kop		38		
Taree		22		
Tower Hill Bauxite		21		
Wagerup–Harvey general			240	
Wannamal–Chittering general			6	
Waroona Bauxite		73		
Willowdale	39			289
Wundowie Bauxite		16		
Wundowie Northeast Bauxite		10	5.4	
Yarragil		60		
Total	**415**	**1106.6**	**653.1**	**1052**

Industrial mineral — clay, kaolin, magnesite, ochre

At Greenbushes, intense deep weathering during the Tertiary has resulted in kaolinization of the pegmatite and its host rocks to a depth of 60 m. Parts of the pallid zone overlying a spodumene-rich section of the pegmatite have been mined for high-grade halloysite and kaolin suitable for high-quality ceramics. A total of 38 400 t of kaolin had been produced up to the end of 1996, and there is a demonstrated resource of 2.3 Mt at 30.0% kaolin.

High-quality kaolin has also formed by deep weathering of granitoid rocks during the Tertiary. Deposits of this type include those in the Tambellup area, Hull, and Saddler.

Fireclays and brick-making clay has formed during lateritic weathering of granitoid rocks, shales of the Cardup Group, and schists of the Jimperding Complex. Only clay deposits with resources in MINEDEX are shown on Plate 1.

Scattered magnesite nodules overlie ultramafic rocks at York and Northam (Abeysinghe, 1996).

Good-quality red ochre has been produced from narrow veins in weathered gneiss near Kendenup. Commercial quantities of yellow ochre have been reported from Carbarup and Kendenup. Sienna ochre also occurs at Carbarup (Muhling and Brakel, 1985).

Mineralization controls and potential

Bauxite

The residual lateritic bauxite (Fig. 10) of the Darling Range is mainly underlain and derived from deeply weathered Precambrian granitic and gneissic rocks, and, to a lesser extent, basic rocks. Deeply weathered aluminous metasedimentary rocks also provide some potential for bauxite formation. Warm temperature, high rainfall, moderate relief, good drainage, and dense vegetation are important factors in bauxite formation (Hickman et al., 1992). Lower rainfall, subdued relief, and/or lack of dense vegetation outside the main bauxite areas have inhibited bauxite formation, and iron-rich laterite (ferricrete) predominates.

All areas mapped as ferricrete (laterite) can be considered to have potential for bauxite. Most areas of known bauxite mineralization are included in State Agreement Act leases held by Alcoa and Worsley Alumina. Urban development and conservation reserves have sterilized a significant proportion of the known occurrences. To the south of the State Agreement Act leases, in the Manjimup area, there are some occurrences of bauxite that are not covered by mining tenements.

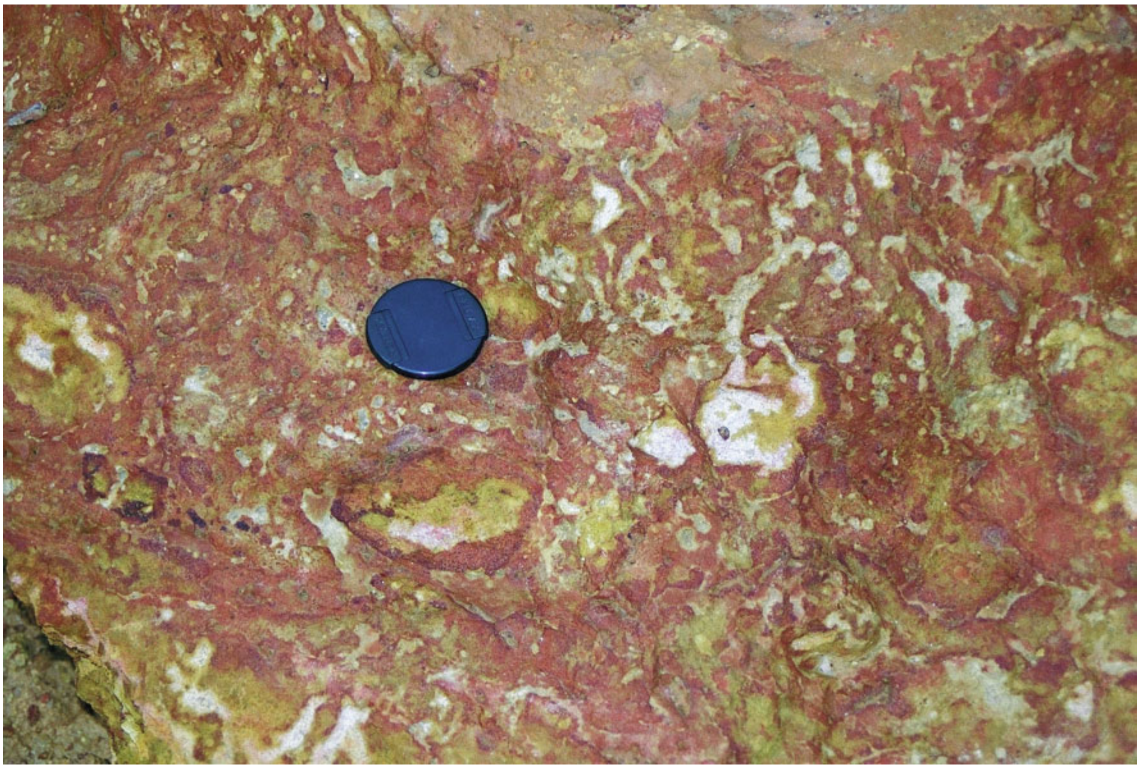

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Figure 10. Residual lateritic bauxite from Huntly mine

