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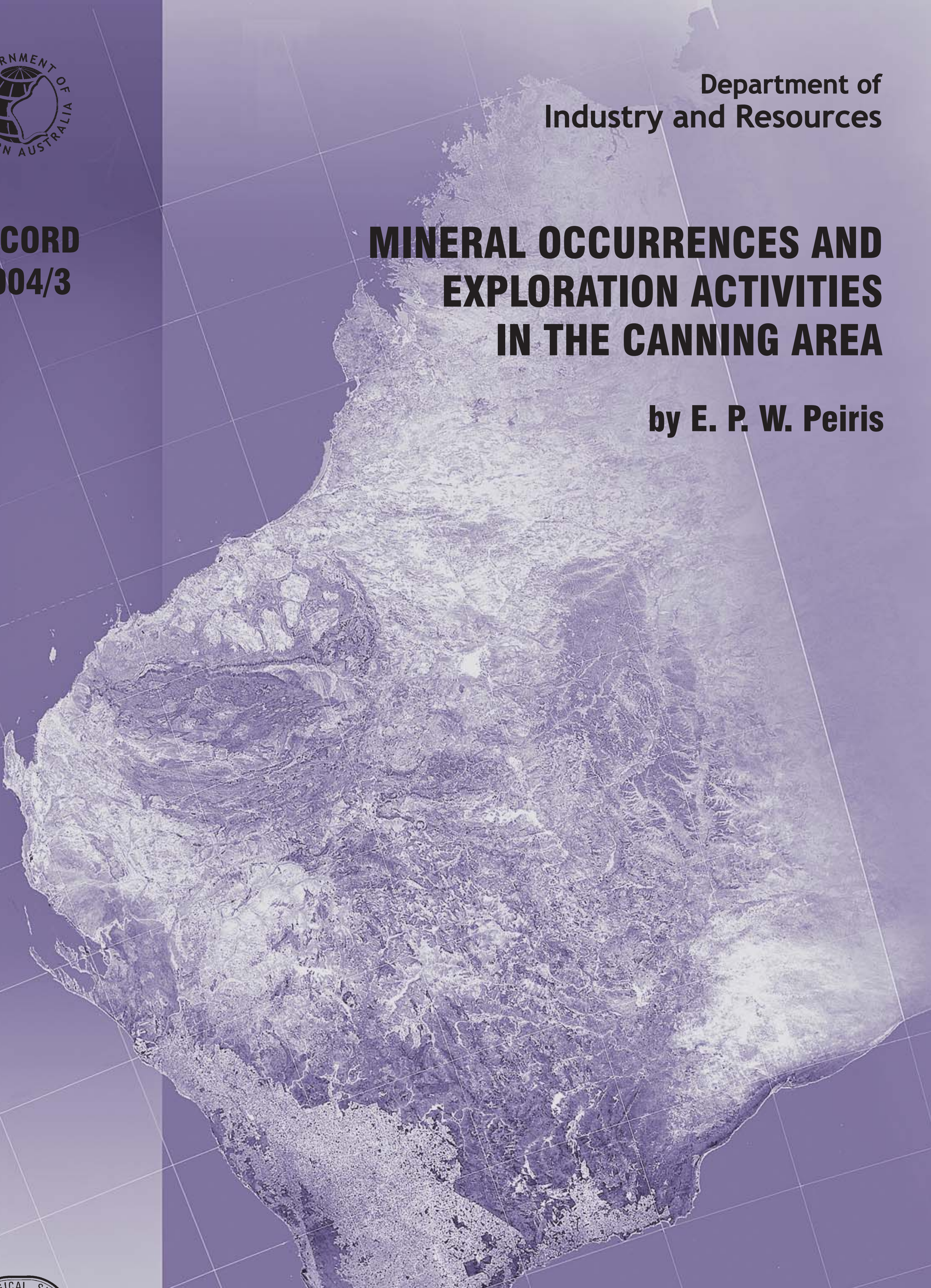
2004/3

MINERAL OCCURRENCES AND EXPLORATION ACTIVITIES IN THE CANNING AREA

by E. P. W. Peiris



Geological Survey of Western Australia

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

RECORD 2004/3

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Perth 2004

REFERENCE
The recommended reference for this publication is:
PEIRIS, E. P. W., 2004, Mineral occurrences and exploration activities in the Canning area: Western Australia Geological Survey, Record 2004/3, 37p.

National Library of Australia Card Number and ISBN 0 7307 8950 0

Grid references in this publication refer to the Geocentric Datum of Australia 1994 (GDA94). Locations mentioned in the text are referenced using Map Grid Australia (MGA) coordinates, Zone 51. All locations are quoted to at least the nearest 100 m.

Cover image modified from Landsat data, courtesy of ACRES

Published 2004 by Geological Survey of Western Australia
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Contents

Appendices

Figures

Table

Mineral occurrences and exploration activities in the Canning area

by

E. P. W. Peiris

Abstract

The Canning area in the north of Western Australia includes parts of the following tectonic units: the Phanerozoic Canning and Gunbarrel Basins, and the dominantly Neoproterozoic Officer and Amadeus Basins.

Mineral occurrences within the area not related to hydrocarbons include stratabound sedimentary Mississippi Valley-type lead–zinc–silver; sedimentary halite, anhydrite, potash, gypsum, coal, phosphate, limestone, and alunite; vein gold; and heavy mineral sands and construction material in the regolith. There has been no mineral production from the area except for the extraction of limestone and construction material in the vicinity of Broome.

The most significant mineralization is along the Admiral Bay Fault Zone where extensive base metal exploration from 1986 to 1991 located Mississippi Valley-type deposits of zinc–lead–silver, with inferred resources of 140 Mt at 5.63% Zn, 4.39% Pb, and 35.6 g/t Ag, occurring in Ordovician rocks between 1200 and 1600 m below surface. Similar mineralization occurs along the Abutilon Fault on the Barbwire Terrace, in a zone of extensive dolomitization, but exploration to date has not located any significant deposits. A large halite deposit, the Upper Ordovician Mallowa Salt, occurs mainly on the Broome Platform, in the Kidson Sub-basin, and in the Willara Sub-basin. The halite also contains significant potash mineralization. Halite is also present in the core of the Woolnough Hills Diapir in the Neoproterozoic Officer Basin. Gold–copper was located in 1998 at the Magnum prospect in basement dolerite below the Anketell Shelf. Further exploration is continuing for Telfer-style gold–copper mineralization in sedimentary sequences elsewhere in the Anketell project area.

Other mineral commodities in the area are coal, mainly in the Middle Jurassic Wallal Sandstone, alunite within the Cretaceous Bejah Claystone, phosphate within the Jurassic Jarlemai Siltstone, limestone in the Cainozoic Bossut Formation near Broome, chalcedony in the Cainozoic Lawford Formation along the Fenton Fault, heavy mineral sands in beach placers along the coast, and gypsum in playas of inland lake systems.

There may be nickel, chromium, and platinum group element potential in postulated layered mafic intrusions that may form basement rocks beneath the Warri Arch.

KEYWORDS: Mineral occurrences, exploration activities, Canning Basin, Officer Basin, Gunbarrel Basin, Admiral Bay Fault Zone, Barbwire Terrace, regolith, base metals, gold, halite, potash, coal, heavy mineral sands, phosphate, limestone, alunite, chalcedony, construction material.

Introduction

Present study

This Record presents an up-to-date review of the mineral occurrences and mineral exploration activities in the remote Canning area of Western Australia. The Canning area has the central Canning Basin (Phanerozoic) as its core, and extends south to the adjoining Gunbarrel Basin (Phanerozoic) and underlying Officer and Amadeus Basins (Neoproterozoic–Cambrian). The study collates information held in various databases maintained by the Geological Survey of Western Australia (GSWA) and Department of Industry and Resources (DoIR) covering mineral exploration activity, mineral occurrences, and mineral resources, and reviews the geology of the area.

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

- open-file statutory mineral exploration reports held in the Western Australian mineral exploration (WAMEX) database at the Department of Industry and Resources (DoIR);
- the database of Western Australia's mines and mineral deposits information (MINEDEX) held at DoIR;

- books, journals, industry publications, and datasets, Australian Stock Exchange reports and announcements, and company web sites; and
- regional geological and airborne geophysical surveys, and remote-sensing datasets.

This mineral prospectivity study of the Canning area has two main parts: this Record and a digital dataset on CD-ROM. The Record reviews the regional geology of the area, the main mineral occurrences, and exploration activities. The list of mineral occurrences is provided in Appendix 1.

Appendix 2 defines the terms used in the Western Australian mineral occurrences database (WAMIN) and the mineral exploration activity spatial index database (EXACT) maintained by GSWA. Where mineral occurrences are referred to in the Record they are also identified by the WAMIN 'deposit name' and the WAMIN 'deposit number' shown thus: Woolnough Hills Diapir (10630). Appendix 3 gives a brief description of the digital datasets included on the CD-ROM.

The accompanying CD-ROM includes all the data used to compile the Record and also includes files of geophysical, remote-sensing, topographic, and mining tenement location data. The CD-ROM contains the files necessary for viewing the data in the ArcView GIS environment plus a self-loading version of the ArcExplorer software package modified to suit this particular dataset. Metadata statements on the geological, geophysical, and topographic datasets are also provided.

Location, physiography, climate, and access

The Canning area spans fifteen 1:250 000-scale geological map sheets: MANDORA*, PENDER, BROOME, LAGRANGE, MUNRO, ANKETELL, MCLARTY HILLS, JOANNA SPRING, SAHARA, CROSSLAND, DUMMER, PERCIVAL, URAL, MORRIS, and WARRI (Fig. 1). The main population centre is Broome (population about 16 000, including a large tourist fraction).

Four main physiographic units have been recognized within the project area (Purcell, 1984a): the Fitzroy Valley, Canning Plain or Desert Plateau, Dampier Peninsula and coastal plain, and Percival Valley. The Rudall Highlands bound the Canning Plain to the south of the project area (Fig. 2).

The Fitzroy Valley is an area of low relief and occupies a small part of the project area along the northeastern edge of the Canning Plain of the Great Sandy Desert (Guppy et al., 1958). The major part of the project area lies within the Canning Plain of the Great Sandy Desert (the Desert Plateau of Guppy et al., 1958) and consists mainly of sand dunes. It also includes areas of dissected plains, isolated mesas, and erosional remnants. The Dampier Peninsula in the north represents a restricted area of the Canning Plain between the Indian Ocean and King Sound (Guppy et al., 1958). The coastal plain extends along the northwestern coast and is typically 16 km wide, except in the southwest where it is 60 km wide (Purcell, 1984a). The coastal plain comprises coastal dunes and samphire marshes; Mezosoic rocks form isolated cliffs along the coastline and form scattered mesas towards the interior. The Percival Valley is a relic of a Lower Cainozoic drainage system (van de Graaff et al., 1977) and is marked by a chain of salt lakes (Purcell, 1984a). Further to the south of the area, extensive parts of WARRI are covered by well-developed duricrust (Jackson and van de Graaff, 1981). The Rudall Highlands are located at the southern tip of Percival Valley and mark the edge of the Canning Plain.

The climate of the Canning area is monsoonal in the north to arid in the south. At Broome, the median annual rainfall is 532 mm spread over an average of 44 days, and most of the rainfall occurs between December and March. Temperatures at Broome range between 12° and 33°C with January as the hottest month and July as the coolest†. Away from the coast, summer temperatures are considerably higher.

The northern part of the area is accessible via the Great Northern Highway, which runs parallel to the coastline. Additional vehicular access to the interior is provided by scattered station and community tracks, seismic and drilling access tracks that were constructed during petroleum exploration programs, and the Canning Stock Route. Air services operate between Perth and Broome, and shipping services are available through the Broome port.

Previous work

Towner and Gibson (1983) and Purcell (1984a) provide extensive summaries of the history of settlement and geological investigation of the Canning Basin, including petroleum and mineral exploration.

Colonel P. E. Warburton made an inland crossing in 1875 from Alice Springs to the Oakover River, via the Musgrave Ranges and Joanna Spring, and named the Great Sandy Desert. H. W. B. Talbot made the first geological record of the area in 1910 along the Canning Stock Route (Talbot, 1910). Ernest Kidson recorded magnetic observations in 1914 along the same route (Kidson, 1921). L. J. Jones travelled along the Canning Stock Route in 1922 to investigate the petroleum potential of the area (Jones, 1922). Clapp (1926a,b) traversed from Broome to McLarty Hills in 1925, made geological observations, and collected fossils.

Aerial geological reconnaissance was carried out in 1940 and 1942 along the southern margin of the Canning Basin on ANKETELL (Bremner, 1940, 1942). In 1949 F. Reeves conducted an exploration program for the Vacuum Oil Company and located some Permian fossils at Lake Blanche and Well No. 26 on the Canning Stock Route (Reeves, 1949; Guppy and Lindner, 1949). The Bureau of Mineral Resources (BMR) conducted

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

† Climate data is from the Bureau of Meteorology website <http://www.bom.gov.au>.

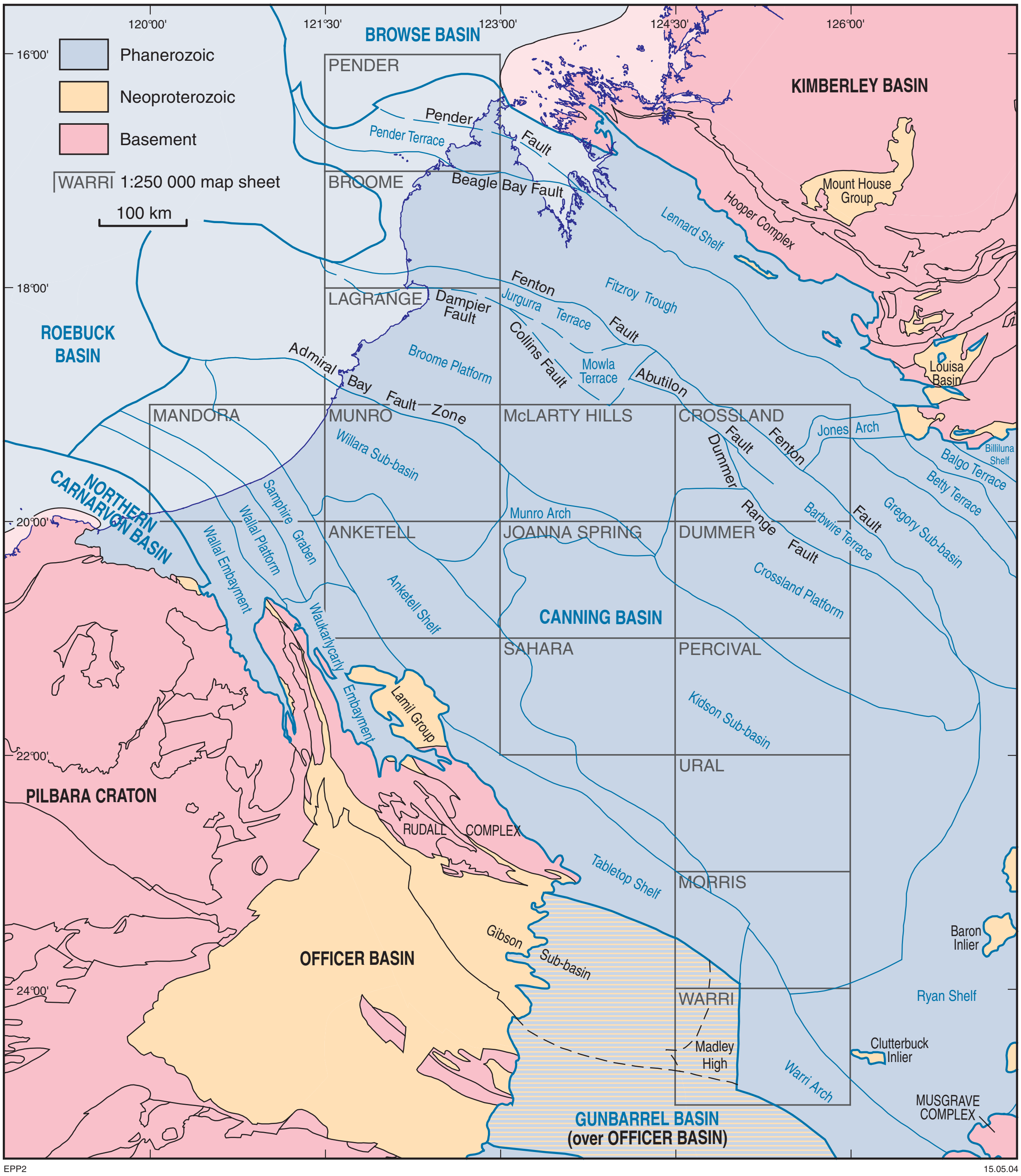


Figure 1. Location of the Canning area in the context of basin framework and published 1:250 000 geological map sheets

reconnaissance work (Guppy and Lindner, 1949) prior to systematic mapping that began in 1953 and led to reports by Traves et al. (1956), Veevers (1957), Guppy et al. (1958), Veevers and Wells (1961), and Casey and Wells (1964). The BMR also undertook gravity and airborne magnetic surveys at this time (Flavelle and Goodspeed, 1962; Darby and Fraser, 1969; Flavelle, 1974; Fraser, 1976). West Australian Petroleum Pty Ltd (WAPET) undertook an extensive field and drilling program in parallel with BMR work that continued into the early 1970s (Towner and Gibson, 1983; Purcell, 1984a). The stratigraphic overview by McWhae et al. (1958) arose largely from the WAPET and BMR work.

