REPORT 70

GOVERNMENT OF WESTERN AUSTRALIA

MINERAL OCCURRENCES AND EXPLORATION POTENTIAL OF THE WEST PILBARA

by I. Ruddock

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

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Perth 1999

Copy editor: J. F. Johnston

REFERENCE
The recommended reference for this publication is:
RUDDOCK, I., 1999, Mineral occurrences and exploration potential of the west Pilbara: Western Australia Geological Survey, Report 70, 63p.

National Library of Australia
Cataloguing-in-publication entry

Ruddock, Ian
Mineral occurrences and exploration potential of the west Pilbara.

Bibliography.
ISBN 0 7309 6661 5.

1. Geology, Structural — Western Australia — Pilbara.
2. Mines and mineral resources — Western Australia — Pilbara.
I. Geological Survey of Western Australia.
II. Title. (Series: Report (Geological Survey of Western Australia); 70).

553.409941

ISSN 0508–4741

Printed by Haymarket Digital Prepress and Print, Perth, Western Australia

Cover photograph:
Radio Hill nickel mine and processing plant at sunset

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Mineral occurrences and exploration potential of the west Pilbara

by

Ian Ruddock

Abstract

The west Pilbara area is one of the cornerstones of the State's economy and future prosperity, with major contributions from the North West Shelf Gas Project at Burrup Peninsula, the Robe River iron ore mines, and the iron ore export facilities at Dampier and Cape Lambert. Geologically the area mainly includes the Archaean Pilbara Craton, except in the southwest where it includes the northern edges of the Palaeoproterozoic Ashburton Basin and the Phanerozoic Carnarvon Basin.

The region has a long mining history stretching back to the 1870s, when copper and lead–silver were found near Roebourne, and gold discoveries at Mallina in 1888 sparked a rush that spread through the whole Pilbara. Mining activity waned in the early part of the 20th century, but this changed dramatically in the west Pilbara in the early 1960s with the surge in iron ore exploration in the Robe River area. Exploration resulted in the discovery of three to four billion tonnes of pisolitic iron ore, of which some 426 Mt has been mined for shipment since 1972.

During the 'nickel boom' of the late 1960s and early 1970s the area from Dampier to Whim Creek was a major focus for nickel–copper and copper–zinc exploration. Nickel–copper discoveries were made in 1970 at Mount Sholl, Ruth Well and Sherlock Bay. Vanadium–titanium deposits were outlined in the middle to late 1960s at Balla Balla, Don Well, and Andover. Base metal exploration continued from the end of the boom until the late 1970s, and in 1977 the Salt Creek base metal deposit was discovered. Further nickel exploration in the early 1980s resulted in the discovery of the nickel–copper deposit at Radio Hill in 1984. In the mid-1980s the west Pilbara became a focus for platinum-group element exploration in layered-mafic intrusions, with the discovery of the Munni Munni deposit in 1984.

Since the 1980s mineral exploration in the area has fallen behind other parts of the State because it has been perceived as having a comparatively lower prospectivity for large mineral deposits (except for iron ore). Despite this, the west Pilbara must still be considered as one of the most prospective underexplored parts of the State for a large range of commodities in a variety of mineralization styles, but they have yet to be fully tested by the latest geochemical and geophysical methods, and be assessed in the light of new geological concepts arising from the current 1:100 000-scale mapping program and airborne geophysical surveys of the Geological Survey of Western Australia and the Australian Geological Survey Organisation.

Most recently there has been renewed interest in the area with the reopening of the Radio Hill nickel mine in April 1998. The announcement of gold discoveries in mid-1997 at the Indee project, covering the Mallina Basin, confirm the area's potential for major deposits of turbidite-hosted gold. In addition, exploration has begun to focus on the potential of the layered-mafic intrusions of the west Pilbara for nickel–copper–cobalt occurrences similar to the huge deposit discovered at Voisey's Bay in northeastern Canada in late 1994. Trial mining commenced in April 1999 at the small, but very rich, Elizabeth Hill silver deposit (discovered in 1987) and there are plans to reopen copper operations at Whim Creek and Mons Cupri. In late 1998, plans were announced to examine the possible development of the vanadium deposits at Balla Balla and Don Well.

KEYWORDS: Mineral exploration, mining, mineral occurrences, North Pilbara granite–greenstone terrane, Hamersley Basin, Ashburton Basin, Mount Minnie Basin, Carnarvon Basin, regolith, iron ore, nickel, base metals, gold, silver, platinum-group elements, titanium, vanadium, antimony, tin, beryl, chrysotile, heavy minerals, uranium.