Gold

Gold mineralization at Boddington and Hedges is both in laterite–saprolite in the weathering profile, and in diorite and felsic volcanic rocks of the Saddleback greenstone belt. The primary gold mineralization at Boddington was interpreted by Roth et al. (1990) to be similar in origin to Phanerozoic porphyry copper deposits. However, Allibone et al. (1996) found that the mineralized quartz veins at Boddington post-date the youngest ductile deformation at 2675–2611 Ma, and concluded that the mineralization could not be of porphyry copper type and was analogous in timing to many other structurally late gold deposits in the Yilgarn Craton (e.g. Mount Magnet, Mount Charlotte, and Wiluna).

There is potential for further lateritic and primary gold mineralization in the Saddleback and Morangup greenstone belts. There is also potential for gold mineralization in as yet undiscovered slices of greenstone, potentially preserved along northwest-trending faults that cut the Yilgarn Craton. These faults are inferred to have been active since the Archaean (Myers, 1995). The Kendenup gold deposit is situated close to a northwest-trending fault that extends into the Albany–Fraser Orogen. Later movement on these northwest-trending faults during the Phanerozoic could also conceivably have resulted in the preservation of alluvial gold mineralization in the Permian basins.

There is a spatial association between the Wongamine, Blackboy Hill, and Bolgart gold occurrences, and the shear zone dividing the Boddington Terrane from the Lake Grace Terrane, suggesting that this tectonic zone has potential for gold mineralization.

Some small gold workings are associated with BIF in the Balingup, Jimperding, and Chittering Complexes whereas others are related to shear zones. The metamorphic complexes have potential for gold deposits of metasedimentary origin and for structurally controlled gold deposits.

Epithermal gold mineralization occurs in fault splays off the Darling Fault and in the Leeuwin Complex. These deposits are interpreted to be related to major rifting associated with the breakup of Gondwana. At Donnybrook, there is evidence that the mineralization in the Early Permian sedimentary rocks preceded the Bunbury Basalt indicating an age between Early Permian and Early Cretaceous. It is unusual to have epithermal deposits that are not related to igneous rocks; all the epithermal vein-deposit models described in Cox and Singer (1986) are related to calc-alkaline or bimodal volcanism. However, Pirajno and Surtees (1993) have also proposed a model in which epithermal gold deposits are related to rifting, with no associated igneous activity, in the Limpopo Region, South Africa.

There is potential for further rift-related epithermal gold deposits of Early Permian to Early Cretaceous age in the vicinity of the Darling Fault and to the west of the Dunsborough Fault in the Leeuwin Complex.

Coal

The Permian coal deposits in the Collie, Wilga, and Boyup Basins, and in the Sue Coal Measures within the Perth Basin, immediately post-date the glacial diamictite and outwash deposits that mark the end of the Gondwana continental glaciation. The coal-bearing fluvial deposits formed on lacustrine deltas developed over the exposed glacial sedimentary rocks (Le Blanc Smith, 1990). Thin peaty coal seams formed in lacustrine–fluviatile sedimentary rocks within the Cretaceous Leederville Formation in the Perth Basin. Peat deposits have also formed in Cainozoic swamp deposits at Cowerup Swamp near Lake Muir, at Lake Surprise, and at Melaleuca Park on the Swan Coastal Plain.

The Collie Basin is bounded by major northwest-trending faults together with other more localized faults. The Wilga and Boyup Basins are also remnants of a formerly more extensive Permian sequence preserved in fault-bounded grabens. Whilst it is unlikely that a basin the size of Collie would have remained undetected, it is possible that basins the size of the Wilga Basin remain to be found beneath cover in the vicinity of the northwest-trending faults.

Block faulting of the Vasse coal deposit during the Mesozoic resulted in the coal being buried to a depth of several kilometres, with a consequent maturation of the peat seams into bituminous coal. Subsequent uplift of the Vasse Shelf probably took place in the Lower Cretaceous, bringing the coal deposits close to the surface. On the basis of current technology, only the coal within 600 m of the surface could be exploited.