GSWA began a study of the Devonian reef complexes along the northern margin of the Canning Basin in the early 1960s, with an initial bulletin by Playford and Lowry (1966) and continuing papers since then (summarized in

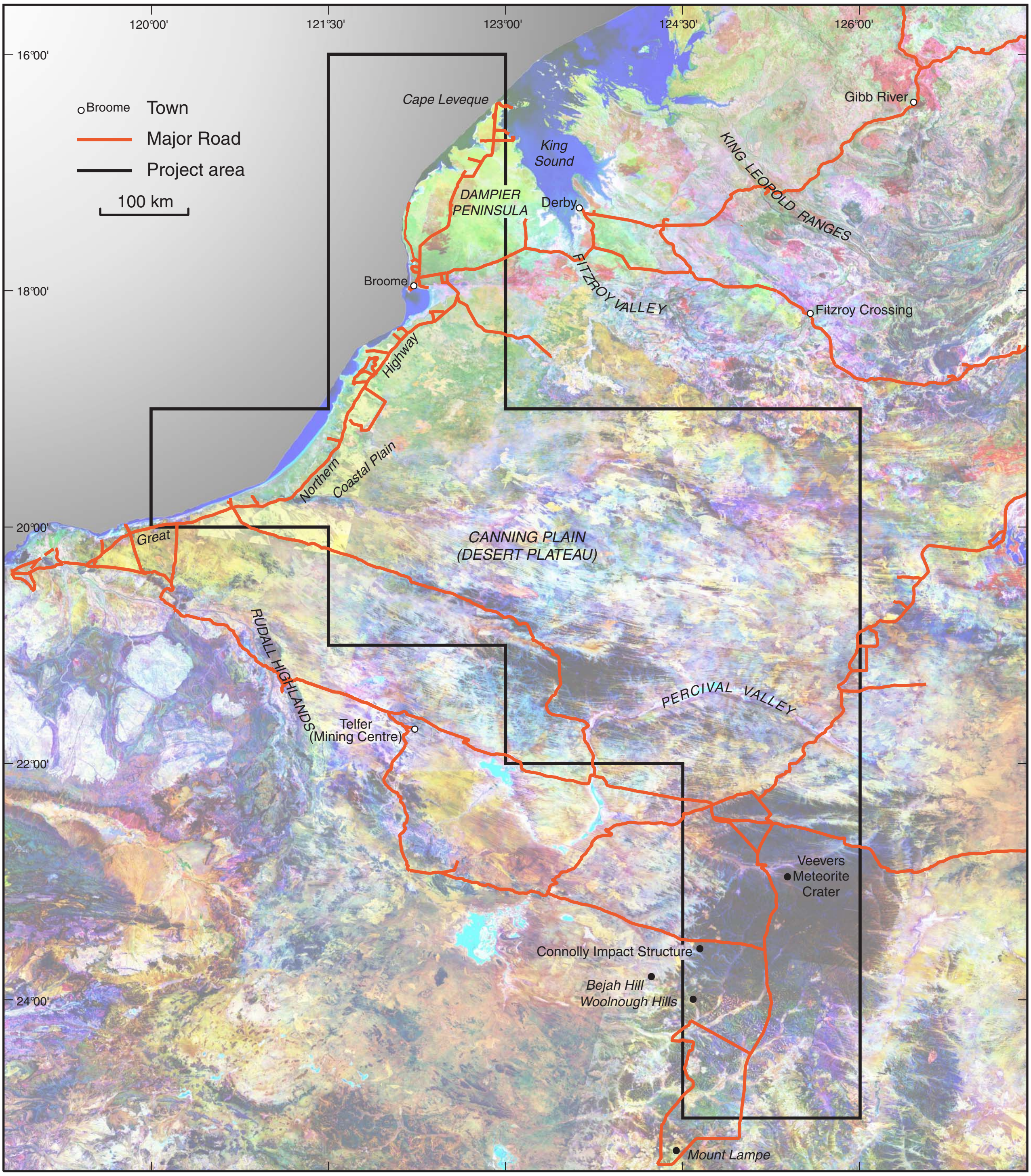


Figure 2. Location map of the Canning area, showing physiographic units, towns, and roads

Playford, 1992). The Canning Basin was remapped systematically at 1:250 000 scale in the early 1970s by the BMR and GSWA, with major reports by Towner et al. (1976), Gorter et al. (1979), Forman and Wales (1981), Towner and Gibson (1983), and Yeates et al. (1984). The most comprehensive overview of the Canning Basin arose from a symposium held in 1984 (Purcell, 1984b). Later symposia (Purcell and Purcell, 1988, 1994, 1998; Keep and Moss, 2002) also contain significant contributions on the Canning Basin. Environmental geological mapping at a scale of 1:50 000 was carried out around Broome in the late 1980s (Gozzard, 1988).

Summaries of the stratigraphy and depositional sequences of the Canning Basin were provided by Middleton (1990), Kennard et al. (1994), Romine et al. (1994), and Shaw et al. (1994). Jackson and van de Graaff (1981) presented an integrated view of a joint BMR–

GSWA mapping program in the Officer Basin in the early 1970s, and Iasky (1990) reviewed the geology and stratigraphy of the Officer Basin. The Ordovician and younger strata of the former Officer Basin were assigned to a new tectonic unit named the Gunbarrel Basin (Hocking, 1994; Tyler and Hocking, 2002). A new phase of work began in the Officer Basin in the mid-1990s. Major reports on the northern Officer Basin arising from this work are by Perincek (1996), Moors and Apak (2002), Haines et al. (in press), and Grey et al. (in press).

Base metals were discovered and mined along the northern margin of the Canning Basin, at Narlarla on Napier Downs, in the early 20th century (Ringrose, 1989), with subsequent economic discoveries further southeast in the 1970s, 1980s, and 1990s at Cadjebut, Pillara, Goongewa, and Kapok (Murphy, 1990; Ringrose, 1989; Ferguson, 1999; Copp, 2000; Hassan, 2004). Of these, only Pillara is now operational. In the central Canning Basin, base metals were first intersected in a petroleum exploration well by Meridian Oil NL in 1981. Subsequently, in 1986 Sydney Oil Pty Ltd drilled Cudalgarra 1 and intersected extensive base metal mineralization (McCracken et al., 1996). Between 1986 and 1991 this base metals discovery was followed up by Conzinc Rio Tinto of Australia (CRA) with a major exploration program to target Mississippi Valley-type zinc–lead–silver and barite mineralization within the Admiral Bay Fault Zone. CRA tested the zone of base metal mineralization with 24 diamond drill holes totalling 37 472 m (Connor, 1990; McCracken et al., 1996; Williams, 1999).

Regional geology

Tectonic divisions

The Canning area extends over four sedimentary basins (Figs 1 and 3). About 95% of the area is within the Phanerozoic Canning Basin. The southern part of the area (WARRI and MORRIS) is within the Phanerozoic Gunbarrel Basin. Neoproterozoic to Lower Palaeozoic inliers of the Officer and Amadeus Basins (Tyler and Hocking, 2002) are present in the Madley and Woolnough Diapirs and Clutterbuck Hills. The Canning and Gunbarrel Basins were continuous during widespread marine transgressions in the Carboniferous–Permian and Early Cretaceous.

The major tectonic subdivisions present in the Canning area are shown on Figure 3 and follow Hocking (1994) and Tyler and Hocking (2002).

Canning Basin

The Canning Basin occupies an area of about 430 000 km^2 onshore, and initially developed in the Early Palaeozoic as an intracratonic sag between the Precambrian Pilbara and Kimberley blocks (Forman and Wales, 1981; Purcell, 1984b and papers therein; Middleton, 1990; Hocking et al., 1994). The succession in the basin consists of mixed carbonate and clastic, continental to marine shelf sedimentary rocks (Fig. 4). Major evaporitic basins were present in the Ordovician, with lesser such accumulations in the Silurian and Early Devonian. Significant tectonic events affecting the basin (Kennard et al., 1994) were in the Early Ordovician (extension and rapid subsidence: Samphire Marsh Movement); Early Devonian (compression and erosion: Prices Creek Compressional Movement); Middle Devonian (extension and subsidence: Pillara Extension); mid- and Late Carboniferous – Permian (compression — Meda Transpressional Movement — then subsidence followed by minor uplift), and Early Jurassic (transpressional dextral uplift and erosion).

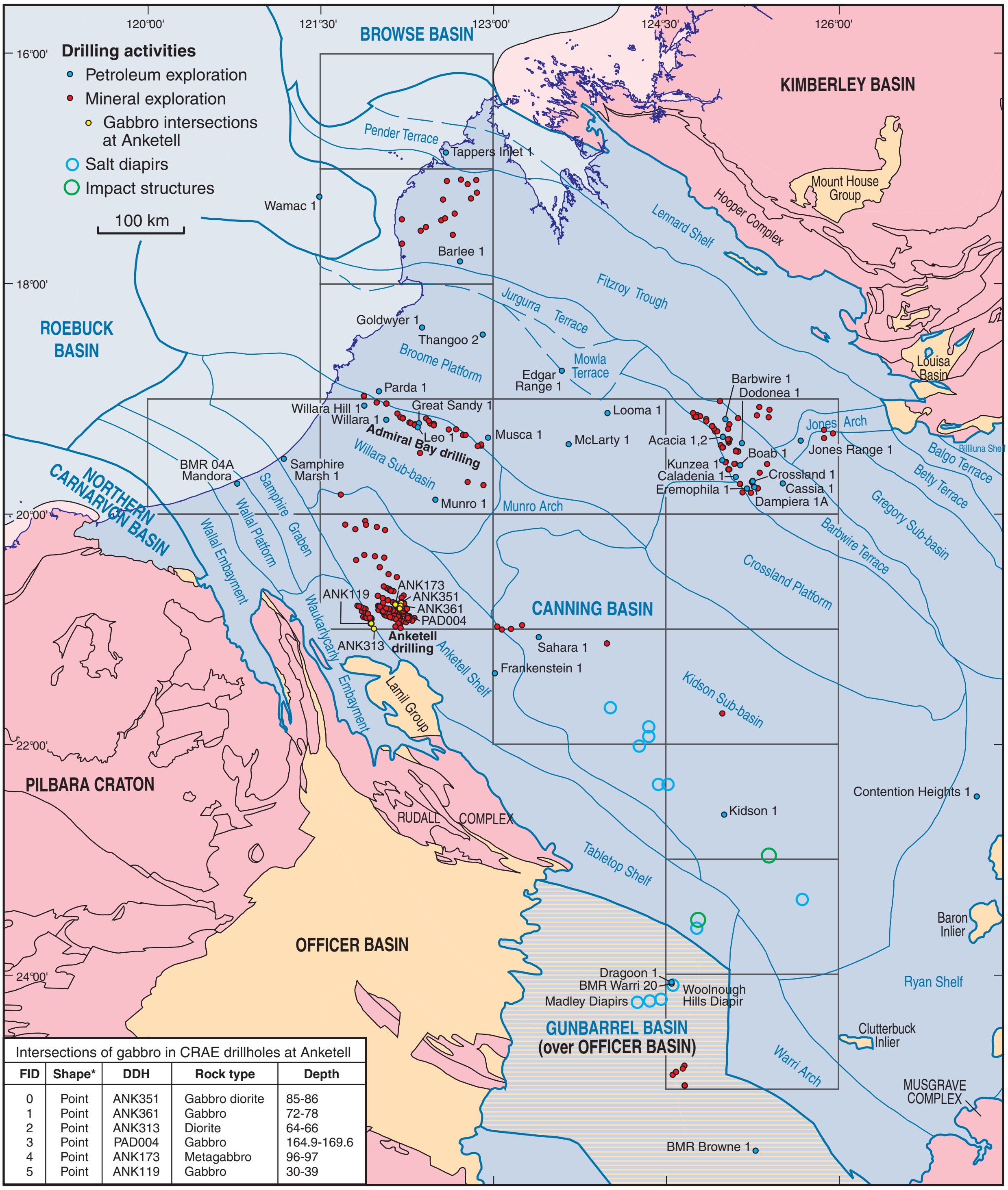
The basin contains two major northwesterly trending troughs separated by a mid-basin arch, and marginal shelves. The northern trough is divided into the Fitzroy Trough and the Gregory Sub-basin, which are estimated to contain up to 15 km of predominantly Palaeozoic rocks. The southern trough includes the Kidson and Willara Sub-basins, in which there are thinner sedimentary successions (4–5 km in thickness) of predominantly Ordovician to Silurian and Permian age, with extensive Mesozoic cover. The central arch is divided into the Broome and Crossland Platforms, and structural terraces (Barbwire, Mowla, and Jurgurra Terraces) step down from it into the troughs on either side. These structural units are largely delineated by northwesterly trending faults (Tucker et al., 1984; Anfiloff, 1984; Smith, 1984). Growth faulting is apparent along some fault systems, for example the Admiral Bay Fault Zone (McCracken et al., 1996).

The subdivisions of the basin (Figs 1 and 3) are based on presently expressed structural elements, although growth faulting initially developed some of these elements, and troughs developed and were active at different times during the basin's history. The southern Canning Basin is less intensely deformed than the north, in that the evidence of major fault-block movements seen in the northern Canning Basin is absent in the south. Only those basin subdivisions that are present in the area covered by this report are described below.

Pender Terrace and Lennard Shelf

The Pender Terrace (Fig. 1) is bounded by the Beagle Bay and Pender Faults on the south and north. Part of the Pender Terrace corresponds with the Derby Ramp of Veevers and Wells (1961; p. 215 and figure 131). Lehmann (1986) identified five cycles of Devonian reef building over the Pender Terrace, with the upper Pillara reefs as potential hydrocarbon reservoirs.