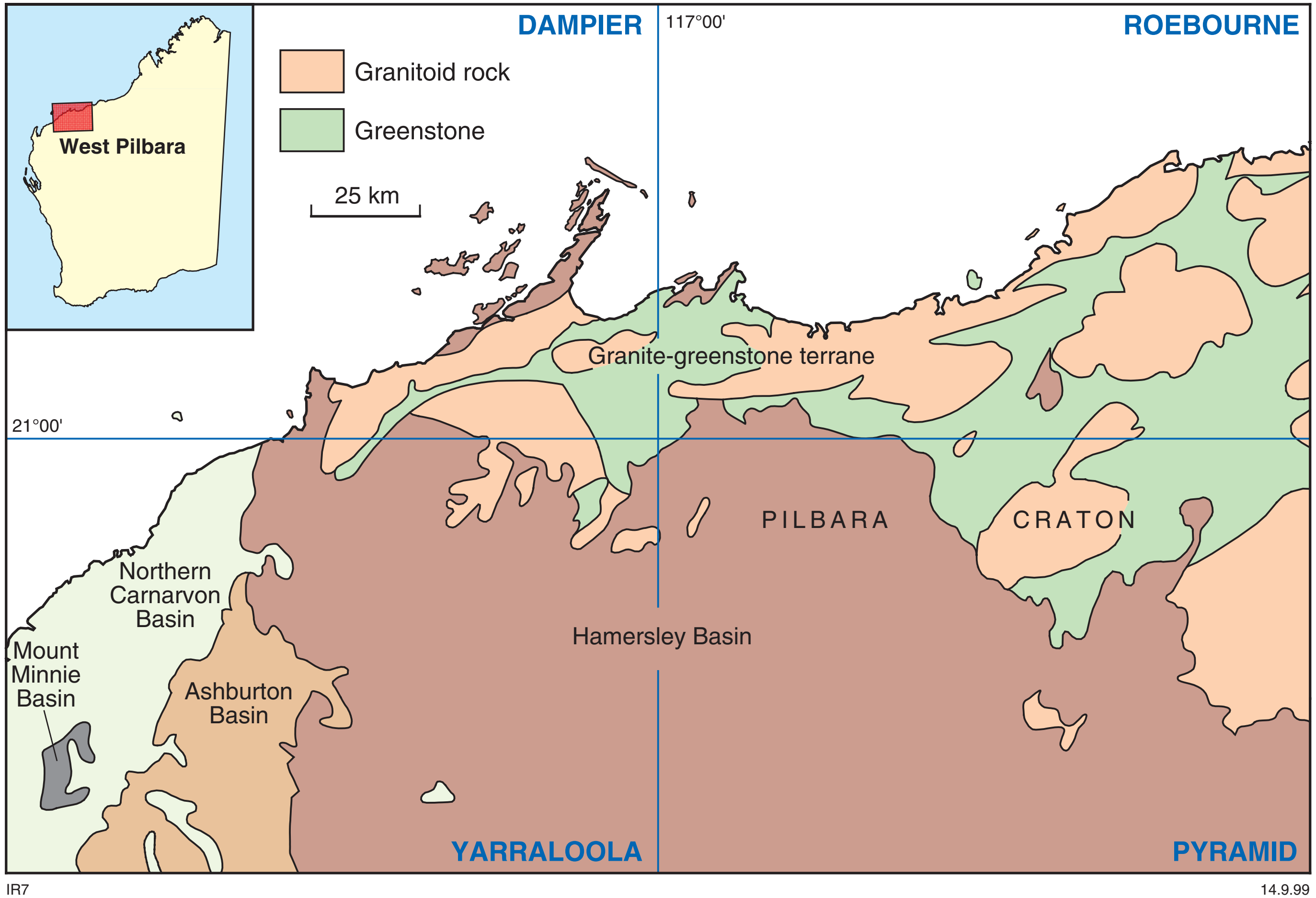

Figure 1. Tectonic units of the west Pilbara, showing the boundaries of the four 1:250 000-scale geological maps included in the area

Introduction

Present study

This study aims to promote and enhance mineral prospectivity in the west Pilbara, a region of major economic importance to the State with major contributions from the North West Shelf Gas Project at Burrup Peninsula, iron ore mining at Robe River, port operations for iron ore export at Dampier and Cape Lambert, and solar salt operations at Dampier. Apart from iron ore few other commodities are mined in the area at present, although it has a long history of mining going back to the 1870s. There is one nickel mine at Radio Hill, which reopened in 1998, and a new silver mine opened in mid-1999 at Elizabeth Hill. Plans were announced in late 1998 to examine the possible development of the vanadium deposits at Balla Balla and Don Well, and there are plans to restart copper mining at Mons Cupri and Whim Creek. There is also intermittent small-scale gold mining at a number of prospects throughout the area.

The west Pilbara was a major focus for mineral exploration from the early 1960s to the mid-1970s, but since the 1980s exploration activity in the area has fallen behind other parts of the State because many exploration companies have perceived it as having a comparatively lower prospectivity for large mineral deposits (except for iron ore). However, there are signs that this is changing, with the recent renewal of interest in gold and nickel exploration.