Heavy minerals

Heavy-mineral concentrations, including the Beenup deposit, formed in higher energy estuarine–fluviatile facies sedimentary rocks within the Leederville Formation. Other heavy-mineral deposits in the Southwest, including those in the Busselton to Bunbury area, have formed by concentration of heavy minerals on fossil or modern strandlines.

The Capel, Waroona, Yoganup, and Happy Valley shorelines in the Bunbury–Busselton area have been intensively explored, and it is likely that the resources in these areas are well defined. The northern part of the Waroona shoreline has potential for further discoveries, but unless town planning takes the prospective areas along the shoreline into account, much of the area is likely to be sterilized by urban development and environmental restrictions.

Geomorphological studies could lead to the discovery of further heavy-mineral deposits in fossil shorelines on the Scott Coastal Plain. There is significant potential for further deposits of the Beenup type in higher energy fluviatile and estuarine facies rocks of the Cretaceous Leederville Formation.

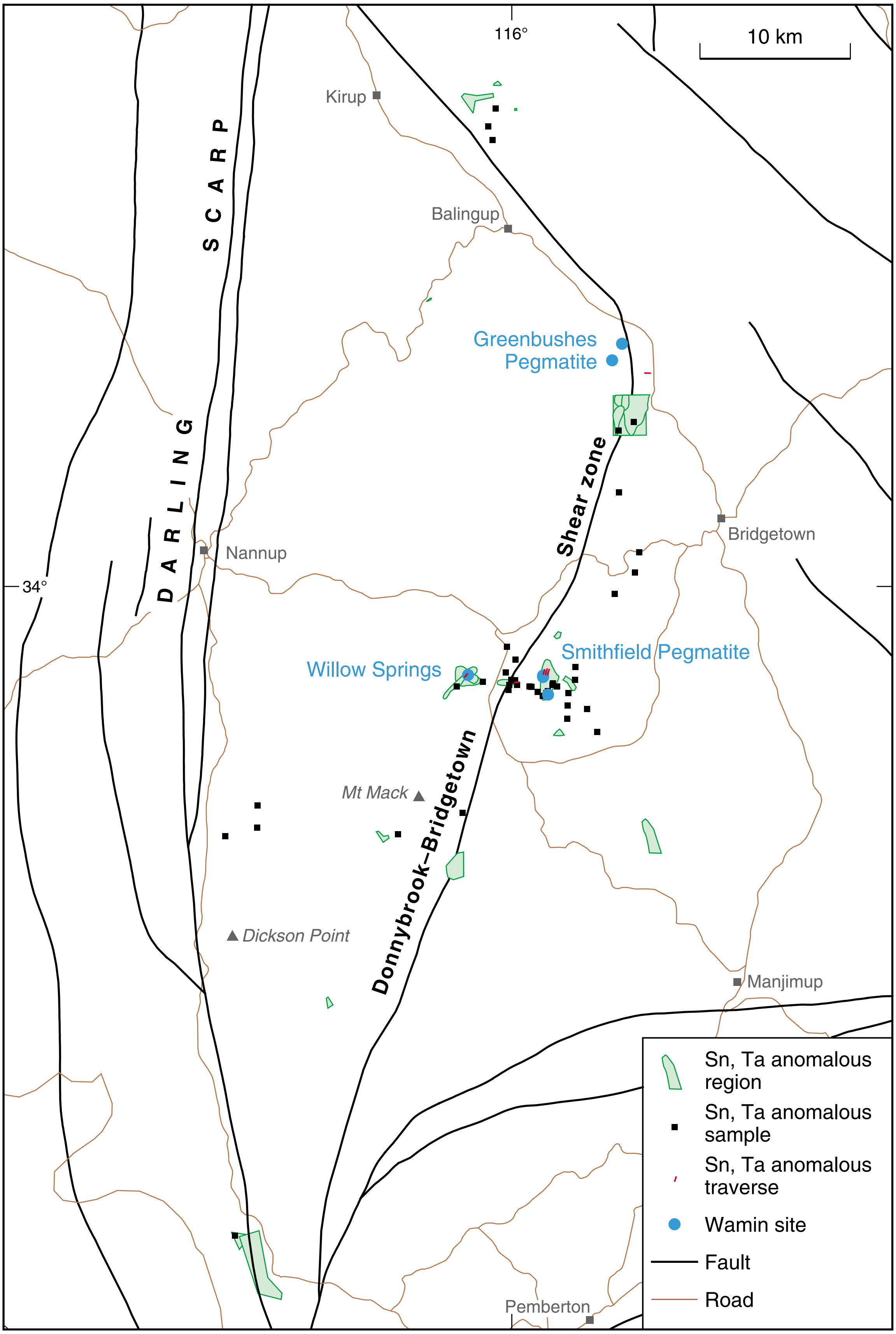

Figure 11. Mineral occurrences and anomalies in the vicinity of Donnybrook–Bridgetown Shear zone

Rare-metal pegmatites

The Greenbushes Pegmatite was intruded and crystallized synchronously with deformation along the Donnybrook–Bridgetown Shear zone under a high-temperature, medium-pressure metamorphic environment. Movements along the Donnybrook–Bridgetown Shear zone controlled not only the intrusion of the pegmatite but also its crystallization sequence and unusual reverse internal zonation (Bettenay et al., 1985; Partington, 1986; Partington et al., 1995). The Smithfield and Willow Springs tin occurrences, and numerous other tin, tantalum, and niobium anomalies, lie within a zone about 3 km wide on either side of the Donnybrook–Bridgetown Shear zone (Fig. 11), indicating that this zone is highly prospective for further occurrences of Greenbushes-type pegmatite deposits.