The extreme northwestern part of the Lennard Shelf cuts across the study area near Cape Leveque. Deposition on the Lennard Shelf began in the Early Ordovician in shallow-marine to coastal settings, and resumed in the Middle Devonian with the development of fringing reef complexes (Playford and Lowry, 1966; Playford, 1984; Hall, 1984; Cooper et al., 1984; Dörling et al., 1998; Playford and Wallace, 2001). Reefal development continued through most of the Late Devonian, and was followed by mixed carbonate–clastic deposition in the latest Devonian and Early Carboniferous, and by glacial depositon in the Late Carboniferous and Early Permian. The reef complexes are host to small hydrocarbon



Intersections of gabbro in CRAE drillholes at Anketell

FID	Shape*	DDH	Rock type	Depth
0	Point	ANK351	Gabbro diorite	85-86
1	Point	ANK361	Gabbro	72-78
2	Point	ANK313	Diorite	64-66
3	Point	PAD004	Gabbro	164.9-169.6
4	Point	ANK173	Metagabbro	96-97
5	Point	ANK119	Gabbro	30-39

Figure 3. Mineral and petroleum exploration in the Canning area

accumulations (Crostella, 1998) and base metal mineralization. Knowledge of the portion of the shelf in the study area is minimal.

Fitzroy Trough

The Fitzroy Trough (Fitzroy Graben of Forman and Wales, 1981) is a north-facing half graben (Drummond et al., 1988; Middleton, 1990) more than 10 km deep (Copp, 1994). The trough is bounded to the northeast by the Beagle Bay Fault and, to the southeast of the study area, the Pinnacles Fault, and to the southwest by the Fenton Fault; the latter coincides with a steep gravity gradient. Maximum estimated vertical movement on the Fenton Fault is 4000 m, and its northwestern and southeastern ends are poorly defined (Towner and Gibson, 1983). Drummond et al. (1988) described the boundary between the Lennard Shelf and the Fitzroy

Trough as a flexure or hinge line because the thickness of the sedimentary sequence increases towards the southwest (Towner and Gibson, 1983; Brown et al., 1984). The Carribuddy Group (essentially dolomite and evaporites) may also have been deposited in the Fitzroy Trough (Cadman et al., 1993) but rocks of the group have not yet been intersected in exploration drilling. However, Mory and Dunn (1990) noted that salt structures in the area seen on seismic sections may represent the Carribuddy Group.

The Fitzroy Trough and Gregory Sub-basin were active depocentres, with syndepositional faulting and subsidence, primarily between the Late Devonian and Early Permian (Yeates et al., 1984; Kennard et al., 1994). Carbonate and clastic rocks on the southern terraces and Broome Platform were also deposited at this time (Forman and Wales, 1981; Yeates et al., 1984). A relatively thin Triassic sequence is preserved in broad synclines.

Gregory Sub-basin

The Gregory Sub-basin is similar in depth and geometry to the Fitzroy Trough (O'Brien et al., 1998; Browne et al., 1984; Copp, 1994), with slightly more extensive Triassic cover. Yeates et al. (1984) and Cadman et al. (1993) considered that it was the deepest depocentre of the Canning Basin, although Copp (1994) showed the area as slightly shallower. The sub-basin is characterized by a thick pile of Permian–Triassic sedimentary rocks (Smith, 1984; Cadman et al., 1993) above older Palaeozoic sedimentary rocks.

Jones Arch

The Jones Arch is a basement high that separates the Gregory Sub-basin from the Fitzroy Trough (Yeates et al., 1975; Hocking, 1994). Pre-Grant Group erosion was not extensive, and it appears that the sedimentary sequence was deposited over the basement high in lagoonal to shallow-marine or deltaic environments. Jones Range 1 (Fig. 3) was drilled in the area to intersect anticipated reefal carbonates like those of the Lennard Shelf, but instead intersected Upper Devonian restricted marine to prodelta sedimentary rocks of the Luluigui Formation (Broad and McDermott, 1974).

Jurgurra and Mowla Terraces

The Jurgurra and Mowla Terraces are complexly faulted areas transitional between the Fitzroy Trough and Broome Platform (Bentley, 1984). The Jurgurra Terrace is estimated to be downfaulted by some 1000–1500 m (Bentley, 1984) against the Broome Platform, along the Collins and Dampier Faults. Further movement along the faults, during the Fitzroy Transpressional Movement, produced strike-slip movements (wrench faults) that formed a series of west-northwesterly trending tight anticlinal structures controlled by high-angle faults (Bentley, 1984, figure 7). The thickness of sedimentary rocks varies from 2000 to 7000 m on the Jurgurra Terrace (Begg, 1987). Salt structures (swells) have been recognized in the area (Purcell and Poll, 1984, figure 15). The Mowla Terrace is a similar structural terrace between the Jurgurra Terrace and the Broome Platform. Hocking (1994) included the terraces within the Broome Platform, as marginal subdivisions.

Barbwire Terrace

The Barbwire Terrace is an intermediate terrace between the deeper Fitzroy Trough and Gregory Sub-basin (to the north), and the Crossland and Broome Platforms to the south (Playford and Lowry, 1966; Towner and Gibson, 1983; Purcell and Poll, 1984; Begg, 1987; Hocking, 1994). The northeastern boundary is the Fenton Fault, the southwestern boundary is the Dummer Range Fault and, at the northwestern end of the terrace, the Abutilon Fault (Fig. 1). Seismic data from BHP were reinterpreted by PASMINCO (Davies, 1997) and indicate that the Abutilon Fault converges with the Dummer Range Fault. In the area where the two faults join, the Dummer Range Fault displacement decreases substantially northwards, and the Abutilon Fault changes its character from a complex series of faults to one fault with a very large throw at the extreme southern end. Acacia 2 intersected Precambrian basement at 1502.5 m (D'Ercole et al., 2003) in the central Barbwire Terrace. The terrace deepens to the southeast, to 4.5 km (Towner and Gibson, 1983) or to perhaps more than 5 km (Copp, 1994).

A thick sequence of Upper Devonian carbonates has been intersected in petroleum and mineral exploration drilling on the terrace, beneath Lower Permian Grant Group. The carbonates are characterized by remarkably extensive dolomitization (Wallace, 1990). The Mellinjerie Formation (Wallace, 1990; Kempton, 1992), a correlative of the Pillara Limestone (the Givetian–Frasnian platform facies on the Lennard Shelf), was intersected in Boab 1, Eremophila 1, Dampiera 1A, Barbwire 1, Dodonea 2, Cassia 1, Caladenia 1, Typha 1, and Acacia 1 and 2 (D'Ercole et al., 2003; Fig. 3). The carbonate sequence was interpreted as a sabkha sequence (Wallace, 1990; Kempton, 1992) containing minor but widespread pyrite–sphalerite–galena mineralization along the Abutilon Fault and other faults (e.g. in Kunzea 1; Davies, 1997). Preliminary examination of dolomite from the Barbwire Terrace indicates that dolomitization post-dates pyrite and sphalerite mineralization but the timing of the mineralization could not be established (Davies, 1997). Possible salt domes on the Barbwire Terrace may indicate underlying Carribuddy Group (Begg, 1987; Kirsner, 1994).

Broome Platform

The Broome Platform (Bentley, 1984; Hocking, 1994; Broome Swell of Veevers and Wells, 1961; Broome Arch of Towner and Gibson, 1983, and Yeates et al., 1984) is a basement high separating the Fitzroy Trough to the north from the Willara Sub-basin to the south that has remained a positive feature through most of its history (Yeates et al., 1984). The platform is characterized by an elongated, northwesterly trending, positive Bouguer anomaly (Veevers and Wells, 1961) with higher frequency magnetic anomalies than adjacent troughs. The edges of the platform are defined by the Dampier–Collins and Dummer Range Faults to the northeast and the Admiral Bay Fault Zone to the southwest (Fig. 1). The latter fault splays out and dissipates to the south (Bentley, 1984; Kennard et al., 1994; Shaw et al., 1994). The Broome Platform contains a sequence of gently southeasterly dipping Ordovician to Cretaceous sedimentary rocks, commonly less than 2 km thick, marked by long depositional breaks and mild structural deformation (Bentley, 1984; Karajas and Kernick, 1984).

The Broome Platform was affected by several tectonic episodes, beginning with faulting in the Early Ordovician. The Admiral Bay Fault Zone originated at this time, as a normal fault that later became a syndepositional fault with a maximum measured displacement of 500 m. During the Devonian faults were reactivated. An erosional unconformity marks a pre-Grant Group depositional surface, and indicates Carboniferous arching of the Broome Platform. In the Late Carboniferous, Permian and Triassic the Broome Platform was a relatively stable block while large-scale downwarping and rapid sedimentation occurred to the northeast in the Fitzroy Trough, and to the southwest in the Willara and Kidson Sub-basins. The Upper Triassic – Lower Jurassic Fitzroy Transpressional Movement had little effect on the Broome Platform apart from reactivation of the Admiral Bay Fault Zone (Bentley, 1984). Salt domes were intersected recently in Fruitcake 1 and Looma 1 (D'Ercole et al., 2003), and salt was previously intersected in McLarty 1 (Total Exploration, 1968; Bentley, 1984; Yeates et al., 1984). The northern limit of the Mallowa Salt was defined by Shell Development Australia in 2000 (D'Ercole et al., 2003).

Crossland Platform

The Crossland Platform is an extension of the Broome Platform (Hocking, 1994; Fig. 3), transitional into the Barbwire Terrace to the north. The southern boundary with the Kidson Sub-basin is ill defined (Hocking, 1994). The Crossland Platform and Barbwire Terrace are relatively stable structural units consisting of mildly deformed Ordovician and Devonian rocks overlain by Permian strata (Wyborn, 1977; Bentley, 1984; Smith, 1984).

Willara Sub-basin

The Willara Sub-basin lies to the southeast of the Admiral Bay Fault Zone (Fig. 1), and contains an Ordovician–Silurian succession up to 4500 m thick, beneath comparatively thin Permian and Mesozoic sedimentary rocks (Towner and Gibson, 1983; D'Ercole et al., 2003). Salt sequences of the Carribuddy Group form large salt swells (Karajas and Kernick, 1984; Cathro et al., 1992; Haines, 2004). Along its northern edge, the Admiral Bay Fault Zone hosts zinc–lead–silver mineralization within the Ordovician Goldwyer and Nita Formations (McCracken, 1994; McCracken et al., 1996; Williams, 1999; Haines, 2004). The fault zone is offset near Great Sandy 1 by a sinistral transfer zone (Great Sandy Transfer Zone), which was important in localizing the precipitation of base metals (McCracken et al., 1996) and the accumulation and preservation of hydrocarbons (Norlin, 1984).

Munro Arch

The Munro Arch is a gravity high (Flavelle, 1974) between the Willara and Kidson Sub-basins (Fig. 3) that has been interpreted as a low basement rise (Towner and Gibson, 1983). Shaw et al. (1994) referred to the area as the Munro Terrace. The arch appears to have developed during the Ordovician.

Kidson Sub-basin

The Kidson Sub-basin is the major depocentre of the southern Canning Basin, containing up to 6 km in total of Ordovician and younger sedimentary rocks (Copp, 1994). The Ordovician–Silurian section is at least 3000 m thick (Mory and Dunn, 1990; Kennard et al., 1994; Romine et al., 1994), and is overlain by Devonian, Upper Carboniferous – Permian, and Jurassic–Cretaceous successions (Kennard et al., 1994).

Lower and Middle Ordovician shallow-marine carbonate and clastic deposition (Forman and Wales, 1981; Haines, 2004) was followed by regional-scale evaporite and redbed deposition in the Late Ordovician and Silurian (Romine et al., 1994). Redbed deposition resumed in the late Early Devonian, with marginal-marine carbonate deposition in the Middle and Late Devonian (Lehmann, 1984). Upper Carboniferous – Permian and Middle Jurassic – Lower Cretaceous successions blanketed older rocks.

Anketell Shelf

The Anketell Shelf is a northeastwards-deepening area transitional between the northwest Paterson Orogen and the Willara and Kidson Sub-basins, with Permian and Jurassic–Cretaceous sedimentary rocks above Proterozoic rocks. Basement topography near the margin of the shelf is pronounced. The older Palaeozoic successions found in the Willara and Kidson Sub-basins, including 500 m of Ordovician, are present on SAHARA in the well Frankenstein 1 (Haines, 2004), overlain by 2000 m of younger sediment .

During mineral-exploration drilling in the northwestern part of ANKETELL (in and around the Magnum prospect), BHP intersected a sequence of metasediments that could be metamorphosed Yeneena Group or part of the Rudall Complex (Williams, 1990). Depth to basement ranged from 97 to 256 m (Davis, 1994a,b; Davis et al., 1997; Taylor, 1999a,b). The overlying rocks are siltstone, sandstone, and conglomerate of Permian age, probably Grant Group. Drilling by BHP also intersected gabbro in six drillholes (Fig. 3) at depths of 30–96 m below the surface (Davis, 1994a; Sandl, 1995). These gabbros are possibly part of the northeastern zone of the Yeneena Group. Further into the basin, Frankenstein 1 intersected basement at 2666 m.

Samphire Graben, Wallal Platform, and Wallal Embayment

The Samphire Graben is a narrow, northwest-deepening basement depression on MANDORA, separated from the Willara Sub-basin by a northwest-trending ridge of shallow basement (Towner, 1982c; Towner and Gibson, 1983). The graben was described as a subsidiary depocentre by Romine et al. (1994). Samphire Marsh 1, located close to the Samphire Graben, intersected Ordovician Nambeet Formation above Precambrian basement at 2006 m. The graben is transitional to the southeast into the Waukarlycarly Embayment, which at its southern end was shaped by Late Palaeozoic glacial scouring.

The Wallal Platform is an elongate, upfaulted, northwesterly trending spine of shallow basement between the Samphire Graben and the Wallal Embayment. The platform is an extension of the core of the northwestern Paterson Orogen (Hocking, 1994). Upper Carboniferous – Permian glacigene rocks overlie basement, and are in turn overlain by Jurassic–Cretaceous rocks to the northwest.

The Wallal Embayment is a narrow half-graben within the basement of the Anketell Shelf and is recognized as a gravity low (Towner and Gibson, 1983). Permian rocks (the Grant Group, Poole Sandstone, and Liveringa Group) were intersected in petroleum exploration wells, beneath thin Cretaceous cover.

Ryan Shelf

The Ryan Shelf (Gorter et al., 1979; Hocking, 1994; Haines, 2004) is a poorly known area at the southeastern end of the Kidson Sub-basin, in which up to 3 km of Ordovician, Carboniferous–Permian, and Mesozoic sedimentary rocks overlie Proterozoic rocks of the Amadeus Basin and Arunta Complex (Tyler and Hocking, 2002). Outliers of the Amadeus Basin are exposed in the Clutterbuck and Baron Hills.

Tabletop Shelf and Warri Arch

The Tabletop Shelf and Warri Arch together form a northwesterly trending structural link between the Proterozoic Rudall Complex and Musgrave Complex (Williams and Myers, 1990). The structural link is indicated by a gravity feature that was initially identified by the BMR during gravity surveys in the 1950s. It was first described as the Anketell–Warri Regional Gravity Ridge (Flavelle, 1974) and later as the Anketell Regional Gravity Ridge (Fraser, 1976). The gravity ridge has also been called the Paterson–Musgrave structural trend (Austin and Williams, 1978). The Tabletop Shelf was included in the Anketell Shelf by Hocking (1994), but was recognized as a separate unit by Tyler and Hocking (2002) because it is a gravity high.

Mineral exploration drilling by CRA in 1990 tested for possible diamond-bearing diatremes in the western part of WARRI. Instead, tuffaceous siltstone and volcanic breccia of Permian age were intersected at a depth of 132 m (Clifford et al., 1991; Perincek, 1998).

Officer, Amadeus, and Gunbarrel Basins

To the south of the Canning Basin there are two stacked basins, the Officer and Gunbarrel Basins (Fitzpatrick, 1966; Iasky, 1990; Hocking, 1994; Perincek, 1998; Tyler and Hocking, 2002) on WARRI and MORRIS (Fig. 1). The Officer Basin originally included the entire Proterozoic and Phanerozoic sedimentary succession (Jackson and van de Graaff, 1981; Iasky, 1990) but was redefined by Hocking (1994) as two stacked basins, the Neoproterozoic to Cambrian Officer Basin, overlain by the Palaeozoic to Mesozoic Gunbarrel Basin. The Upper Cambrian Table Hill Volcanics, which are the oldest rocks that have not undergone deformation in the Paterson–Petermann Ranges Orogeny, are the basal unit of the Gunbarrel Basin (Hocking, 1994; Tyler and Hocking, 2002). Seismic, gravity, and limited exploration drilling data indicate that there are at least 6 km of Neoproterozoic sedimentary rocks in the Officer Basin (Shevchenko and Iasky, 1997; Moors and Apak, 2002; Apak and Carlsen, 2003; Simeonova, 2003). Only two subdivisions of the Officer Basin, the Gibson area and the Madley High, are present (Fig. 1) in the Canning area.