The main theme of the study is to provide GIS-based spatial indexes for mineral exploration activities (the EXACT database) and mineral occurrences (the WAMIN database). These indexes have been developed as a major initiative to improve access to minerals information in the State.

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

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

The mineral prospectivity study of the west Pilbara has three main parts: this report, Plate 1 of this report, and a digital dataset on CD-ROM. The report reviews the regional geology of the area, the history of mining and exploration, the main mineral occurrences, the mineralization controls, and the potential for further mineral discoveries. Plate 1 shows the mineral occurrences, indicating commodity and mineralization style, on a geological map (a simplified interpretation of the solid geology and regolith) with a key list alongside showing mineral occurrences grouped according to commodity and mineralization style. Where mineral occurrences are mentioned in the report they are also identified by the WAMIN 'deposit number' shown thus: Radio Hill (2958).

Appendix 1 defines the terms used in the Geological Survey of Western Australia (GSWA) Western Australian mineral occurrence database (WAMIN) and mineral exploration activity database (EXACT). Appendix 2 gives brief descriptions of the digital datasets included on the CD-ROM. Appendix 3 (Tables 3.1–3.8) provides production figures for the main commodities that have been mined in the west Pilbara.

The CD-ROM includes all the data used to compile the report and Plate 1, and it also includes files of geophysical, remote-sensing, mining tenement positions, and topographic data. The CD-ROM contains the files necessary for viewing the data in the ArcView GIS environment plus a self-loading version of the ArcExplorer software package modified to suit this particular dataset. Metadata statements on the geological, geophysical, and topographic datasets are also provided.

Location, physiography, climate and access

The west Pilbara area of this report is covered by four 1:250 000-scale maps — DAMPIER*, ROEBOURNE, YARRALOOLA, and PYRAMID (Fig. 1). Main centres of population (shown in the 1996 census) on the north coast are at Karratha, the regional capital (population 10 390), Dampier (1424), Wickham (1504), and Roebourne (1600), with an additional population centre in the southwest at the mining town of Pannawonica (1621).

The area is broadly divided into the following physiographic units based on the criteria used by Hickman (1983) and shown on Figure 2:

- Coastal and/or tidal flats
- Alluvial plains and valley floors
- Strike ridges and low hills
- Dissected plateau

The coastal flats include tidal mangrove swamps, samphire flats, extensive silt and mud flats, and areas of coastal dunes. Inland from this marine environment, the alluvial plains form areas of low relief that include broad river floodplains, valley floors, and adjacent gently dipping pediment plains that abut the higher relief areas of ridges, hills, and dissected plateau.

The physiographic division of strike ridges and low hills, in the north, is underlain by Archaean granite–greenstone rocks (metamorphosed volcanic and sedimentary rocks, gabbroic intrusions, and granitic complexes). In the southwest, the division includes low hills and mesas formed by folded Proterozoic sedimentary (and volcanic) rocks and flat-lying Cretaceous and Cainozoic sedimentary rocks.