Vanadium, titanium, chromium, nickel, and PGE

The vanadium-bearing titaniferous magnetite in the Coates, Army Reserve, and Tallanalla vanadium deposits and the ilmenite in the Wannamal–Mogumber titanium deposit are magmatic in origin and an integral part of the mafic intrusive rocks in which they occur. The Coates deposit contains a significant resource of vanadium that could become economic in the future. Other mafic rocks in the area could also host vanadiferous magnetite.

A subeconomic deposit of PGE associated with an ultramafic complex is present at Yarawindah in the northern part of the Jimperding complex. Anomalous PGE values have been reported from the Yornup area suggesting that the ultramafic rocks in the Balingup Complex also have potential for PGE as indicated by Harrison (1986). Minor occurrences of nickel associated with layered mafic–ultramafic intrusions have been reported from both Yarrawindah in the Jimperding Complex, and Yornup and Palgarup in the Balingup Complex. Subeconomic chromium occurrences have also been recorded from the Yornup area. The nickel, copper, and PGE mineralization in the Yarawindah prospect is interpreted to be a primary component of the ultramafic–mafic intrusion that has been redistributed during regional metamorphism.

There is potential for the discovery of further PGE, nickel, and chromium occurrences in other ultramafic rocks in the area. The major east-northeasterly trending dolerite dykes also have potential to host nickel–PGE deposits similar to those in the Jimberlana dyke (Campbell, 1991).

Base metals

Small high-grade lead–silver deposits in the area (e.g. Mundijong) are epithermal in origin and probably related to rifting on the Darling Fault. There is potential for further epithermal base-metal deposits in the vicinity of the Darling and Dunsborough Faults.

Felsic volcanic rocks in the greenstone belts have the potential to host volcanogenic massive-sulfide (VMS) type deposits similar to Golden Grove (Frater, 1983), but no evidence has been reported of this type of deposit. There is potential for sedimentary-exhalative (sedex-type) deposits in the black shales of the Cardup Formation. Highly anomalous lead values have been recorded from carbonaceous shales in the Collie Basin. There is potential for lead deposits to have formed by concentration of this lead along faults.

Iron ore

The Southdown deposit in metamorphosed BIF of the Biranup Complex to the east of the area covered by Plate 1 contains 75.8 Mt at 27% Fe (Townsend, 1994) and indicates that the Biranup Complex has some potential for this type of iron ore.

Diamonds

No diamonds have been reported from the area. However, there are many deep-seated fractures in the area (including those that mark terrane boundaries), and the possibility that lamprophyres or kimberlites occur along these should not be discounted.

Silica sand

Sand is abundant in the Cainozoic sediments of the Perth Basin. Where this sand has been leached of impurities it has the potential to be suitable for glass making. Where the alumina content is about 2%, as at Kemerton, it also has the potential to be used in container glass. Proximity to urban development and environmental considerations are likely to sterilize many potential deposits.

Kaolin

High-grade kaolin is currently being mined from the weathered Greenbushes Pegmatite (halloysite and kaolin), and from lacustrine sedimentary rocks at Goomalling. High-grade kaolin has also been found in the lateritic weathering profile in the Tambellup area. There is potential for substantial deposits of high-grade kaolin formed by lateritic weathering of granitic rocks.

Other industrial minerals

Other industrial mineral deposits in the Southwest formed by sedimentary processes include: gypsum dunes near salt lakes (e.g. Pootenup), diatomaceous earth (e.g. Lake Gnangara and Yeal Swamp), glauconite and phosphate (e.g. Molecap Hill), limesand and limestone, and spongolite (e.g. Woogenellup).

Graphite, kyanite, and sillimanite deposits have both stratigraphic and metamorphic controls; graphite forms from carbonaceous shales, and both kyanite and sillimanite form from aluminous sedimentary rocks of the metamorphic complexes during metamorphism.

Many of the talc deposits in the area (e.g. Glen Lynn, Bolgart, and Meaneys Bridge) formed by metamorphism of ultramafic rocks.

Epithermal vein deposits of barite are associated with rifting on the Darling Fault and with faults in the Stirling Range Formation.

Weathering processes have led to the formation of magnesite from ultramafic rocks at York and Northam and the formation of ochre in veins in weathered gneiss at Kendenup and Carbarup.