The boundary between the Canning Basin and the Officer Basin is taken along the southern edge of the Warri Arch (Towner and Gibson, 1983; Iasky, 1990; Tyler and Hocking, 2002). The boundary between the Canning and Gunbarrel Basins is entirely arbitrary.

The Amadeus Basin lies to the east of the southern Canning Basin, and two inliers of Proterozoic sedimentary rocks, the Clutterbuck and Baron Inliers (Hocking, 1994), are present on the Ryan Shelf. The westernmost tip of the Clutterbuck Inlier lies on WARRI. The rocks in the inlier are a moderately dipping, siliciclastic cyclic succession of uncertain age, and they are onlapped by subhorizontal Carboniferous–Permian glacigene rocks. The dip suggests a structural control over the position of the inlier.

Madley High

The Madley High is a basement high located between the Gibson area and the rest of the Officer Basin (Iasky, 1990). It is defined by the 3 km depth to the magnetic basement contour and is a probable western extension of the Warri Arch (Hocking, 1994).

Gibson area

Moors and Apak (2002) considered that the tectonic unit formerly known as the Gibson Sub-basin (Iasky, 1990; Hocking, 1994) was invalid, because of the lack of evidence for a discrete sedimentary depocentre, and referred to it as the Gibson area. Simeonova (2003) later referred to the southeastern Gibson area as the ‘Minibasins zone’, because it is characterized by numerous small basins (minibasins) developed through halotectonics. This character does not appear to be present in the northwestern part of the area where it is sandier and adjacent to exposed Paterson Orogen rocks. Two major salt diapirs, the Woolnough Hills and Madley Diapirs, pierce the Phanerozoic Gunbarrel Basin succession to expose Neoproterozoic salt. Subsurface data are available from two petroleum exploration wells, Dragoon 1 and Hussar 1, a stratigraphic corehole, GSWA Lancer 1, scattered mineral exploration drillholes, and a regional seismic grid.

The sedimentary succession in the northern Officer Basin (Grey et al., in press) consists of a lower mixed clastic and carbonate succession containing a major salt-dominated evaporite sequence (850 – c. 700 Ma in age), overlain by a glacigene interval (c. 600–580 Ma), and then by synorogenic eolian and fluvial sandstone (c. 550 Ma). The dominant agent of deformation has been halotectonics, triggered by regional tectonic events (Simeonova, 2003). The succession in the overlying Gunbarrel Basin consists of discontinuous, Upper Cambrian basal mafic volcanics, the Table Hill Volcanics, overlain in turn by an Ordovician or Devonian sandstone, Upper Carboniferous – Permian glacigene rocks, and thin Jurassic–Cretaceous sandstone and shale.

Two meteoritic impact structures have been found in the study area. The Veevers crater, 80 m in diameter, was located in 1975 at latitude 22°58'06"S and longitude 125°22'07"E in the southern part of URAL (Yeates et al., 1976; Bevan, 1996). It has impact breccia, distributed ejecta, and shock metamorphism. The Connolly impact structure is located at latitude 23°32'S and longitude 124°45'E on MORRIS (Bevan, 1996).

Stratigraphy

Canning Basin

The stratigraphic column for the Canning area (Fig. 4) is assembled primarily from information in Towner and Gibson (1983), Yeates et al. (1984), Middleton (1990), Mory and Dunn (1990), Kennard et al. (1994), and D'Ercole et al. (2003), with ages as shown on Jones et al. (1998).

Four major periods of sedimentation occurred in the Canning Basin (Mory and Dunn, 1990; Kennard et al., 1994; D'Ercole et al., 2003). Initial rifting and the first marine transgression occurred in the Early Ordovician, except over the southern Anketell Shelf, and was followed by progressive shallowing in the Middle Ordovician (Mory and Dunn, 1990, figure 2; Haines, 2004). From Late Ordovician time, deposition of carbonate and evaporitic sequences of the Carribuddy Group continued through the Silurian, mainly in the Kidson Sub-basin and Willara Sub-basin and to a limited extent on the Broome Platform. A period of minor folding, erosion, and regional uplift (the Prices Creek Compressional Movement) followed in the Early Devonian. Carbonate and clastic deposition resumed in the late Early Devonian in the Willara and Kidson Sub-basins and Barbwire Terrace, followed by a phase of major extension and rifting in the basin during the mid-Givetian (Middle Devonian) to Frasnian (Late Devonian). The Fitzroy Trough and Gregory Sub-basin became depocentres during this period. Deposition largely ceased in the mid-Carboniferous, during the Meda Transpressional Event (Kennard et al., 1994; D'Ercole et al., 2003).

Rifting began again in the Late Carboniferous and continued until the Early Triassic. Deposition resumed in the Late Carboniferous, with continental-scale glaciation beginning in the Late Carboniferous and extending into the Early Permian. Further sedimentation continued, under a warmer climate, in the late Early Permian, Late Permian, and Triassic. The Fitzroy Transpressional Movement (Upper Triassic – Lower Jurassic) affected the Fitzroy Trough, resulting in right-lateral wrenching along major faults (the Fenton Fault) as well as en echelon anticlinal structures (Forman and Wales, 1981; Romine et al., 1994, figure 2; Kennard et al., 1994, figure 3). The southern Canning Basin was relatively less deformed than the northern Canning Basin. The last significant sedimentary phase comprised two regional transgressions in the Middle and Late Jurassic, and the Early Cretaceous, during which the Wallal Sandstone, Barbwire Sandstone, Alexander Formation, Jarlemai Siltstone (Middle and Late Jurassic), and Cronin Formation, Callawa Formation, Broome Sandstone, Samuel Formation, Melligo Sandstone, Parda Formation, Frezier Sandstone, Bejah Claystone, Anketell Formation, and Emeriau Sandstone (Cretaceous) were deposited. These are a complexly inter-related set of units showing multiple lateral facies changes reflecting position in the basin and local depositional changes. The Lampe Formation and Lake George Formation are localized Lower Palaeogene ?lacustrine deposits. The Bejah Claystone, Samuel Formation, and Lampe Formation extend south into the Gunbarrel Basin, with the southernmost outcrops at about latitude 27°30'S.

Basement rocks (Precambrian)

Drillholes that intersected basement within the Canning area, the depth to basement, and the lithology intersected, are tabulated in Table 1. Rock types range from granite and gabbro through gneiss to schist and phyllite. The depth to basement varies considerably, from abundant shallow intersections, commonly less than 100 m, on the edge of the Anketell Shelf, to just above 3496 m in Wilson Cliffs 1 in the Kidson Sub-basin.

Nambeet Formation (Ordovician)

The Nambeet Formation is the oldest known part of the Canning Basin succession, and was deposited in the Tremadoc in a sag setting, as on the central Broome Platform (Bentley, 1984) and around the margin of the basin (Conolly et al., 1984). The formation consists of quartz arenite, shale, and dolomite deposited in subtidal to intertidal environments (Haines, 2004). Its maximum known thickness is 327.5 m in Setaria 1, on the Barbwire Terrace. The sediments were transported from the southeast during a marine transgression.

The Nambeet Formation does not outcrop, and has not been intersected on the Tabletop Shelf, Ryan Shelf, or

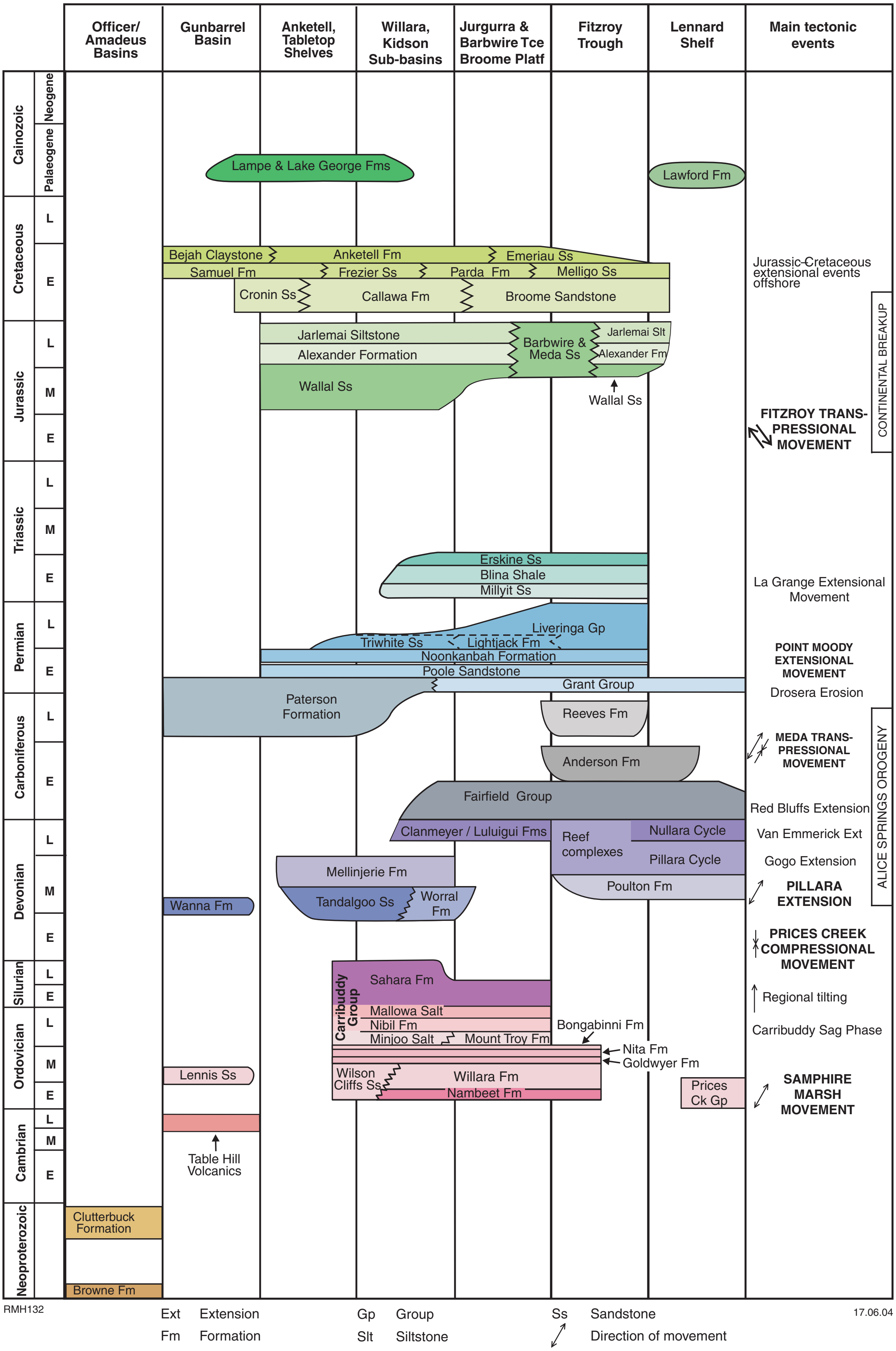


Figure 4. Stratigraphy of the Canning area

Table 1. Selected drillholes intersecting Precambrian basement rocks within the Canning area (see Fig. 3 for locations)

Well/drillhole name	*Basement interval drilled (m below rotary table)*	*Rock type*
Acacia 2	1502.5 – 1575	Phyllite
Anketell DDH ANK119	30–39	Gabbro
Anketell DDH ANK173	96–97	Metagabbro
Anketell DDH ANK313	64–66	Dolerite
Anketell DDH ANK351	85–86	Gabbro diorite
Anketell DDH ANK361	72–78	Gabbro
Anketell DDH PAD004	164.9 – 169.6	Gabbro
BMR Warri 20	0 – 265.48	Shale, halite
Edgar Range 1	1916–1968	Quartz–mica schist
Frankenstein 1	2666–2803	Metamorphic rock
Goldwyer 1	1421–1439	Granite
Hedonia 1	1531–1543	Granite
Looma 1	2494–2535	Shale, minor quartzite
Munro 1	2106–2116	Granite
Parda 1	1777–1909	Granite gneiss
Samphire Marsh 1	2006–2022	Granite and gneiss
Tappers Inlet 1	2813–2834	Metabasalt
Thangoo 1	1382–1482	Biotite phyllite
Thangoo 2	1245–1279	Gneiss
Wilson Cliffs 1	3496–3722	Red shale over graphitic shale

Wallal Embayment (Towner and Gibson, 1983), or along the northern margin of the basin. It is possibly thinly present on the northern Anketell Shelf (Haines, 2004).

Willara Formation (Ordovician)

The Willara Formation conformably overlies the Nambeet Formation and is a subtidal to intertidal, carbonate and clastic sequence, about 300 m thick (King, 1998). Reef build-up took place towards the top of the formation (Conolly et al., 1984; Bentley, 1984), and local emergence resulted in karstic weathering and localized dolomitization of carbonates. A fine-grained sandstone, the Acacia Sandstone Member, is present in some intersections, for example in Thangoo 1 and Solanum 1. The sandstone occurs in the middle of the formation and was deposited following a period of exposure and erosion (Bentley, 1984; Haines, 2004).

The Willara Formation, as with the Nambeet Formation, is not exposed and has not been intersected on the Tabletop Shelf, Ryan Shelf, and Wallal Embayment (Towner and Gibson, 1983, plate 2).

Goldwyer Formation (Ordovician)

The Goldwyer Formation conformably overlies the Willara Formation, and complete sections were intersected in petroleum exploration wells Willara 1 (736 m), Edgar Range 1 (431 m), McLarty 1 (378 m), and Parda 1 (232 m). Three informal units were identified within the Goldwyer Formation in the northwestern Canning Basin: a lower unit of shale and limestone; a middle limestone unit; and an upper shale unit (Bentley, 1984). CRAE drilling along the Admiral Bay Fault Zone indicated that the Goldwyer Formation is significantly different at the uplifted footwall of the fault zone with subtidal to supratidal biohermal associations of microbial boundstones, bryozoan grainstones, and evaporitic carbonate mudstones (McCracken et al., 1996). Another characteristic feature at Admiral Bay is a thickening of the Goldwyer Formation and other Canning Basin sequences. At the Admiral Bay Fault Zone the Goldwyer Formation is heavily overprinted by (?hydrothermal) alteration assemblages, such as barite–carbonate massive veins and the pervasive replacement of host rocks by siderite, iron oxides (including magnetite), silica, and bituminous material. Massive galena or galena–chalcopyrite assemblages up to 1 m across have been intersected in barite-carbonate veins (Williams, 1999).

Over the Barbwire Terrace, the Goldwyer Formation consists of four informal units recognized by Western Mining Corporation (WMC). Units 1 (about 70 m thick) and 2 (about 100 m thick) are interbedded shale and limestone, deposited in mid- to outer-ramp marine settings. Unit 3 (40–90 m thick) contains a shoaling upwards succession of limestone and minor shale deposited in an inner- to mid-ramp setting. Unit 4 (50–200 m thick) consists predominantly of shale and argillaceous limestone deposited in a subtidal–lagoonal environment and may have petroleum source potential. All four units of the Goldwyer Formation can be identified throughout most of the southern Canning Basin (King, 1998; Haines, 2004).

The Goldwyer Formation is relatively thin (110 m) on the Anketell Shelf (Haines, 2004), doubtfully present on the Ryan Shelf, and has not been intersected on the Tabletop Shelf or in the Wallal Embayment (Towner and Gibson, 1983, plate 2).