* Capitalized names refer to standard map sheets

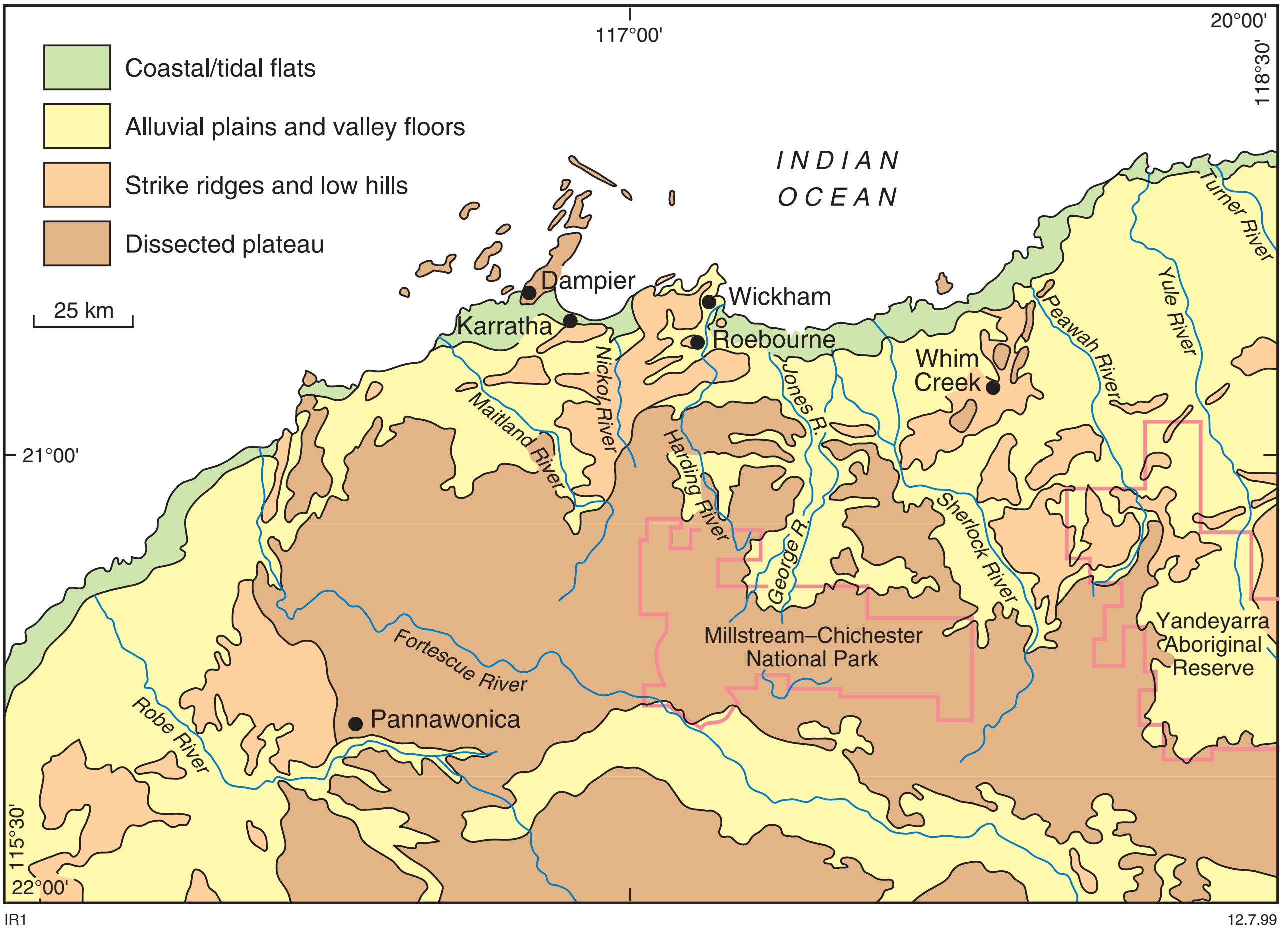

Figure 2. Location map of the west Pilbara, showing physiographic units, towns, and boundaries of the Millstream–Chichester National Park and the Yandeyarra Aboriginal Reserve

The dissected plateau comprises a scenic region of hills and deeply incised narrow valleys of the partly eroded surface of a Tertiary peneplain called the Hamersley Surface (Campana et al., 1964; Twidale et al., 1985). Most of this physiographic division is underlain by the volcanic and sedimentary rocks of the lower parts of the Fortescue Group and the Cooya Pooya Dolerite. In the south-central area much of this scenic region is within the Millstream–Chichester National Park.

The rivers and creeks flow only after heavy rain, but there are numerous permanent waterholes throughout the area: natural springs at Millstream are a popular tourist attraction. The main rivers are the Robe, Fortescue, Maitland, Nickol, Harding, Jones, George, Sherlock, Peawah, Yule, and Turner (Fig. 2).

The area has a semi-arid steppe-type tropical climate. The average annual rainfall is about 300 mm and most of this occurs in the summer months of January to March, associated with tropical ('monsoonal') thunderstorms and cyclones. At times, during the winter months, intense depressions and associated cold fronts in the southern part of the State extend northward (often interacting with moist tropical upper-air streams) to produce short periods of heavy rain in the region. Temperatures in the summer are very high, with uncomfortable daytime maxima of 36° to 43°C and very warm night-time minima of 27° to 30°C. In winter the temperatures are more pleasant, with maxima of 26° to 30°C and minima of 7° to 12°C.

The area is served by major infrastructure corridors of highways, iron ore railways, electricity transmission lines, gas pipelines, and water pipelines. Telecommunications are supported by a network of microwave towers, and there are local mobile-phone networks centred on Karratha and Wickham. A daily air service operates between Perth and Karratha, and there is another, smaller, airfield at Roebourne. The west Pilbara area is also one of the main tourist regions in the State, and a number of facilities throughout the area have been developed to support this.

The sealed North West Coastal Highway provides the main road access, linking with a number of graded shire roads and numerous pastoral station tracks. A private road owned by Hamersley Iron follows the railway line from Dampier to Tom Price (use of the road requires an access permit).

Pastoral leases cover about 55% of the area, National Parks and conservation areas occupy about 8%, Aboriginal

Reserves occupy about 6%, and Vacant Crown Land makes up about 31% of the region. There are various requirements relating to access for exploration and mining activities and these are referred to in guidelines issued by the Department of Minerals and Energy (1994, 1995).