Acknowledgements

Geologists from the BRS (Yanis Miezitis, Subhash Jaireth, Aden McKay, and Stuart Girvan) and panel members for the RFA assessment contributed ideas to the RFA mineral assessment project, of which this study forms an extension. Special thanks are due to Ian Chalmers of Multi Metal Consultants for sharing his ideas on epithermal mineralization, and for providing access to the Donnybrook drillcore.

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Appendix 1

Mineral occurrence definitions

The Geological Survey of Western Australia's (GSWA's) Western Australian Mineral Occurrence database (WAMIN) contains geoscience attribute information on mineral occurrences in Western Australia. The database includes textual and numeric information on the location of occurrences, accuracy of the locations, commodities, mineralization classification, the resource tonnage, estimated grade, mineralogy of ore, gangue mineralogy, details of host rocks, and both published and unpublished references.

The WAMIN database uses a number of authority tables to constrain the essential elements of a mineral occurrence, including the operating status, commodity group, and style of mineralization. In addition, there are parameters that dictate whether the presence of a mineral or analysed element is sufficiently high to rank occurrence status; this Report only deals with mineral occurrences. Other attributes were extracted from reports provided by mineral exploration companies or from authoritative references.

Those elements of the database that were used to create the mineral occurrences symbols and tabular information displayed in Plate 1 are:

- operating status and occurrence name (occurrence number style);
- position and spatial accuracy (symbol position);
- commodity group (symbol colour);
- mineralization style (symbol shape);
- determination limits;
- source and reliability of the data.

The elements of the database used for the symbols in Plate 1 are operating status, commodity group, and mineralization style. These parameters have been defined for the mineral prospectivity enhancement studies that have been completed for southwestern Western Australia, the north Eastern Goldfields, and the Bangemall Basin. The definitions presented here will be used in future prospectivity studies.

Operating status

The database includes mineralization sites ranging from small but mineralogically significant mineral occurrences to operating mines. The classification takes into account all deposits and mines with established resources in the Department of Minerals and Energy (DME) mine and mineral deposits information database (MINEDEX; Townsend et al., 1996). All occurrences in the WAMIN database are assigned a unique, system-generated number. The style of this number (bold, italicized, and so on) is used as the coding to indicate operating status, both on Plate 1 and in the accompanying table. The system used is:

- mineral occurrence — any economic mineral exceeding an agreed concentration and size found in bedrock or regolith (italic, serif numbers, e.g. *5*);
- prospect — any working or exploration activity that has found subeconomic mineral occurrences, and from which there is no recorded production (italic, serif numbers, e.g. *3175*);
- mineral deposit — economic mineral for which there is an established resource figure (serif numbers, e.g. 33);
- 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 (bold, italic, sans serif numbers, e.g. ***181***);
- operating mine — workings that are operating, including on a care-and-maintenance basis, or that are in development leading to production (bold, sans serif numbers, e.g. **37**).

The name of an occurrence and any synonyms that may have been used are derived from the published literature and from company reports. As some occurrences will not have been named in the past, these appear without names in the WAMIN database — no attempt has been made to provide names where none is currently recognized. The name that appears in the MINEDEX database (Appendix 2) is used where possible, although there may be differences because MINEDEX reports on production and resources whereas WAMIN notes individual occurrences.

Commodity group

The WAMIN database includes a broad grouping based on potential or typical end-use of the principal commodities comprising a mineral occurrence. The commodity group as given in Table 1.1 determines the colours of the mineral occurrence symbols in Plate 1.

The commodity groupings are based on those published by the Mining Journal Ltd (1997), and are modified as shown in Table 1.2 to suit the range of minerals and end-uses for Western Australian mineral output.

Table 1.1. WAMIN authority table for commodity groups

Commodity group	*Typical commodities*	*Symbol colour*
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	
Iron	Fe	
Aluminium	Al (bauxite)	
Energy mineral	Coal, U	
Industrial mineral	Asbestos, barite, kaolin, talc	
Construction material	Clay, dimension stone, limestone	

Mineralization style

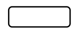
There are a number of detailed schemes for dividing mineral occurrences into groups representing the style of mineralization. The most widely used scheme is probably that of Cox and Singer (1986). The application of this scheme in Western Australia would necessitate modifications to an already complex scheme, along the lines of those adopted by the Geological Survey of British Columbia (Lefebure and Ray, 1995; Lefebure and Hoy, 1996). Representing the style of mineralization on a map cannot be simply and effectively achieved if the scheme adopted is too complex.

GSWA has adopted the principles of ore-deposit classification from Evans (1987). This scheme works on

Table 1.2. Modifications made to the Mining Journal Ltd (1997) commodity classification

Commodity group (Mining Journal Ltd, 1997)	*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
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

Table 1.3. WAMIN authority table for mineralization styles and groups

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

NOTE: (a) The white symbol colour used in this table does not indicate the commodity group in Table 1.1

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 here is based on an environment – rock association classification, with elements of genesis and morphology where they serve to make the system simpler and easier to apply and understand (Table 1.3).