Nita Formation (Ordovician)

The Nita Formation conformably overlies the Goldwyer Formation. The intersected thickness ranges from 45 m up to a maximum of 216 m, in mineral and petroleum exploration drill holes on the Jurgurra and Mowla Terraces, Broome Platform, and Barbwire Terrace, with abundant intersections in the vicinity of the Admiral Bay Fault Zone (D'Ercole et al., 2003; Haines, 2004). The formation has not been intersected in the southern Kidson Sub-basin (Howell, 1984). In CRAE drill holes at Admiral Bay, its relationship with the overlying Carribuddy Group is gradational and conformable (Williams and Harvey, 1989; Haines, 2004). The sequence is a shallowing-upward succession of subtidal or intertidal to supratidal carbonate and mudstone. McCracken (1994) defined two members, the Leo Member and the Cudalgarra Member.

The Nita Formation has been the target of most petroleum and mineral exploration programs along the Admiral Bay Fault Zone (Kennard et al., 1994; King, 1998; Haines, 2004).

The Leo Member, along the Admiral Bay Fault Zone, is a fining-upward cyclic sequence 62.6 m thick of basal intraclastic and echinoidal grainstone (1 to 2 m thick), overlain by strongly bioturbated crinoidal wackestone and minor intraclastic grainstone at the top of the cycle (McCracken, 1994). Elsewhere across the Broome Platform it is 27–80 m thick (Haines, 2004). The Cudalgarra Member was deposited under subtidal to supratidal conditions and is also cyclic (McCracken et al., 1996; Haines, 2004). A typical cycle consists of basal bioclastic and intraclastic grainstone, overlain by bioturbated wackestone and mudstone, rare ooid grainstone, microbial boundstone, cross- and ripple-laminated mudstone, and supratidal evaporitic mudstone. Anhydrite nodules and veins are common in the supratidal intervals. Deformation due to solution collapse breccia is also common in this interval. The upper zinc-rich zone of the Admiral Bay base metal mineralization is hosted in the Cudalgarra Member. The thickness of the Cudalgarra Member varies between 12 and 21 m (Haines, 2004).

Carribuddy Group (Upper Ordovician to Upper Silurian)

The Upper Ordovician to Upper Silurian Carribuddy Group (originally named as the Carribuddy Formation, but raised to group status by Lehmann, 1984) is present in the Willara and Kidson Sub-basins, the Samphire Embayment, the Jurgurra, Mowla, and Barbwire Terraces, and the Broome Platform. Its presence in the Fitzroy Trough is speculative, and it has not been found further north on the Lennard Shelf (Towner and Gibson, 1983; Kennard et al., 1994; Romine et al., 1994). The unit was originally subdivided into five members, A to E, now named, in ascending order, the Bongabinni Formation, Minjoo Salt and laterally equivalent Mount Troy Formation, Nibil Formation, Mallowa Salt, and Sahara Formation (Lehmann, 1984; Middleton, 1990; Haines, 2004).

The Bongabinni Formation, the basal unit of the Carribuddy Group, consists of claystone with interbeds of dolomite. Veins or scattered crystals of halite and anhydrite are present in its basal part. The claystone is red, red-brown, mottled green, calcareous, and dolomitic with rare fine to silt-size quartz (Lehmann, 1984; Middleton, 1990; Haines, 2004).

The Minjoo Salt is an evaporitic sequence of halite, minor claystone, and dolomite up to 166 m thick. Very fine to coarse and rounded quartz grains occur in some parts of the claystone with rare anhydrite (Glover, 1973; Lehmann, 1984; Middleton, 1990). The Minjoo Salt has been intersected in drilling in the Kidson Sub-basin, Ryan Shelf, Anketell Shelf, and Mowla Terrace. Along the edges of the Broome Platform, the Minjoo Salt grades into the Mount Troy Formation, a thin (<35 m) unit of dolomite with interbedded red-brown shale (Lehmann, 1984) which extends over the platform.

The Nibil Formation overlies the Minjoo Salt, and is up to 404 m thick. It consists of grey calcareous to dolomitic claystone grading locally into limestone, dolomite, and fine-grained sandstone. Anhydrite is often present in the limestone and claystone. Some beds of halite are present at the base (Lehmann, 1984).

The Mallowa Salt is a strongly cyclic and thick evaporite unit conformably overlying the Nibil Formation (Glover, 1973; Lehmann, 1984). Cathro et al. (1992) estimated that the Mallowa Salt attained a thickness of 800 m or more and possibly covered a surface area of 200 000 km^2. The main authigenic minerals within halite veins and beds are halite, dolomite, anhydrite, and quartz, together with hematitic pigment and hematite euhedra. Minor dolomite and dolomitic siltstone with claystone occur at the base of the Mallowa Salt. A high bromine content (179–186 ppm) in the Mallowa Salt (Glover, 1973) suggested conditions favourable for potash evaporite deposits (Williams and Taylor, 1986). Detailed studies of the Mallowa Salt in BHP Minerals Brooke 1, a potash exploration well, are provided in BHP Minerals Ltd (1989) and Cathro et al. (1992), and in Gingerah Hill 1 are provided in BHP Minerals Ltd (1987), and Foster and Williams (1991).

The Mallowa Salt has undergone several stages of regional salt dissolution and its present distribution is a combination of primary deposition and secondary dissolution (Romine et al., 1994). Three major phases of salt dissolution were identified along the Admiral Bay Fault Zone (McCracken, 1994) where the Mallowa Salt is absent or thin due to dissolution (McCracken et al., 1996).

The Sahara Formation, the uppermost member of the Carribuddy Group, is up to 279 m thick and consists mainly of dolomite, dolomitic siltstone, and rare sandstone beds. Anhydrite is scattered throughout the formation as inclusions and fracture fillings (Lehmann, 1984).

Worral Formation (Lower and Middle Devonian)

The Worral Formation is a sequence of carbonate, siltstone, and sandstone, deposited under marginal marine conditions, that was first identified by WMC in Barbwire 1

(Lehmann, 1984). The formation unconformably overlies the Carribuddy Group and is considered to be Early to Middle Devonian in age, based on stratigraphic position (Lehmann, 1984; King, 1998; D'Ercole et al., 2003). The Poulton Formation is a correlative of the Worral Formation and Tandalgoo Sandstone on the Lennard Shelf.

Tandalgoo Sandstone (Lower and Middle Devonian)

The Tandalgoo Sandstone is a red sandstone unit with a maximum thickness of 1000 m (in Sahara 1; West Australian Petroleum Pty Ltd, 1966; Lehmann, 1984) that is laterally equivalent to the Worral Formation. Following Early Devonian regression, there was widespread eolian deposition across the southern and central Canning Basin (Willara Sub-basin, Kidson Sub-basin, Broome Platform, Jurgurra Terrace, and Barbwire Terrace), with local marginal marine siliciclastic deposition, forming the Tandalgoo Sandstone. Extensive erosion later took place over the platform, and the sandstone is locally absent, as in Edgar Range 1 and Musca 1 (Bentley, 1984). Both the Worral Formation and the Tandalgoo Sandstone were deposited south of the Fitzroy Trough.

Mellinjerie Formation (Middle to Upper Devonian)

The Mellinjerie Formation overlies the Tandalgoo Sandstone in the southern and central Canning Basin (Lehmann, 1984). It is up to 300 m thick and contains limestone with subordinate shale, evaporite, and dolomite (King, 1998). Across the Barbwire Terrace, extensive dolomitization within the Mellinjerie Formation limestone was observed during Western Mining Corporation drilling. The limestone also displays 'chicken wire' texture due to nodular anhydrite formed in a sabkha environment (Ashton, 1984). Thus dolomitization is interpreted to have occurred as a result of both local near-surface sabkha environments and as a widespread regional process (Wallace, 1990; Kempton, 1992). The formation is a correlative of, and locally has similar facies to, the Pillara Limestone of the Lennard Shelf. Lehmann (1984, figure 15) recognized the Mellinjerrie Formation as a sabkha facies south of reefal platform facies he assigned to the Pillara Limestone, whereas Yeates et al. (1984) recognized the Pillara Limestone only in the northern Canning Basin.

Reef complexes (Middle to Upper Devonian)

Middle and Upper Devonian reef complexes are exposed along the northern margin of the Canning Basin (Playford and Lowry, 1966; Playford, 1980, 1984; Playford et al., 1989). They have been divided into Givetian–Frasnian reefal platform facies (Pillara Limestone), marginal slope facies (Sadler Limestone, Virgin Hills Formation) and basinal facies (Gogo Formation, Virgin Hills Formation), and Famennian platform facies (Windjana and Nullara Limestones) and marginal slope to basinal facies (Virgin Hills, Napier and Piker Hills Formations, Bugle Gap Limestone). The platform facies in particular is important as a petroleum reservoir rock (Lehmann, 1984). The reef complexes have been recognized in many wells in the central Canning Basin (Lehmann, 1984; D'Ercole et al., 2003; e.g. in Tappers Inlet 1 between 1532 and 1948 m). In the south and southeast, the Frasnian and older parts of the complexes are correlated with the Mellinjerie Formation. The Gogo Formation has been recognized on the Barbwire Terrace.

Paterson Formation (Upper Carboniferous to Lower Permian)

The Paterson Formation is present in the southern Canning Basin and extends into the Gunbarrel Basin. It outcrops in the southwestern corner of ANKETELL in the Waukarlycarly Embayment, at the southern end of the Samphire Graben. The formation consists of diamictite, sandstone, siltstone, and claystone formed in fluvioglacial, glaciolacustrine, and fluvial environments. It correlates with the Reeves Formation (Carboniferous) and the Grant Group (lowermost Permian) of the central and northern Canning Basin, but according to Haines et al. (in press), much of the Paterson Formation appears to be Late Carboniferous in age rather than Early Permian.

Grant Group (Upper Carboniferous and Lower Permian)

The Grant Group (Grant Formation of Guppy et al., 1952; amended by Crowe and Towner, 1976) is characterized by marine- and fluvio-glacial siliciclastic rocks, and is widely distributed across most of the Canning Basin (Towner and Gibson, 1983, plate 2; Bentley, 1984; Yeates et al., 1984; O'Brien and Christie-Blick, 1992; Apak, 1996; Apak and Backhouse, 1998, 1999).

Subdivisions of the Grant Group followed the evolution of geological knowledge in the northern Canning Basin, especially on the Barbwire Terrace, where it has been intersected by numerous exploration drillholes. Crowe and Towner (1976) divided the group into the Betty (base), Winifred, and Carolyn (top) Formations, based on surface mapping in the Fitzroy Trough. Redfern and Millward (1994) and Kennard et al. (1994) recognized a lower and upper Grant Group. The lower unit was present in deep troughs, and absent over the Barbwire Terrace, where Redfern and Millward (1994) divided the Grant Group into the Hoya, Calytrix, and Clianthus Formations. Apak and Backhouse (1999) named the Reeves Formation for the sequence referred to as the lower Grant Group by Kennard et al. (1994) and Redfern and Millward (1994), and recognized a disconformity between it and the upper Grant Group, on palynological grounds, as suggested by Kennard et al. (1994) The Grant Group is a known reservoir unit and is an important target for petroleum exploration (Bentley, 1984; D'Ercole et al., 2003). It is also considered to be one of the main Palaeozoic aquifers in the Canning Basin (Ghassemi et al., 1992). Minor coal and fossiliferous limestone is reported from the sequence now assigned to the Reeves Formation (Singleton, 1965).

Poole Sandstone, Noonkanbah Formation, Triwhite Sandstone, Liveringa Group (Lower to Upper Permian)

The Permian sequences that overlie the Grant Group are known primarily from the Fitzroy Trough (Towner and Gibson, 1983; Yeates et al., 1984). In the southern Canning Basin they consist of shallow-marine to fluvial or coastal siltstone and sandstone, and are generally undifferentiated and poorly defined (King, 1998). Scattered discontinuous outcrops adjoin the northwestern part of the Paterson Orogen, and there are intersections in wells such as Kidson 1, Sahara 1, Crossland 1, and Contention Heights 1 of Poole Sandstone, Noonkanbah Formation, Triwhite Sandstone, and lower Liveringa Group (Yeates et al., 1984).

Deposition appears to have been restricted to the northern Canning Basin in the Triassic, and these units (see Fig. 4) are largely outside the map sheets of the Canning area.

Middle and Upper Jurassic units

The Middle Jurassic Wallal Sandstone (Forman and Wales, 1981) is a shallow-marine to fluvial, in part deltaic, mixed siliciclastic unit that blankets the Permian succession in the western part of the central and southern Canning Basin (Forman and Wales, 1981; Yeates et al., 1984, figure 30; Bentley, 1984). The thickest section of the Wallal Sandstone, 308 m, was intersected in petroleum exploration well BMR04A Mandora. In petroleum exploration well Leo 1, the Wallal Sandstone is 224 m thick and is composed predominantly of poorly sorted, mostly unconsolidated sandstone, with minor interbeds of claystone and siltstone (Command Petroleum, 1989). Pyrite frequently replaces wood fragments. Lignite is common between depths of 417.57 and 527.3 m in petroleum well Willara Hill 1 (Reid, 1968).

The Upper Jurassic Alexander Formation is conformable on the Wallal Sandstone, and extends through the western part of the central and southern Canning Basin, except towards the Samphire Graben and Wallal Embayment, where it grades into and is overlain by the Jarlemai Siltstone (Yeates et al., 1984, figure 30). The formation is a mixed sandstone and mudstone sequence deposited in nearshore to tidal conditions (based in part on the presence of glauconite and fossil fragments). The 54 m-thick type section is one of a series of hills and mesas in the area around Mount Alexander on MOUNT ANDERSON to the north of MCLARTY HILLS (Command Petroleum, 1989).

The Upper Jurassic Jarlemai Siltstone is a coarsening-upward sequence up to 259 m thick that overlies the Alexander Formation or Wallal Sandstone, and consists mainly of claystone and siltstone with minor sandstone interbeds. Glauconite and pyrite are abundant in the claystone and minor pyrite was noted in the sandstone. A nodular phosphate bed is known from the base of the unit 40 km south-southwest of Derby (outside the Canning project area) together with phosphatic ironstone (Yeates et al., 1984). The formation was deposited in shallow-marine to intertidal environments, in the western part of the southern and central Canning Basin.

Lower Cretaceous units

The Jarlemai Siltstone is overlain by the Broome Sandstone in the western Canning Basin, the Callawa Formation in the southern Canning Basin, the Frezier Sandstone in the central southern Canning Basin, and the Mowla Sandstone in the central Canning Basin in the Edgar Ranges area on MOUNT ANDERSON.

The Broome Sandstone is a fluvial to coastal to nearshore succession in the western Canning Basin that appears to lie unconformably on the Jarlemai Siltstone. The maximum thickness noted by Towner and Gibson (1983) and Yeates et al. (1984) was 274 m, in Tappers Inlet 1. The petroleum well Leo 1 intersected a 217.6 m-thick section consisting of siltstone, claystone, and interbedded sandstone (Yeates et al., 1984; Middleton, 1990), and Willara Hill 1 intersected a 190 m-thick section of sandstone interbedded with claystone and argillaceous sandstone. The upper horizons of the Broome Sandstone contain heavy minerals (Towner and Gibson, 1983). Psilomelane (manganese oxide) was observed in the 9.14 m interval from 149.35 to 158.49 m in Willara Hill 1 (Reid, 1968). The Broome Sandstone is noted for its Lower Cretaceous plant fossils and, in the Broome area, dinosaur footprints (Playford et al., 1975; Gibson, 1983b).

The Callawa Formation is a probable correlative of the Broome Sandstone which is present along the southwestern margin of the Canning Basin. It consists of sandstone, conglomerate, and lesser siltstone in a succession possibly up to 80 m thick (Towner and Gibson, 1983), contains scattered plant fossils, and was deposited in a fluvial setting (Yeates et al., 1984).