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

Previous work

The west Pilbara was one of the first areas of the State to be visited by the new Government Geologist, Harry Woodward, in 1887 (Woodward, 1890, 1895) and detailed field investigations were later undertaken by the GSWA between 1904 and 1909, in 1912, and in 1921 (Montgomery 1907; Maitland 1906, 1908, 1909; Woodward, 1911; Blatchford, 1913; Wilson, 1922). In the late 1930s the Aerial Geological and Geophysical Survey of Northern Australia (AGGSNA) carried out field investigations and issued a number of reports on gold, copper, antimony, and chrysotile at various centres in the west Pilbara (Finucane, 1937; Finucane and Sullivan, 1939; Finucane and Telford, 1939a,b; Finucane, Jones, and Telford, 1939; Finucane, Sullivan, and Telford, 1939; Telford, 1939a,b).

The first systematic regional mapping of the area at 1:250 000 scale was undertaken by the GSWA during the period between 1962 and 1964 (Kriewaldt, 1964; Ryan, 1966; Kriewaldt and Ryan, 1967; Williams, 1968). As a result of this work in the west Pilbara an initial appraisal was made of the geology and mineral resources (Ryan, 1964). From 1979 to 1981 the northern coastal area, between Dampier and Roebourne, was mapped at 1:50 000 scale during the GSWA urban geology program (Archer, 1979a,b; 1981; Biggs, 1979a,b,c; 1980). The first comprehensive regional synthesis of the geology and mineral resources of the northern Pilbara Craton was produced by Hickman (1981, 1983), which incorporated all the results that were available up to 1981 from regional mapping, mineral exploration, and various researchers.

Between the 1960s and 1980s the GSWA published a number of commodity-specific studies and these included details of mineral occurrences in the west Pilbara: copper (Low, 1963; Marston, 1979); iron ore (MacLeod, 1966); lead–zinc–silver (Blockley, 1971); vanadium (Baxter, 1978); tin (Blockley, 1980); nickel (Marston, 1984). An updated lead–zinc–silver study by the GSWA has recently been completed (Ferguson, 1999). Details of platinum-group elements and nickel–copper in some layered-mafic intrusions of the area were published by the Australian Geological Survey Organisation (AGSO) (Hoatson et al., 1992). From the mid-1970s there have been numerous important research papers and articles (other than studies by GSWA and AGSO), and references to these are provided in other parts of this report where appropriate.

In addition there have been GSWA studies of three tectonic units in which the geology of the west Pilbara has been included, in part or in full: Carnarvon Basin (Hocking et al., 1987); Ashburton Basin (Thorne and Seymour, 1991); Fortescue Group, Pilbara Craton (Thorne and Trendall, in prep.). Several project maps were produced as part of these studies: north Pilbara Craton 1:1 000 000 scale (Hickman, 1983); Carnarvon Basin 1:1 000 000 scale (Hocking et al., 1987); Ashburton Basin and Southwestern Hamersley Basin 1:500 000 scale (Thorne and Seymour, 1991); and Fortescue Group, Pilbara Craton 1:500 000 scale (Thorne and Hickman, 1998).

In conjunction with AGSO, the GSWA is currently remapping the northern part of the Pilbara Craton at 1:100 000 and 1:250 000 scales, as part of the National Geoscience Mapping Accord (NGMA) project (Hickman, 1997a; Hickman, in prep.; Hickman and Smithies, in prep.; Hickman and Strong, in prep.; Kojan and Hickman, in prep.; Smithies, 1998a,b, 1999; Smithies and Farrell, in prep.; Strong et al., in prep.).

An important part of the NGMA project is a major program of airborne geophysical data acquisition. Surveys commenced in 1995 and a number of products covering the west Pilbara have been released, including high-resolution aeromagnetic data and radiometric data (Wellman, 1999). Remote sensing data for the project have also been obtained from Landsat-5-TM, SPOT, and Airborne Multispectral Scanner Geoscan (AMSS) imagery.

Regional geology

The west Pilbara area includes the western part of the Archaean–Proterozoic Pilbara Craton, the northern parts of the Proterozoic Ashburton Basin and Mount Minnie Basin, and the northeastern part of the Phanerozoic Carnarvon Basin (Fig. 1). The geological map showing the regional geology (Plate 1) and the digital geological data on the CD-ROM, accompanying this report, are based on the GSWA 1:100 000-scale geological maps that have been published, or are in preparation (see **Introduction**), the 1:500 000-scale geological map Plate 1A of Bulletin 144 (Thorne and Hickman, 1998), and the 1:250 000-scale map of YARRALOOLA (Williams, 1968). Solid geology interpretation has been facilitated by aeromagnetic and Landsat TM images for the area. The regolith units were also obtained from the 1:500 000-scale map of Thorne and Hickman (1998) and the YARRALOOLA sheet of Williams (1968).