To fully symbolize all the mineralization-style groups would result in a system that is too complex. As the full details of the classification are preserved in the underlying WAMIN database, the chosen symbology has been reduced to nine shapes.

Mineral occurrence determination limits

The lower cutoff limit for a mineral occurrence is more reliably based on WAMEX exploration company information. Minimum intersections in drillholes or trenches for a number of commodities are in Table 1.4.

Professional judgement is used if shorter intercepts at higher grade (or vice versa) are involved. Any diamonds or gemstones are classified as mineral occurrences, including diamondiferous kimberlites.

Table 1.4. Minimum intersections for mineral occurrences in drill-holes 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
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

References

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Appendix 2

Description of digital datasets

The following datasets have been used in compiling this Report, Plate 1, and the accompanying CD-ROM.

Geology

Precambrian geology, Permian geology, Cretaceous to lower Tertiary geology, and regolith geology maps have been compiled in digital format and are supplied as separate layers or themes. Linear features such as faults, lineaments, fold hinges, and dolerite dykes are also supplied as separate themes. The full details of each layer are given on the CD-ROM.

Mineral occurrences (WAMIN)

The mineral occurrence dataset as used in this Report and on Plate 1 is described in Appendix 1. The dataset on the CD-ROM includes textual and numeric information on:

- location of the occurrences (AMG coordinates, 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;
- published and unpublished references.

WAMEX

All relevant open-file company mineral exploration reports held in the DME WAMEX database and library were referred to for this study. Information extracted from these reports was used in the activity and anomaly layers of SPINDEX (spatial index to exploration database) and in the WAMIN database.

MINEDEX

The MINEDEX database has current information on all mines, process plants, and deposits, excluding petroleum and gas, in Western Australia. Mineral resources included in MINEDEX must conform to the JORC (1996) 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, which do not conform to the JORC (1996) code, and are not included in MINEDEX.

TENGRAPH

The TENGRAPH database (DME's electronic tenement-graphics system) shows the position of mining tenements relative to other land information. It provides information on the type and status of the tenement and the name(s) and address(es) of the tenement holders. Only parts of the Southwest are currently covered by TENGRAPH. In the areas not covered by TENGRAPH, tenements that were current or applied for at the end of 1997 are shown as a separate theme. 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.

SPINDEX

A GIS-based spatial activity index (SPINDEX) to historical open-file mineral exploration in the study area has been assembled (Ferguson, 1995). The index contains spatial and textual information defining the location of exploration activity in the area. SPINDEX, for the Southwest, 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 hard-copy maps of various scales, from company reports, located from coordinate and/or geographical information, transferred on to 1:50 000-scale maps, and then digitized. Table 2.1 lists the activity types.

Table 2.1. Exploration activity types

Activity	*Description*
ACH	Airborne geochemistry
AEM	Airborne electromagnetic surveys
AGRA	Airborne gravity surveys
AMAG	Airborne magnetic surveys
ARAD	Airborne radiometric surveys
DIAM	Diamond drilling
EM	Electromagnetic surveys (includes TEM, SIROTEM)
GEOL	Geological mapping
GEOP	Other geophysical surveys (includes IP, resistivity)
GRAV	Gravity surveys
HYDR	Groundwater surveys
LSAT	Landsat TM data
MAG	Magnetic surveys
NGRD	Non-gridded geochemical surveys (includes chip, channel, dump, and gossan)
RAB	RAB drilling (includes other shallow geochemical drilling, such as auger)
RAD	Radiometric surveys (includes downhole logging)
RC	RC drilling
REGO	Regolith surveys (includes laterite, pisolite, and iron-stone)
RES	Resistivity
ROT	Rotary drilling (predominantly percussion drilling)
SEIS	Seismic surveys
SOIL	Soil surveys
SSED	Stream-sediment surveys

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

Geochemical and mineral anomalies

Anomalies are a subset of the mineral occurrence database and have been derived solely from WAMEX reports included in the SPINDEX database. They are included in the digital data but are not shown on Plate 1. The anomaly layer contains information for polygons, lines, and points defining the location of anomalies identified during mineral exploration activity. Textual and numeric information on the type of anomaly, and anomalous elements and their abundance, are contained in the index, together with the unique reference code to the report in WAMEX. This index is related to SPINDEX by use of a common field called ACTIVITYID.

Anomaly thresholds for elements were selected from company data where large regional surveys of the area gave statistically derived thresholds for soils, stream, laterite, and hard rock. These thresholds were used for other reports where no statistical analyses were carried out. For drill intersections and channel samples, a value equal to one tenth of the value used to define a mineral occurrence was used as a lower cutoff. Special cases are listed below.