The Cronin Sandstone is present in the Cronin Hills area on RUNTON (west of MORRIS) in the extreme southern Canning Basin, and based on lithology and stratigraphic setting, may correlate with or be equivalent to the Callawa Formation. Towner and Gibson (1983) suggested that the Anketell Formation might also be a correlative, although Yeates et al. (1984) showed the 'Anketell Sandstone' as younger than the Cronin Sandstone. Unequivocal stratigraphic relationships cannot be established for either correlation. Plant fossils suggest a Jurassic–Cretaceous age (Towner and Gibson, 1983).

The Samuel Formation, Frezier Sandstone, Parda Formation, and Melligo Sandstone appear to be facies variants from different areas of the central and southern Canning Basin. Stratigraphic relationships are commonly inferred rather than explicit, as the units are found as scattered poor exposures and there is minimal palaeontological control. The reader is referred to Towner and Gibson (1983) and Yeates et al. (1984) for further details.

In the extreme southern Canning Basin and Gunbarrel Basin, the Bejah Claystone overlies the Samuel Formation.

This unit marks a major transgression over much of Australia, with similar correlative units in the Southern and Northern Carnarvon Basin, the Eromanga Basin in central Australia, and the Darwin area in the Northern Territory. The units locally contain high proportions of radiolarians, and are prospective for opal where they have undergone diagenetic porcelanous silicification.

Igneous intrusions

Igneous intrusions of Late Carboniferous to Jurassic age have been intersected in exploration wells in the northwestern Canning Basin, both onshore and offshore (Gibson, 1983a; Reeckmann and Mebberson, 1984). An example is a dolerite that was intersected in Barlee 1 between 2385 and 2394 m (West Australian Petroleum Pty Ltd, 1961a). The offshore well Wamac 1 also intersected a dolerite sill up to 104 m thick. Seismic and magnetic data also suggest that such intrusions are widely distributed in the area. The intrusive mafic rocks range from tholeiitic basalt to dolerite. Maturation of hydrocarbons in adjacent sedimentary rocks has locally been increased as the result of the thermal effect of the intrusions (Reeckmann and Mebberson, 1984).

Stratigraphy of tectonic units outside the Canning Basin

Aspects of the geology of the Officer Basin have been described in Jackson and van de Graaff (1981), Phillips et al. (1985), Townson (1985), and Iasky (1990). More recent reviews are provided by Stevens and Grey (1997), Perincek (1998), Ghori (1998), Apak and Moors (2000, 2001), Moors and Apak (2002), and the stratigraphy was comprehensively updated and synthesized by Grey et al. (in press). At least 6 km of Neoproterozoic and Cambrian sedimentary rocks, including interbedded stromatolitic dolomite, sandstone, chert, mudstone, and thin evaporite, occurs in the basin (Stevens and Grey, 1997; Grey et al., in press). Evaporites of the Browne Formation outcrop in the cores of the Woolnough Hills Diapir and at the Madley Diapirs (Wells, 1980; Jackson and van de Graaff, 1981; Moors and Apak, 2002; Grey et al., in press).

The Amadeus Basin lies predominantly in the Northern Territory, with an extension into Western Australia between the Musgrave and Arunta Complexes. The basin contains a similar Neoproterozoic succession to that in the Officer Basin. An overlying Palaeozoic succession has been left in the Amadeus Basin, rather than being excised and placed in a separate basin as with the Gunbarrel Basin in Western Australia (Korsch and Kennard, 1991; Lindsay and Korsch, 1991). A small inlier of the basin, the Clutterbuck Inlier, is present at the southeastern edge of the Canning area.

The Gunbarrel Basin was defined by Hocking (1994) to include the Palaeozoic and Mesozoic succession (with the Upper Cambrian Table Hill Volcanics as the basal unit). These rocks were previously included in the Officer Basin. The Table Hill Volcanics are absent in most of the Gibson area (Perincek, 1998; Moors and Apak, 2002) and are not included in the discussion here. Upper Carboniferous – Lower Permian Paterson Formation, and the Cretaceous Samuel Formation, Bejah Claystone, and Palaeogene Lampe Formation are present in the study area.

Browne Formation (Neoproterozoic)

The Browne Formation (Moors and Apak, 2002) forms the core of the Woolnough Hills Diapir on WARRI (Veevers and Wells, 1961; Wilson, 1967; Jackson and van de Graaff, 1981; Moors and Apak, 2002) where it is exposed as powdery gypsum with highly contorted bands and shearing. In the Madley Diapirs, just outside the study area, the Browne Formation is composed of red shale and siltstone, interbedded with stromatolitic dolomite, halite, minor anhydrite, and sandstone. The Browne Formation was deposited under shallow marine to sabkha conditions (Moors and Apak, 2002) in an arid climatic phase.

Clutterbuck Formation

The Clutterbuck Formation (Clutterbuck Beds of Lowry et al., 1972, amended by Cockbain and Hocking, 1989) is a sandstone succession, over 4500 m thick, found in the Clutterbuck Hills on COBB and easternmost WARRI, in the Clutterbuck Inlier. The inlier is fault bounded and moderately to steeply dipping (Jackson and van de Graaff, 1981), suggesting that the thickness of the sandstone succession may be related to syndepositional faulting and creation of accommodation. The age of the Clutterbuck Formation is uncertain. Grey (1990) tentatively correlated the formation with the Maurice Formation and Sir Frederick Conglomerate of the western Amadeus Basin. These are of latest Proterozoic age, and are synorogenic with the Paterson and Petermann Ranges Orogenies. The thickness and steep dip of the Clutterbuck Formation support this correlation.

Paterson Formation (Upper Carboniferous to Lower Permian)

The Paterson Formation is present throughout the Gunbarrel Basin and southern Canning Basin, and consists of diamictite, grey to red sandstone, claystone, and siltstone formed in fluvioglacial, glaciolacustrine and fluvial environments. It unconformably overlies older units, and correlates with the Grant Group of the central and northern Canning Basin. Much of the Paterson Formation, both outcropping and where intersected by scattered drillholes, appears to be Late Carboniferous in age rather than Early Permian (Haines et al., in press).

Samuel Formation (Cretaceous)

The Samuel Formation (Lowry et al., 1972; Jackson and van de Graaff, 1981) consists of interbedded marine sandstone and claystone. The sandstone is laminated to thinly bedded, moderately well sorted, moderately rounded, and indistinctly cross-bedded. Bioturbation and trace fossils are common. Glauconite-rich sandstone units are widespread in the Samuel Formation (van de Graaff, 1974; Gorter et al., 1979).

Bejah Claystone (Cretaceous)

The Bejah Claystone (Veevers and Wells, 1961; Lowry et al., 1972; Jackson and van de Graaff, 1981) is a white siliceous claystone and siltstone with a few intercalations of very fine grained sandstone on WARRI and MORRIS. It conformably overlies the Samuel Formation and disconformably overlies the Paterson Formation. Its upper limit on WARRI and MORRIS (in the southern part of the study area) is erosional (Jackson and van de Graaff, 1981). Bedding in the unit is indistinct, and the rocks are soft, friable, and light-weight due to their high radiolarian content. The rocks can be hard in localities where silicification has occurred. The Bejah Claystone has been dated by molluscan fauna as Aptian (Early Cretaceous) and has potential for radiolarite, porcellanite or local opal (Veevers and Wells, 1961).

Lampe Formation (?Palaeogene)

The Lampe Formation (defined as Lampe Beds, amended but not defined by Cockbain and Hocking, 1989) unconformably overlies the Bejah Claystone (Lowry et al., 1972; Jackson and van de Graaff, 1981). The formation is preserved as thin remnants of an originally widespread fluvial conglomerate on WARRI and MORRIS (Crowe, 1979; van de Graaff, 1974; Jackson and van de Graaff, 1981). It occurs on the divides of palaeodrainage systems that have been largely inactive since the Miocene or, locally, Late Eocene (van de Graaff et al., 1977), but was only mapped where the underlying bedrock is fine grained, rather than coarse grained. If the latter, as with the conglomeratic Paterson Formation, surficial coarse-grained material could be a residual weathering lag, rather than a fluvial deposit (Jackson and van de Graaff, 1981). Intense lateritization of the conglomerate suggests that it is pre-Miocene, and its preservation on Upper Eocene interfluves suggests that it is mid-Eocene or older. Marine and marginal marine siliciclastic deposits of Early to Middle Eocene age are widespread elsewhere in the onshore Eucla Basin (including the former Bremer Basin; Hocking, 1990; Clarke et al., 2003), which led van de Graaff et al. (1977) and Jackson and van de Graaff (1981) to infer an Eocene or Paleocene age for the Lampe Formation.

The Lake George Formation is a similar unit to the Lampe Formation that has been mapped further north in the central and southern Canning Basin (Towner and Gibson, 1983). The unit forms cappings on mesas in drainage interfluves. Towner and Gibson considered it to be partly of pedogenic origin. The Lake George Formation, by comparison with the Lampe Formation, is also probably Early Eocene or Paleocene in age.

Regolith

Regolith materials cover most of the area, and developed in the Cainozoic and possibly late Mesozoic as the products of weathering, mass wasting, erosion, and transport. Most regolith components are identified by the environment of formation, such as lacustrine, but some distinctive units have been given stratigraphic names. These include the Lawford, Bossut, Lampe, and Lake George Formations. The Lampe and Lake George Formations could also be in part a residual regolith unit. On the accompanying extract of the 1:500 000 State regolith digital dataset, the regolith is divided into eolian, coastal, lacustrine, residual, depositional, and exposed (older outcrop). The following sections discuss regolith in the context of the process-oriented scheme developed by GSWA (Hocking et al., 2001).

The Canning area was subjected to erosion for a prolonged period throughout the Cainozoic, alternating with periods of activity in state-wide drainage systems currently preserved as inactive palaeodrainage remnants (van de Graaff et al., 1977), and eolian reworking and deposition of surficial sands. Deep weathering has produced siliceous or ferruginous duricrust that may be up to 15 m thick, and locally up to 60 m thick (Veevers and Wells, 1961), with leached pallid zones extending to greater depths.

Palaeodrainage systems on SAHARA, PERCIVAL, URAL, and MORRIS (Towner et al., 1976; van de Graaff et al., 1977; Hocking and Cockbain, 1990) are preserved as scattered salt lakes either cutting through well-developed lateritic profiles or infilling the lower parts of undulating laterite surfaces. Most of the salt lake beds contain precipitated gypsum (Jones, 1993). Calcrete formed along some drainage channels. Sand dunes at the coast often contain heavy minerals.

Siliceous and ferruginous duricrust (R) — residual

Cappings of pisolitic or massive duricrust (ferricrete or laterite) and silcrete developed over pre-existing rocks during periods of humid climate conditions. Ferruginous duricrust is well developed over fine-grained clastic rocks (Towner, 1982a), whereas siliceous duricrust locally shows preferential development over sandy substrate (van de Graaff, 1983). Well-developed duricrust profiles occur on MORRIS (Veevers and Wells, 1961) and on SAHARA (Yeates and Towner, 1978) over horizontal clayey Cretaceous–?Palaeogene rocks (Bejah Claystone and Lampe Formation), over the Jarlemai Siltstone on MCLARTY HILLS (Gibson, 1982), the Parda Formation on MUNRO (Towner, 1982d), over the Broome Sandstone on BROOME (Gibson, 1983b), and over the Anketell Formation on URAL (Towner, 1978). Some of these duricrusts are iron-rich and were noted as having potential as low-grade pisolitic iron ores by Veevers and Wells (1961).

Calcrete (A) — residual

Pedogenic and fluviolacustrine deposits of calcrete are present on CROSSLAND (Towner, 1977), MCLARTY HILLS (Gibson, 1982), and SAHARA (Yeates and Towner, 1978). On WARRI, 30 m of calcrete has been recorded at 24°09'05"S, 124°38'30"E (van de Graaff, 1974). Calcrete in general developed by precipitation in pre-existing sediments in more arid conditions than silcrete or laterite, probably in the Late Miocene to Pliocene or Early Pleistocene (Hocking et al., 2001).

Dune sand (E) — transported/deposited

Most of the Canning area is covered by a veneer of eolian sand, arranged into longitudinal dune fields, except in the southern part (MORRIS and WARRI). Veevers and Wells (1961) identified five types of dunes and recorded a maximum height of 36 m. Crowe (1975) simplified the earlier classification to simple and chain longitudinal dunes and net dunes, and suggested the dune form was related to the abundance of sand in a particular area. The dunes show prevailing west-northwesterly trends. Compositionally the sand is composed of quartz, small amounts of feldspar, and locally heavy minerals. Well-rounded zircons and tourmalines have been noted in the sand (Veevers and Wells, 1961). The dunefields are presently relict, and were last active between about 16 000 and 23 000 yrs b.p. (Hocking et al., 2001).

Dune buildups are present along the coastal strip. These are of Pleistocene and Holocene age, and are in part calcareous. Older coastal dunes have been named as the Bossut Formation.

Lacustrine (L) — depositional

Strings of saline lakes, locally containing significant lacustrine deposits, formed in palaeodrainage systems across the Canning area, following cessation of regular flow in the drainages in the Late Eocene to Miocene (van de Graaff et al., 1977; Yeates, 1978; Hocking and Cockbain, 1990; Hocking et al., 2001). Drainages were both internal and external, with the largest internal basin draining into Lake Disappointment, immediately southwest of the current study area.

The lacustrine deposits typically contain gypsum, halite, and anhydrite (Jones, 1993).

Lawford Formation (?Neogene)

The Lawford Formation is a massive muddy limestone unit, locally chalcedonic, that developed under lacustrine conditions (Forman and Wales, 1981; Towner and Gibson, 1983). Outcrops of the Lawford Formation are present at Salmon Bore at Kirkby Range on CROSSLAND, as well as on MOUNT BANNERMAN immediately to the northeast of the study area. The unit is about 29 m thick at this location, where it unconformably overlies the Lightjack Formation (Towner, 1977). The formation contains no age-diagnostic fossils, but is probably of late Neogene age based on its stratigraphic and physiographic position.

Bossut Formation (Neogene)

The Bossut Formation is a unit of sandy calcarenite, oolite, and calcilutite, which outcrops discontinuously along the coastal strip from the Pilbara to the Broome area. The formation is largely an eolian deposit, of Pleistocene age, with some shoreline, nearshore, and coastal lacustrine facies. It correlates with the Tamala Limestone of the west coast of Western Australia. The 'Chimney rock oolite' of Brunnschweiler (1952) at Emeriau Point in the western Dampier Peninsula was considered part of the Bossut Formation (Gibson, 1983a,b,c). The limestone of the Bossut Formation is quarried south of Willies Creek and is a potential future resource (Towner, 1977; Gozzard, 1988).

Mineralization

Petroleum and natural gas have not been considered as commodities in this report, although parts of the Canning area have reasonable prospectivity for hydrocarbons (D'Ercole et al., 2003). The distribution of 113 mineral occurrences identified within the Canning area is shown on Figure 5. Except for two occurrences in the Gibson area, all of the occurrences are located in the Canning Basin. They have been assigned to the following commodity groups: base metal (22 occurrences), energy (22 occurrences), industrial minerals (43 occurrences), precious metal (2 occurrences), speciality metal (11 occurrences), and construction material (13 occurrences); and on the basis of mineralization style: stratabound sedimentary, carbonate- or clastic-hosted groups (39 occurrences), sedimentary basin (22 occurrences), regolith (alluvial or beach placers: 25 occurrences), regolith (lacustrine: 5 occurrences), and vein and hydrothermal (2 occurrences). Mineral commodities are: zinc–lead–copper, halite, gold, coal, carnallite, alunite, gypsum, heavy mineral sands, and barite. Apart from the near-suface regolith commodities of gypsum, alunite, and mineral sands, all of the other mineral commodities in the study area are subsurface intersections in exploration drillholes.