Pilbara Craton

The Pilbara Craton consists of two different tectonic components: an older Archaean North Pilbara granite–greenstone terrane, formed between 3.6 and 2.8 Ga, and an unconformably overlying Archaean–Proterozoic volcano-sedimentary sequence called the Mount Bruce Supergroup, formed between c. 2.77 Ga and c. 2.30 Ga.

North Pilbara granite–greenstone terrane (Archaean)

The granite–greenstone terrane in the west Pilbara is characterized by east-northeasterly striking greenstone sequences that envelop elongate to ovoid granitoid complexes. Both the greenstones and the granitoid complexes were intruded by Archaean mafic–ultramafic layered intrusions at c. 2925 Ma. The dominant structure affecting the terrane is the Sholl Shear Zone, which appears as a sinuous feature trending easterly to east-northeasterly across the northern part of the area.

The greenstones include metamorphosed mafic to ultramafic volcanic rocks, felsic to intermediate volcanic rocks, clastic sedimentary rocks, chert, banded iron-formation, and sills of mafic to ultramafic intrusive rocks. The granitoid complexes consist of syntectonic granitoid intrusions, gneissic granitoid, and migmatite, and some contain enclaves of metamorphosed greenstones or layered mafic–ultramafic bodies.

An initial regional synthesis for the northern Pilbara Craton was produced by Hickman (1981, 1983), based on GSWA 1:250 000-scale mapping of the 1960s and 1970s, which showed a basic regional structural pattern of granitoid-complex domes with intervening greenstone synclines. In the west Pilbara the main trend of the synclinal axes is east-northeasterly. Hickman (1981, 1983) proposed that the volcanic and sedimentary rocks from each of the greenstone areas showed a stratigraphic consistency across the craton, essentially forming a tabular sheet on an unknown basement, and he grouped all of the greenstones as the Pilbara Supergroup. In this synthesis Hickman considered the tectonic evolution of the terrane to be predominantly influenced by vertical tectonics resulting from the gravitational uprise of granitoid-complex domes and syntectonic granitoid intrusions. Hickman et al. (1990) reaffirmed this interpretation in a review of subsequent studies of the Pilbara that had been carried out in the 1980s.

However, the stratigraphy and tectonic evolution proposed above continue to be the subject of considerable debate, and a number of authors have presented alternative correlations and tectonic models of the North Pilbara granite–greenstone terrane (Fitton et al., 1975; Horwitz, 1979, 1990; Barley, 1987; Barley et al., 1992; Eriksson et al., 1994; Krapez, 1993; Krapez and Barley, 1987; Krapez and Eisenlohr, 1998; Kiyokawa and Taira, 1998; and Smith et al., 1998).

A number of these studies proposed that Hickman's (1981, 1983) synthesis contained some stratigraphic inconsistencies when various greenstone belts were compared, and suggested that the greenstone areas may instead represent separate tectonic domains formed in different geotectonic settings. In support of this, tectonic accretion models and strike-slip pull-apart (extensional) basin models have been proposed that provide alternative interpretations to those of the GSWA for the stratigraphy and the structural evolution of the North Pilbara granite–greenstone terrane.

Recent information from GSWA's current detailed 1:100 000-scale geological mapping in the west Pilbara has enabled earlier work to be revised and new stratigraphic correlations to be made for this area (Hickman, 1997b; Smithies, 1996, 1997; Smithies et al., 1999). Geochronological information has also been obtained as part of the NGMA Pilbara project (Nelson 1996, 1997, 1998, 1999), and this has enabled new correlations of rock units to support the most recent interpretation by the GSWA of the stratigraphy and tectonic development of the greenstone successions in the west Pilbara (Tables 1 and 2, and Plate 1). The stratigraphy of the Archaean greenstone sequences in the west Pilbara, together with map codes that appear on Plate 1 (and in the digital dataset), are shown in Table 1.

The granitoid complexes and granitoid bodies in the west Pilbara area are listed below, in order of decreasing isotopic age (map codes shown on Plate 1 and in the digital dataset are also listed).

AgL	Carlindi Granitoid Complex	c. 3480–2950 Ma
AgY	Yule Granitoid Complex	c. 3421–2930 Ma
Agka	Karratha Granodiorite	c. 3270 Ma
AgC	Cherratta Granitoid Complex	c. 3130–2944 Ma
AgR	Caines Well Granitoid Complex	c. 3095–2925 Ma
AgH	Harding Granitoid Complex	c. 3015–2970 Ma
AgD	Dampier Granitoid Complex	c. 2990 Ma
Agpe	Peawah Granodiorite	c. 2950 Ma
AgP	Portree Granitoid Complex	c. 2945 Ma
Agsa	Satirist Granite	c. 2935 Ma
Agya	Yannery Granite	c. 2925 Ma

The geochemistry and geochronology of the granitoid rocks of the west Pilbara have recently been discussed by Smithies and Champion (1998) to show the compositional changes in geochemistry that have occurred during the evolution of the granite–greenstone terrane.