Bauxite

All bauxite information has been collated using company reports and Hickman et al. (1992). The only bauxite anomalies delineated in the Mineral Exploration Anomaly Index are those outside of the State Agreement Act tenements. Anomalies were defined on the basis of greater than 20% available alumina.

Heavy minerals

As the occurrence of heavy minerals is widespread throughout the Southwest, a strict cutoff was applied in the selection of anomalies. If the anomalies were areally extensive they were included as WAMIN sites. Anomalies were selected on the basis of greater than 5 m averaging greater than 2% heavy mineral (HM). Anomalies were not selected in areas with defined resources or where they coincided with a mineral occurrence (WAMIN) site. Ilmenite anomalies (>2% ilmenite) in situ were ranked much higher than greater than 2% HM anomalies where the valuable heavy-mineral (VHM) content has not been determined and may be low.

Coal

Any coal or peat layers intersected in drillholes were selected as anomalies.

Industrial minerals

All industrial minerals, such as asbestos or talc, were entered as mineral occurrences if the occurrences were considered significant.

No anomalies were entered from MINEDEX or WAMIN sites if the anomalous site was within the deposit outline or the lower grade mineralized halo that surrounded the deposit. Possible extensions to mineralization outside the halo have been entered as anomalies.

Geophysics

The aeromagnetic data covering the area are presented on the CD-ROM in the form of a colour total magnetic intensity (TMI) image. The data used to create the image were flown by AGSO on multiple surveys dating from 1957 at a line spacing of 1500 to 3200 m. The quality of this data varies according to its age and line spacing. The data has been gridded to a cell size of 800 m.

Measurements of the background radiation using an airborne crystal usually took place concurrently with the AGSO aeromagnetic surveys over the area, but only COLLIE, PEMBERTON, and MOUNT BARKER have been covered. 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. The data has been gridded to a cell size of 800 m.

A regional gravity survey by AGSO, at a station spacing of up to 11 km, is presented in the digital dataset as an image showing the Bouguer anomaly. The data has been gridded to a cell size of 5 km.

Landsat

Landsat TM imagery has been acquired for all the 1:250 000 map sheets covered by the Southwest (Plate 1). The raw data are available commercially through the Remote Sensing Services section of the Department of Land Administration. 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 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.

Roads and culture

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

Place names for the area are given in a separate file, and include towns and major hills. More comprehensive topographical and cultural data, including drainage, can be obtained from the Australian Land Information Group (AUSLIG). GSWA is currently completing an initiative that will see the area covered by a fully revised dataset of topography, drainage, and cultural features based on high-resolution satellite imagery.

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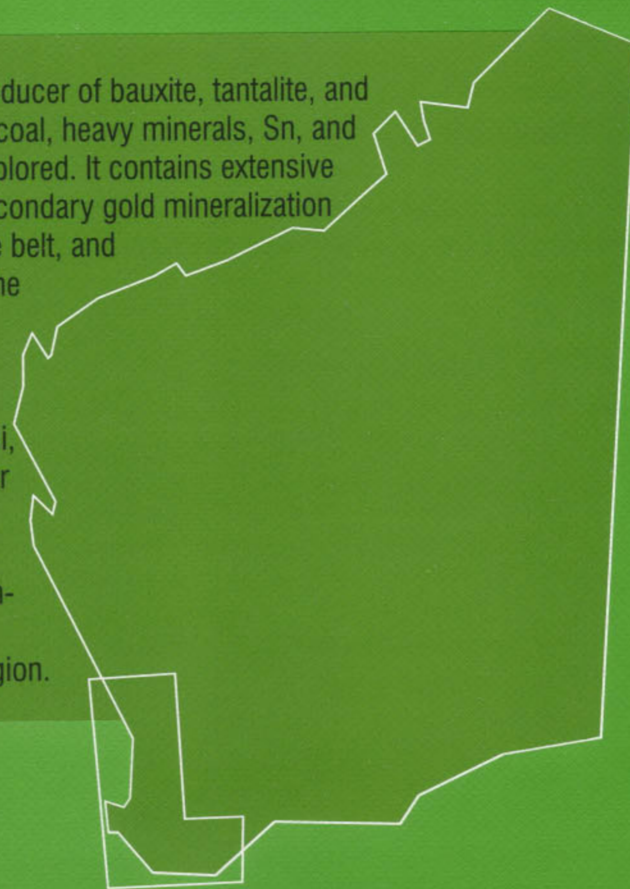


Southwest Western Australia is the world's largest producer of bauxite, tantalite, and spodumene, and is also a significant producer of Au, coal, heavy minerals, Sn, and silica sand. Despite this, the area is relatively underexplored. It contains extensive bauxite deposits in the Darling Range, primary and secondary gold mineralization at Boddington in the Archaean Saddleback greenstone belt, and several epithermal Au and base-metal deposits near the Darling and Dunsborough Faults. Potential exists for more discoveries of Au and base-metals, Sn–Ta–Li pegmatite (Greenbushes-style), coal, and heavy-mineral sands.The area is also prospective for PGE, Ni, Cr, V, iron ore, diamonds, silica sand, kaolin, and other industrial minerals. This Report includes a 1:500 000 map, summarizes the geology and mineralization of southwest Western Australia, and serves as an explanatory note to a major new digital dataset of mineral exploration activity and mineral occurrences in the region.