Canning Basin

Base metals

Significant Mississippi Valley-type zinc–lead–silver mineralization occurs in the Admiral Bay Fault Zone in the Llanvirnian (Middle Ordovician) rocks at depths between 1200 and 1600 m in the Willara Sub-basin. The mineralization was located by CRAE during extensive exploration from 1986 to 1991. Deep drilling showed that the higher grade mineralization extended along strike for more than 16 km and that the mineralized zone was about 200–300 m wide. The deposit consists of four mineralized zones in ascending order: an extensively altered and fractured microbial biohermal zone, a lower lead-rich zone, a hydrothermal dolomite, and an upper zinc-rich zone. The mineralization is epigenetic, and is hosted in Middle and Upper Ordovician carbonate and siliciclastic rocks in the Goldwyer and Nita Formations, and in the lower Carribuddy Group (Connor, 1990; McCracken, 1994; McCracken et al., 1996; McCracken, 1998; Williams, 1999; Haines, 2004). At Admiral Bay there is an estimated inferred resource of 120 Mt at 6.4% Zn, 2.3% Pb, and 32 g/t Ag for the zinc-rich upper zone, and 20 Mt at 16.9% Pb, 0.4% Zn, and 57 g/t Ag for the lead-rich zone (McCracken et al., 1996). The combined inferred resource

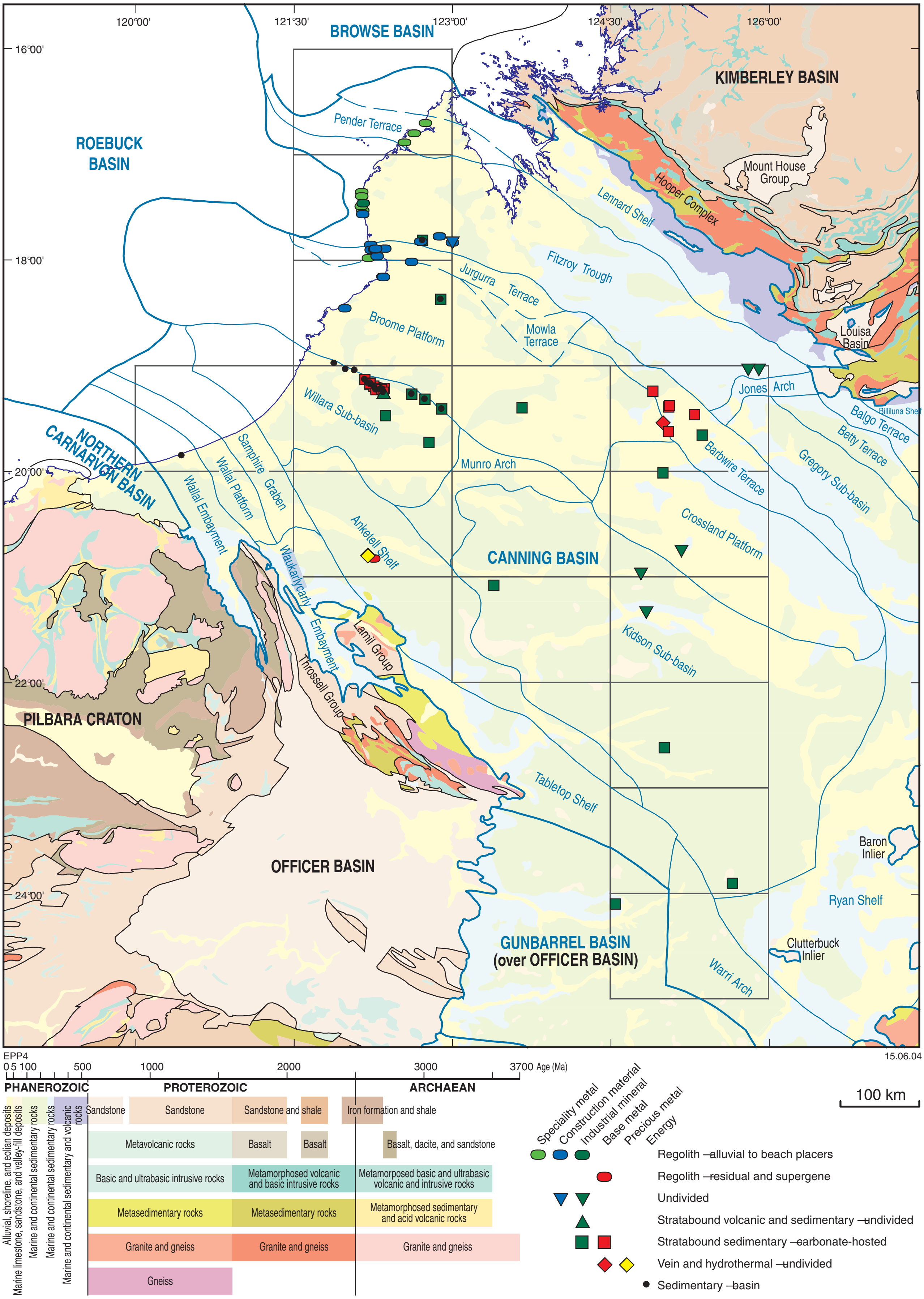


Figure 5. Mineralization and geology of the Canning area

based on the above figures is calculated at 140 Mt with 5.63% Zn, 4.39% Pb, and 35.57 g/t Ag.

Mineralization at Admiral Bay is shown in Appendix 1 as 12 sites (***9778***, ***9880***, ***9886***, ***9941***, ***9910***, ***9911***, ***9915***, ***9916***, ***9948***, ***10708***, ***10711***, ***10721***) that are the main drillhole intersections of zinc–lead–silver. The distribution of high-grade mineralization is at three centres along the Admiral Bay Fault Zone. The best intersection of 15.5 m at site ***9910*** was from drillhole DD89SS14*, between the depths of 1471 and 1486.5 m, with 17.3% Pb, 0.06% Zn, and 63 g/t Ag. Some of the CRAE drillholes intersected a chalcopyrite-rich zone below the lead–zinc zone: for example the 1 m interval from 1477 to 1478 m assayed at 5.8% Cu in DD86SS2* (site ***9886***). Typical ore minerals at Admiral Bay are sphalerite, galena, and chalcopyrite; gangue minerals are dolomite, calcite, barite, and fluorite. Liquid hydrocarbons and bituminous material were observed in the mineralized sections and barite, fluorite, and hydrocarbons are closely associated with the zinc–lead mineralization (Marinelli and Harvey, 1987; McCracken et al., 1996). Hydrocarbons are identified in fluid inclusions in crystalline and colloform sphalerite, calcite, and barite (McCracken, 1998). McCracken et al. (1996) proposed that the Mississippi Valley-type mineralization was sourced from fluids that were expelled from the Willara Sub-basin and reacted with carbonates and sulfates of the Goldwyer, Nita, and Bongabinni Formations.

Similar mineralization occurs along the Abutilon Fault Zone of the Barbwire Terrace, but exploration to date has located only low-grade and rather scattered base metal zones. Between 1981 and 1992, WAPET, Shell, BHP, Western Mining Corporation, CRAE, and PASMINCO conducted exploration on the Barbwire Terrace for petroleum, potash, and zinc–lead minerals. Their work identified extensive dolomitization on the terrace. In 1992, PASMINCO reinterpreted airborne magnetometric and seismic data, gravity surveys, core logs, mobile metal ion (MMI) soil sampling, and diamond drilling. The best mineralized interception of 212 m was obtained in diamond drillhole BW8, between 250 and 462 m. This contained 0.1% Zn and 0.03% Pb, which was uneconomic and not extensive. The mineralization is hosted in dolomite of the Devonian Mellinjerie Formation. PASMINCO demonstrated that mobile metal ion (MMI) soil sampling can still be an effective technique for detecting deeply buried mineralization (Roberts, 1993,a,b).

Gold

Exploration conducted by BHP from 1991 to 1998 led to the discovery of copper–gold mineralization in basement rocks below the Anketell Shelf. Initial exploration included airborne magnetic, ground magnetic, electromagnetic, and gravity surveys; partial leach soil sampling; and percussion, RAB, and diamond drilling. Initial drilling intersected elevated gold values in basement rocks below deep Permian cover, associated with disseminated sulfides (galena, pyrrhotite, chalcopyrite, and rare arsenopyrite) in alteration zones containing chlorite, carbonate, and quartz (Taylor, 1999a,b). Further geophysical surveys and drilling delineated a zone of gold–copper mineralization known as the Magnum prospect, where a 475 m-deep drillhole to test EM anomaly GAN01 intersected gold and copper within a 200 m-thick dolerite sill (Sandl, 1995). Diamond drillhole AKD09 on the prospect reported an impressive grade of 14.07 g/t Au over 14 m at a depth of 420 m (site ***10605***). In 2001 Gindalbie Gold acquired the prospect (formerly held as a JV project with BHP Minerals and Croesus Mining NL). Teck Cominco is currently earning a 50% interest and is carrying out further drilling to test EM targets in sedimentary sequences that may host 'Telfer-style' gold–copper deposits. A further five diamond drillholes were planned in June 2003 to test a new target area represented by a broad electromagnetic anomaly (generated from reinterpretation of previous BHP data) that is coincident with an anomaly identified in aeromagnetic surveys that were recently conducted by Teck Cominco†.

Halite

The Upper Ordovician Mallowa Salt of the Canning Basin is the largest known halite deposit in Australia (Cathro et al., 1992). Petroleum exploration well Brooke 1 intersected the thickest known section (735 m) of halite. The northern boundary of the Mallowa Salt was defined by Shell Australia (D'Ercole et al., 2003). In the Canning area, 14 of the most significant intersections have been recorded as occurrences (at sites ***9828–29*** , ***10033***, ***10035–36***, ***10066***, ***10606***, ***10629–30*** , ***10730***, ***10739***, ***13549***, ***13551–54***). The Mallowa Salt has a high bromine content (Glover, 1973) and a high potassium content (BHP Minerals Ltd, 1987, 1989).

Possible salt diapirs identified by Craig et al. (1984) are shown on Figure 3.

Potash

BHP examined the Mallowa Salt from Gingerah Hill 1 and Brooke 1 drillcores (sites ***9828*** and ***9829***). Using AAS and XRF assay methods, values of up to 1.6% K_2O (equivalent to 10% carnallite) were recorded. One sample (interval 1872–1874 m) from Brooke 1 contained 2.55% K_2O (BHP Minerals Ltd, 1987, 1989). Two further drillholes located nearby did not intersect potash mineralization.

Heavy mineral sands

Beach placers on BROOME and PENDER contain ilmenite, rutile, and zircon concentrations (Brunnschweiler, 1952; Metals Investment Pty Ltd, 1969; Baxter, 1977), possibly derived from the Broome and Melligo Sandstones (Gibson, 1983a,b). At some localities, the concentrations reach a maximum of 16.5% total heavy minerals, with ilmenite as the main component (at sites ***10608–09*** , ***10632***, ***10636–38***).

Limestone

Limestone from the Bossut Formation south of Willies Creek (site ***11751***) is quarried for local consumption and

* Available for viewing at the GSWA Drillcore Library, Perth

† Gindalbie Gold website, 2003

there is potential for further development (Towner, 1977; Gozzard, 1988). Calcrete areas are also potential sources of calcium carbonate or calcium bicarbonate.

Phosphate

The Upper Jurassic Jarlemai Siltstone is a potential host for phosphate mineralization, as noted by Freas and Zimmerman (1965) from Barlee 1 cuttings (site ***10612***). They noted a 12.1 m interval that assayed 4.7% P_2O_5 with 30% Fe_2O_3, and stressed a strong association of phosphate with iron. Another occurrence (site ***10672***) is a 15.2 m interval from Thangoo 1 between the depths of 137.2 and 152.4 m, with 4.3% P_2O_5 (West Australian Petroleum Pty Ltd, 1961b; Freas and Zimmerman, 1965; Gibson, 1983b).

Coal

All the coal occurrences are hosted within the Middle Jurassic Wallal Sandstone at depths between 151 and 600 m. The maximum thicknesses of individual seams may not be more than 2.5 m, but multiple seams are present. Because they have been considered to have little economic potential as sources for coal production, most lithological logs do not describe the coal seams in much detail. Nevertheless, they could still be considered to have potential as raw material for coal gas production. For example, Willara Hill 1 intersected an interval of sandstone between 417.57 and 527.3 m with numerous layers of lignite (Reid, 1968).

Anhydrite

Crossland 2 intersected sandstone with thin beds of anhydrite between 9.1 and 143.8 m. Core from the Woolnough Hills Diapir (site ***10630***) contains an anhydrite cap above the halite, as was observed in the BMR Warri 20 and Dragoon 1 drillcores.

Pisolitic laterite (iron)

Towner (1982a,b) observed abundant pisolitic iron-rich laterite on ANKETELL and JOANNA SPRING where it occurs as mesa cappings.

Manganese

Minor manganese mineralization (psilomelane), occurring as cement in the Broome Sandstone, was observed during drilling of the interval 149.35 to 158.49 m (9.15 m) in Willara Hill 1 (Reid, 1968).

Barite

Barite aggregates were noted between 1620 and 1653 m within dolomitic claystone with halite veins, in the upper part of the Nita Formation in mineralized sections of the Admiral Bay Fault Zone. For example, DD90SS20 contained two intersections of barite: over 29.5 m in the interval 1395.5 – 1425 m, with 15.3% Ba, and over 33 m in the interval 1433–1466 m with 16.1% Ba (site ***9948***).

Chalcedony and opal

Chalcedony or opalite occurs locally within calcrete (Towner, 1977, table 1) and within the Lawford Formation and Bejah Claystone. One occurrence of chalcedony (at site ***11770***) was located on CROSSLAND near the Fenton Fault within the Lawford Formation (Towner, 1977). Units correlative with the Bejah Claystone are considered prospective for precious opal in eastern Australia.

Alunite

One occurrence of alunite in the Bejah Claystone on MORRIS (site ***10746***) has been identified (Veevers and Wells, 1961). Outside the Canning area, in BMR Browne 1, alunite was noted within the Bejah Claystone (Jackson and van de Graaff, 1981).

Silica deposits

Radiolarite and porcellanite occur in the Bejah Claystone (Veevers and Wells, 1961; Jackson and van de Graaff, 1981). Just outside the Canning area, BMR Browne 1 intersected 13 m of porcellanized Bejah Claystone (Jackson and van de Graaff, 1981).

Kaolin

Three areas of kaolinitic sands near Thangoo Homestead, on the southern side of Roebuck Bay, have been identified as a possible source for kaolin following a program of drill sampling and laboratory testing during the mid-1990s. The kaolinitic material is interpreted to be within an old river channel that crosses a zone of dune sands (Mansfield, 1996).

Gibson area

Halite and anhydrite

The Woolnough Hills Diapir on WARRI contains halite and anhydrite (at site ***10630***). BMR drillhole Warri 20, located about 1 km away from the core and on the northwestern flank of the diapir, intersected halite from 206.65 m to the end of the hole at 265.48 m (Wells and Kennewell, 1974). A later drillhole, Dragoon 1, intersected several intervals of halite including thicknesses of 274 m from 692 to 966 m; 208 m from 1108 to 1316 m; 63 m from 1888 to 1951 m; and 7 m from 1969 to 1976 m (Eagle Corporation Ltd, 1983).

Conclusions

The Canning area remains largely unexplored or underexplored for minerals. The most significant mineralization is the zinc–lead–silver mineralization in the Admiral Bay Fault Zone and Barbwire Terrace, halite deposits in the Mallowa Salt, and vein gold in basement rocks underneath the Anketell Shelf. Other potentially exploitable commodities include heavy mineral sands in beach placers, gypsum in lacustrine sediments, and coal (mainly in the Wallal Sandstone).

There is potential for further discoveries of zinc–lead–silver at the Admiral Bay Fault Zone and on the Barbwire Terrace, and of Telfer-style gold in basement rocks below the Anketell Shelf.