A complete new regional synthesis for the North Pilbara granite–greenstone terrane will not be available until the current NGMA has been finalized. However, for the purposes of this report some early results enable a preliminary tectonic scheme to be presented for the granite–greenstone terrane in the west Pilbara (an outline of this is shown in Table 2). The most recent synthesis by Smithies et al. (1999) proposed three distinct parts of the North Pilbara granite–greenstone terrane (Fig. 3). These are the west, central (the Mallina Basin and Whim Creek Belt), and east components, each of which have distinctly different structural styles, stratigraphy, and age distribution patterns. The area covered by this report includes the west and central components, plus a small part of the east component in the southeastern corner.

Table 1. Stratigraphy of greenstones in the west Pilbara

Group/Formation	*Map code*	*Approximate thickness (m)*	*Lithology and relationships* *Age*
Kialrah Rhyolite (new name)	*Ak*	1 000	Feldspar-phyric rhyolite and dacite, commonly flow banded Age 2972 ± 2 Ma
Mount Negri Volcanics	*At*	Unknown	Variolitic and vesicular basalt (with some locally spinifex-textured high-Mg basalt)
Louden Volcanics	*Ae*	300	Undifferentiated basalt and high-Mg basalt (locally pillowed and spinifex textured) and minor komatiite
~ ~ ~ *Local low-angle unconformity on Whim Creek Group* ~ ~ ~			
De Grey Group			
Mallina Formation	*ADm*	Unknown	Interbedded shale, siltstone, and medium- to fine-grained wacke, minor layers of chert; contains minor basalt and high-Mg basalt flows (locally spinifex textured) that may be equivalent to parts of the Louden and Mount Negri Volcanics and interbeds of quartz–feldspar porphryry
Constantine Sandstone	*ADc*	Unknown	Poorly sorted, coarse- to fine-grained subarkose and wacke
(Deposition of Whim Creek Group and De Grey Group interpreted to be largely contemporaneous in the Mallina Basin)			
Whim Creek Group			
Rushall Slate	*ACr*	Unknown	Well-laminated shale and siltstone, locally graphitic; minor sandstone; may be equivalent to part of the Mallina Formation
Comstock Member	*ACrc*		Vesicular basalt and high-Mg basalt
Cistern Formation	*ACc*	?100	Felsic tuff and clastic and volcaniclastic rocks, fine- to coarse-grained wacke, siltstone, and volcanolithic sandstone; includes polymictic cobble conglomerate; minor quartzite and chert
Mons Cupri Volcanics	*ACf*	Unknown	Felsic volcanic and volcaniclastic rocks; lavas and pyroclastic rocks, minor tuff with feldspar and quartz phenocrysts; dacite to rhyolite in composition; locally spherulitic and flow banded Age c. 3010 Ma
Warambie Basalt	*ACw*	300–500	Basalt, vesicular, pyroclastic, and amygdaloidal, with hyalo-clastite and local pillow basalt; interfingers with basal portions of Mons Cupri Volcanics. Basal polymictic conglomerate and sandstone
~ ~ ~ *High-angle unconformity* ~ ~ ~			
Cleaverville Formation	*AGl*	1 500	Banded iron-formation, chert, fine-grained clastic sedimentary rocks, and dacite–rhyolite ?sills Age c. 3020 Ma
~ ~ ~ *?Low-angle unconformity* ~ ~ ~			
Whundo Group			
Woodbrook Formation	*AUw*	1 000	Rhyolite tuff and agglomerate; minor basalt and thin banded iron-formation Age 3117 ± 3 Ma
Bradley Basalt	*AUb*	3 000–4 000	Pillow basalt, massive basalt, and minor units of felsic tuff and chert Age 3115 ± 5 Ma
Tozer Formation	*AUt*	500–2 500	Calc-alkaline volcanic rocks, including felsic pyroclastic units Age c. 3120 Ma
Nallana Formation	*AUn*	2 000	Dominantly basalt, but includes minor ultramafic and felsic units Felsic tuff dated at 3125 ± 4 Ma
~ ~ ~ *Tectonic boundary: Sholl Shear Zone* ~ ~ ~			

(continued overleaf)

Table 1. (continued)