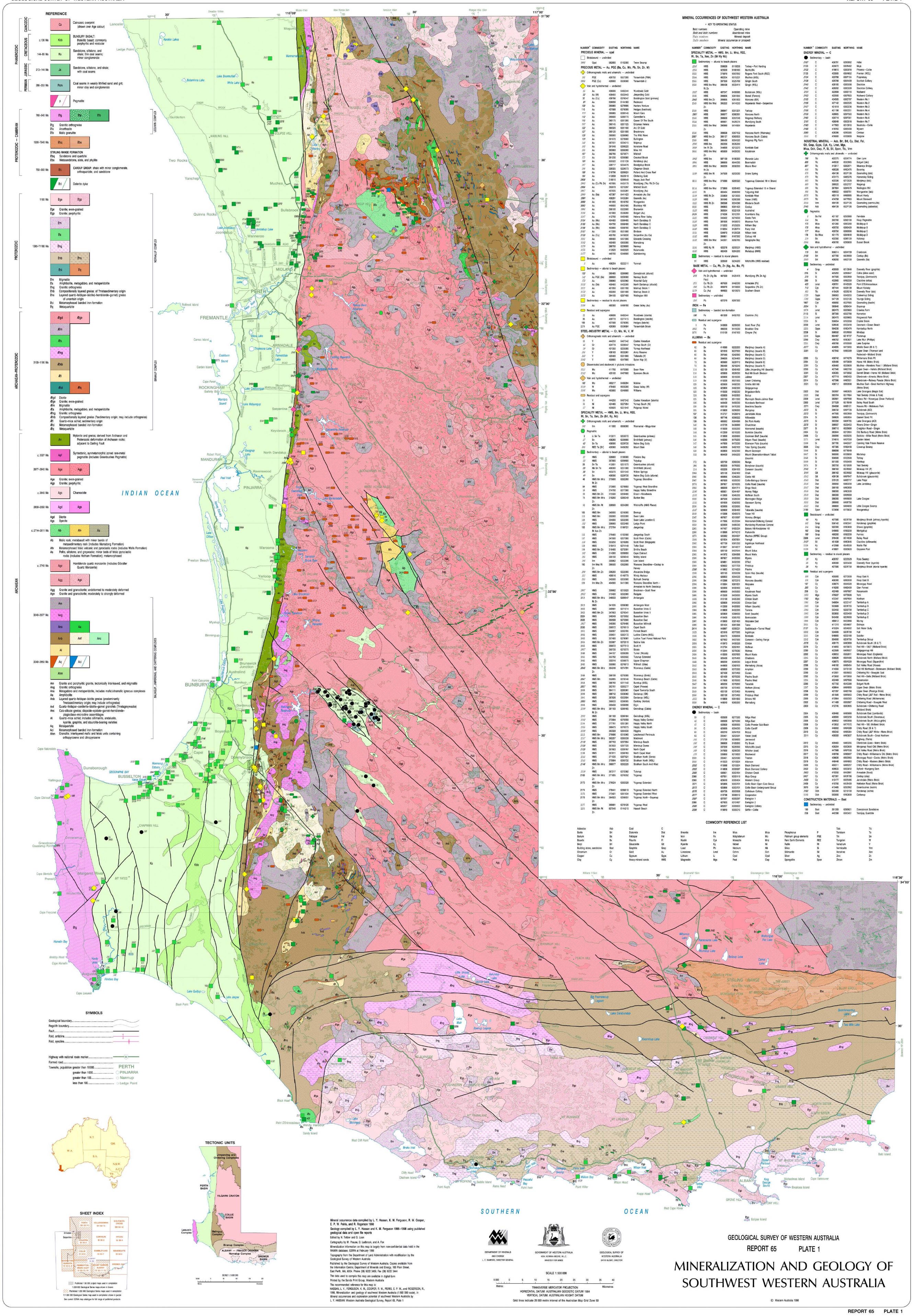
Further details of geological publications and maps produced by the Geological Survey of Western Australia can be obtained by contacting:

Information Centre
Department of Minerals and Energy
100 Plain Street
East Perth WA 6004

Phone: (08) 9222 3459   Fax: (08) 9222 3444

HASSAN   Mineral occurrences and exploration potential of southwest Western Australia   GSWA REPORT 65

SW MIN PROSP



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
REPORT 65 PLATE 1

MINERALIZATION AND GEOLOGY OF SOUTHWEST WESTERN AUSTRALIA