In the south of the study area, the sedimentary sequences in the Gunbarrel and Officer Basins may also have base metal potential, but there has been very little exploration. There is potential for further diamond exploration on WARRI, where drilling of aeromagnetic targets has so far produced inconclusive results. There may be potential for nickel, chromium, and platinum group elements in postulated layered mafic intrusions that may form basement rocks beneath the Warri Arch.

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Appendix 1

List of mineral occurrences in the Canning area

Number	*Commodity*	*Easting*	*Northing*	*Status*	*Deposit name*
PRECIOUS METAL					
Vein and hydrothermal — undivided					
10605	Au Cu	416383	7701039	MIDE	Magnum
10726	Cu Au V	416436	7700461	OCCU	Anketell 1
SPECIALITY METAL					
Stratabound sedimentary — clastic-hosted					
16960	HM	567452	7726290	OCCU	Joanna Spring HM
Regolith — alluvial to beach placers					
10607	ILM Rt Zrn HM	410115	8069819	OCCU	James Price Point N
10608	HM	409347	8061861	OCCU	Cape Boileau
10609	HM	430347	7992697	OCCU	Broome
10632	HM	473192	8153552	OCCU	Pender Bay North
10633	HM	461803	8142824	OCCU	Pender Bay West
10634	Ilm	452050	8133220	OCCU	Beagle Bay
10635	HM	413092	8012328	OCCU	Gantheaume Point
10636	HM	408763	8066132	OCCU	James Price Point S
10637	HM	409144	8081072	OCCU	Coulomb Point N
10638	HM	409140	8076657	OCCU	Coulomb Point S
BASE METAL					
Stratabound sedimentary — carbonate-hosted					
9778	Pb Ag Zn	417747	7880576	MIDE	Admiral Bay 28
9880	Pb Zn Ag	425044	7875849	OCCU	Admiral Bay 2
9886	Pb Zn Cu Ag	428870	7874600	OCCU	Admiral Bay 9
9910	Pb Zn Ag	428702	7874443	MIDE	Admiral Bay 1
9911	Pb Zn Ag	428339	7874780	OCCU	Admiral Bay 3
9915	Pb Zn Ag	429508	7874508	OCCU	Admiral Bay 4
9916	Pb Zn Ag	430355	7874875	OCCU	Admiral Bay 20
9941	Zn Pb	412843	7884980	OCCU	Admiral Bay 10
9948	Pb Zn Ag Brt	417859	7880761	OCCU	Admiral Bay 6
9983	Pb Zn	715260	7855160	OCCU	Crossland 3
9984	Pb Zn	715985	7856560	OCCU	Crossland 4
10060	Zn Pb	740853	7846778	OCCU	Abutilon 1
10063	Zn Pb	699614	7871814	OCCU	Crossland 1
10071	Zn	714630	7829360	OCCU	Crossland 2
10704	Zn Ag Pb	428330	7874863	OCCU	Cudalgarra 1
10705	Pb Zn Ag	423636	7876460	OCCU	Cudalgarra 2
10706	Zn Pb	432237	7875660	OCCU	Great Sandy 1
10708	Zn Pb Ag	421784	7878073	OCCU	Admiral Bay 13
10711	Zn Ag	428911	7875192	OCCU	Admiral Bay 18
10721	Pb Zn Ag	418178	7881193	OCCU	Admiral Bay 7
10735	Zn Pb Brt	431215	7871690	OCCU	Leo 1
10738	Zn	709136	7838861	OCCU	Kunzea 1
ENERGY					
Sedimentary — basin					
10674	Coal	488458	7969212	OCCU	Thangoo 1
10676	Coal	393762	7895516	OCCU	Admiral Bay 16
10677	Coal	415577	7881458	OCCU	Admiral Bay 8
10680	Coal	428873	7874603	OCCU	Admiral Bay 24
10695	Coal	489404	7854326	OCCU	Admiral Bay 34
10700	Coal	412843	7884980	OCCU	Admiral Bay 5
10701	Coal	417859	7880761	OCCU	Admiral Bay 11
10702	Coal	417626	7880422	OCCU	Admiral Bay 12
10707	Coal	421790	7878080	OCCU	Admiral Bay 14
10709	Coal	472736	7864573	OCCU	Admiral Bay 33
10710	Coal	428921	7875182	OCCU	Admiral Bay 17
10712	Coal	459645	7869830	OCCU	Admiral Bay 31
10713	Coal	382203	7901748	OCCU	Admiral Bay 29
10714	Coal	429500	7874500	OCCU	Admiral Bay 26
10715	Coal	428342	7874783	OCCU	Admiral Bay 21
10716	Coal	423872	7874424	OCCU	Admiral Bay 27
10719	Coal	430340	7874860	OCCU	Admiral Bay 19
10720	Coal	418178	7881193	OCCU	Admiral Bay 16
10723	Coal	402713	7894551	OCCU	Admiral Bay 25
10740	Coal	431210	7871685	OCCU	Leo 1A
10741	Coal	470110	8031150	OCCU	Barlee 1A
10742	Coal	231602	7803397	OCCU	Chirup 1

Appendix 1 (continued)

Number	*Commodity*	*Easting*	*Northing*	*Status*	*Deposit name*
INDUSTRIAL MINERAL					
Stratabound sedimentary — carbonate-hosted					
11343	Anh	708667	7786047	OCCU	WAPET Crossland 2
11747	Lsd	432597	8011808	OCCU	Crab Creek
11751	Lst	416800	8034000	AMOP	Willies Creek
13081	Lst	451012	8138364	OCCU	North Head Limestone
Stratabound sedimentary — clastic-hosted					
11748	Lsd	415900	8009750	OCCU	Beacon Hill
11749	Lsd	416000	8010500	OCCU	Beacon Hill N
11750	Lsd	414650	8010000	OCCU	Red Hill
11752	Gvl	416800	8025500	OCCU	Cape Latreille
11753	Sd	416800	8027000	OCCU	Cape Latreille South
11755	Sd	427323	8035458	OCCU	Broome Sand 2
11756	Sd	424027	8031306	OCCU	Broome Sand 1
11757	Gvl	441636	8025474	OCCU	Broome Gravel
11764	Sd	477202	8032298	OCCU	Broome Lake Campion
11767	Gvl	426271	8012710	OCCU	Roebuck Bay Gravel
11768	Lsd	416790	8017286	OCCU	Broome West Sand
11769	Sd	418982	8012755	OCCU	Broome South Sand
Stratabound sedimentary — undivided					
10035	Salt Brt	472730	7864580	OCCU	Admiral Bay 32
10036	Salt	489400	7854340	OCCU	Admiral Bay 35
10066	Salt	748130	7825160	OCCU	Mirbelia1
10612	Phos	470110	8031145	OCCU	Barlee 1
10629	Salt	540821	7669346	OCCU	Sahara 1
10630	Salt Gp	658431	7335462	OCCU	Woolnough Hills Diapir
10672	Phos	488475	7969200	OCCU	Thangoo 1A
10730	Salt	706333	7497677	OCCU	Kidson No 1
10739	Salt	431220	7197680	OCCU	Leo 1B
13549	Salt	508423	7860059	OCCU	Carina 1 Halite
13551	Salt	657141	7846995	OCCU	Fruitcake 1 Halite
13552	Salt	604577	7885191	OCCU	Looma 1 Halite
13553	Salt	495473	7861842	OCCU	Musca 1 Halite
13554	Salt	488944	7853740	OCCU	Vela 1 Halite
9828	Salt K	433579	7847167	OCCU	Gingerah Hill 1
9829	Cnl Salt	476830	7819160	OCCU	Brooke 1
Sedimentary — undivided					
10746	Alu	770138	7354160	OCCU	Morris Alunite
11770	Clc	727636	7879161	OCCU	Salmon Bore Chalcedony
Regolith — alluvial to beach placers					
11762	Gvl	485243	8020624	OCCU	Broome East Gravel
2577	Kln	425200	7988600	OCCU	Roebuck Bay
Regolith — lacustrine					
3853	Gp	686637	7679190	OCCU	Gwenneth Lakes
3865	Gp	670187	7630360	OCCU	Percival Lakes
3866	Gp	725187	7630360	OCCU	Prescott Lakes
3869	Gp	806737	7892560	OCCU	Nicholson Swamp
3870	Gp	794870	7893280	OCCU	Nicholson Swamp West
CONSTRUCTION MATERIAL					
Regolith — alluvial to beach placers					
10137	Gvl	417914	8026210	OCCU	Coconut Wells — Broome
10138	Sd	418456	8021017	OPMI	Waterbank Station
10139	Sd	424338	8014372	OPMI	Fishermans Bend
10140	Sd	422015	8021493	OPMI	Duncan Bore — Broome
10141	Sd	432076	8022298	OPMI	Broome Road South (Brown)
10144	Sd	422777	8022233	OPMI	Water Reserve Broome
10145	Sd	409713	8058413	OCCU	Broome North Sand
10146	Sd	468111	8029883	OPMI	Roebuck Plains N
10147	Sd	458676	8008510	OCCU	Roebuck Plains S
10149	Sd	499888	8028835	OCCU	Roebuck Plains East
10150	Sd	486826	8035258	MIDE	Taylors Lagoon
10151	Sd	430738	7992481	AMOP	Broome Thangoo
10152	Sd	392370	7959660	OPMI	Cape Gourdon

Appendix 2

WAMIN and EXACT databases

WAMIN database (mineral occurrences)

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

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

Those elements of the database that were used to create the symbols for mineral occurrences and tabular information displayed on Figure 5 and in Appendix 1 of this record are:

- occurrence number and name (deposit number and name)
- operating status (font style of deposit number
- position and spatial accuracy (symbol position)
- commodity group (symbol colour)
- mineralization style (symbol shape)

The elements of the database used for symbology in Figure 5 and Appendix 1 are operating status, commodity group, and mineralization style. These parameters have previously been defined for the GSWA mineralization mapping projects that have been completed for prospectivity enhancement studies of southwest Western Australia (Hassan, 1998), the north Eastern Goldfields (Ferguson, 1998), the Bangemall Basin (Cooper et al., 1998), the west Pilbara (Ruddock, 1999), the east Kimberley (Hassan, 2000), the east Pilbara (Ferguson and Ruddock, 2001), the Arunta–Musgrave (Abeysinghe, 2003), and the west Kimberley (Hassan, 2004).

Operating status

The database includes mineralization sites (referred to as deposits) ranging from small, but mineralogically significant, mineral occurrences up to operating mines. The classification includes all MINEDEX sites with established resources. MINEDEX is the Department of Industry and Resources (DoIR) mines and mineral deposits information database (Townsend et al., 1996, 2000; Cooper et al., 2003). All occurrences in the WAMIN database are assigned a unique, system-generated number (deposit number). The system used to describe the operating status is:

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

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

Commodity group

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

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

Mineralization style

There are a number of detailed schemes for classifying mineral occurrences into groups representing different styles of mineralization, with the scheme of Cox and Singer (1986) probably being the most widely used. The application of this scheme in Western Australia would

Table 2.1. WAMIN authority table for commodity groups

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

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).

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

Mineral occurrence determination limits

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

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

EXACT database (exploration activities)

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

In the current WAMEX database, when spatial parameters are used to make data searches, the results of searches are constrained to very large areas. The smallest search polygon that can be effectively used to locate reports in WAMEX is the area of a 1:100 000-scale sheet. Even though a query may be entered as a single point (latitude/longitude coordinates), the resulting search will produce all reports for the 1:100 000-scale sheet in which that single point is located. Hence, for example, it is not possible to restrict report selection to small areas of

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

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

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

Table 2.3. WAMIN authority table for mineralization styles and groups

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

prospective ground of particular interest to the user. As a consequence these WAMEX searches are time consuming, and they have become more time consuming as the number of open-file reports has increased with continuing releases of data.

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

The spatial index consists of an attribute database, developed in Microsoft Access, that is linked to ArcView for spatial representation. On the CD-ROM, the dataset includes tabulated textual and numeric information that has been retrieved from open-file mineral exploration reports and attached to individual exploration activities. The areas of exploration activity are digitized (as polygons, lines, or points) using the computer-assisted drafting (CAD) system Microstation, converted into ArcInfo, and then transferred into ArcView to enable an interactive display of EXACT. The positional data are digitized from hardcopy maps and plans in mineral exploration reports, using various published sources (geological maps, topographic maps, and TENGRAPH — DoIR's electronic tenement-graphics system) for georeference purposes. The types of exploration activity detailed are essentially those used in WAMEX, with some rationalization, and these are listed in Table 2.5. In the table, the 25 activities are grouped as follows:
- geological activities (and remote sensing activities)
- geophysical activities
- geochemical activities
- mineralogical activities
- drilling activities
- mineral resources
- hydrogeological activities.

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

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

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

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

NOTE: na not applicable

The activity data are also linked in the dataset to the following related information taken from WAMEX:

- A-numbers (WAMEX accession numbers for individual reports)
- I-numbers (WAMEX item numbers for single or groups of reports on microfiche)
- company or companies that submitted reports
- period of exploration (years)
- mineral commodities sought
- summaries (annotations) of exploration projects included in individual item numbers.

In ArcView, the exploration activities are included as spatial **themes**, which are displayed as polygons, lines, or points on the interactive on-screen map known as the **view**. The **table of contents** (i.e. map legend) provided alongside the **view** allows access to the **themes**, so that any **theme** or combination of **themes** may be displayed. Details (taken from attribute tables) of any **theme** can be accessed on screen, and **queries** can be carried out either as spatial queries through a **view** or as textual queries direct from the attribute tables. Further details (with examples) of displays, queries, charts, and view layouts are provided by Ferguson (1995).

Table 2.5 Types of exploration activity detailed in the EXACT database

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

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Appendix 3

Description of digital datasets on CD-ROM

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

Mineral occurrences (WAMIN)

The mineral occurrence dataset (from WAMIN, the Western Australian mineral occurrence database) as used in this Record is described in Appendix 2. The dataset on the CD-ROM includes textual and numeric information on:
- location of the occurrences (latitude and longitude, geological province, location method, and accuracy)
- commodities and commodity group
- mineralization classification and morphology
- order of magnitude of resource tonnage and estimated grade
- mineralogy of ore and gangue
- details of host rocks
- both published and unpublished references.

EXACT

The EXACT dataset (from EXACT, Geological Survey of Western Australia's spatial index of exploration activities) as used in this Record is described in Appendix 2. The dataset on the CD-ROM contains spatial and textual information (derived from the Western Australian mineral exploration (WAMEX*) database open-file reports) defining the locations and descriptions of exploration activities in the area. EXACT for the Canning area was compiled between 1998 and 2000, 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 (in the WAMEX database*), or located from coordinate and/or geographical information (from topographic maps, Landsat images, or TENGRAPH*), and then digitized. Table 2.5 (Appendix 2) lists the exploration activity types.

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

WAMEX

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

MINEDEX

The MINEDEX* database (Townsend et al., 1996, 2000) has current information on all mines, process plants, and deposits, excluding petroleum and gas, for Western Australia. Mineral resources included in MINEDEX must conform with the Joint Ore Reserves Committee (JORC) (1999) code to be included in the database. The database contains information relevant to WAMIN under the following general headings:
- commodity group and minerals
- corporate ownership and percentage holding
- site type and stage of development
- location data (a centroid) including map, shire, mining district, and centre
- current mineral resource estimates
- mineralization type
- tectonic unit
- tenement details.

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

TENGRAPH

The TENGRAPH database (DoIR's electronic tenement-graphics system) shows the position of mining tenements

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

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

Interpreted bedrock geology and regolith

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

Geophysics

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

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

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

Landsat

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

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

Cultural features

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

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

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PEIRIS

Mineral occurrences and exploration activities in the Canning area

RECORD 2004/3

This Record is published in digital format (PDF), not hardcopy, as part of a digital dataset on CD. It is also available online at: www.doir.wa.gov.au/gswa.
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