Group/Formation	*Map code*	*Approximate thickness (m)*	*Lithology and relationships Age*
Roebourne Group			
Regal Formation	*A*r*r*	2 000	Basal peridotitic komatiite overlain by pillow basalt and local chert units. Intruded by microgranite and felsic porphyry dated at 3018 ± 2 Ma
~ ~ ~ *Tectonized contact* ~ ~ ~			
Nickol River Formation	*A*r*n*	100–500	Banded chert, iron formation, ferruginous clastic sedimentary rocks, quartzite, felsic volcanic and volcanogenic sedimentary rocks, and local conglomerate; locally intruded by peridotite. Contact with Regal Formation is generally tectonic Rhyolite near Mount Regal dated at 3251 ± 6 Ma, and felsic volcanogenic sedimentary rocks dated at 3269 ± 2 Ma
Ruth Well Formation	*A*r*w*	1 000–2 000	Basalt and extrusive peridotite with thin chert units Intruded by Karratha Granodiorite dated at between 3270 ± 2 Ma and 3261 ± 4 Ma
~ ~ ~ *?Terrane boundary or ?tectonic boundary* ~ ~ ~			
Warrawoona Group	*A*w	Unknown	Unassigned mafic and ultramafic volcanic rocks; minor chert and porphyry

SOURCE: Hickman and Smithies (in prep.)

Table 2. Summary of the tectonic evolution of the Archaean granite–greenstone terrane in the west Pilbara

Time (Ma)	*Event*	*Mineralization*
c. 3470	Deposition of Warrawoona Group (part of east Pilbara succession). Erosion	
>3270	Deposition of Ruth Well Formation and Nickol River Formation	Komatiitic nickel
3270	Intrusion of Karratha Granodiorite	
3130–3100	Granitoids in Cherratta Granitoid Complex. Deposition of Whundo Group and granitoids intruded. Earliest phase of Caines Well Granitoid Complex	VMS base metals
3070	Granitoid intrusion in Cherratta Granitoid Complex	
3020	Deposition of Cleaverville Formation	Contains BIF with later supergene enrichment
c. 3015	DEFORMATION EVENT — Probable time of sinistral movement on Sholl Shear Zone and Maitland Shear Zone. Felsic magmatism. Initial rifting of Mallina Basin. Erosion	
3010	Deposition of lower part of Whim Creek Group	
3000–2940	Periodic granitoid magmatism widespread (including Cherratta, Harding, Dampier and Caines Well Granitoid Complexes). Deposition of sedimentary rocks in Mallina Basin, followed by folding then intrusion by granites (including Peawah Granodiorite and Portree Granitoid Complex). Dextral movement on Sholl Shear Zone	[a]VMS base metals [b]Gold and gold–antimony
2925	Emplacement of layered-mafic intrusions and associated granitoids	Nickel–copper (cobalt) sulfides, vanadium–titanium, chromium, PGE (gold, silver) in layered intrusions. [b]Gold and copper–gold in later veins

NOTES: (a) Lead dates indicate base metal mineralization was later than 3010 Ma, at c. 2950–2930 Ma
(b) Gold mineralization post-dates dextral movement on Sholl and Mallina Shear Zones; some veins (Station Peak and Carlow Castle area) post-date layered-mafic intrusions
VMS: Volcanogenic massive sulfide
Source: Hickman and Smithies (in prep.)

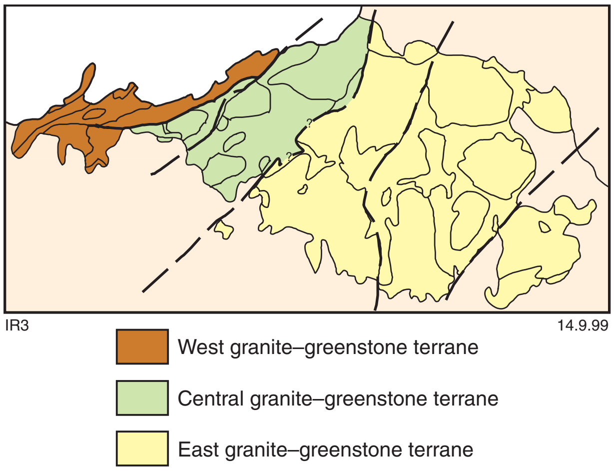

Figure 3. Areas of the North Pilbara granite–greenstone terrane proposed as the west, central, and east components (modified after Smithies et al., 1999)

In the west component, initial work since 1995 (Hickman, 1997b) has defined two main greenstone sequences known as the Roebourne Group and the Whundo Group (Table 1). These are separated by the major east-northeasterly trending Sholl Shear Zone. The main structures in the greenstone sequences are north-easterly to east-northeasterly trending folds, and there appear to have been two deformation events. The first event occurred probably around 3015 Ma, after deposition of the Cleaverville Formation (c. 3020 Ma) but prior to the development of the unconformity at the base of the Whim Creek Group (c. 3010 Ma). During this deformation there was sinistral movement along the Sholl Shear Zone, and this may have been associated with the initial rifting of the Mallina Basin in the east. The second event occurred prior to 2925 Ma, predating the non-foliated layered-mafic intrusions and associated granitoids.

In the central component, initial work (Smithies, 1997; Smithies et al., 1999) has newly defined the development and extent of the northeast-trending Mallina Basin. Along the northwestern edge of the basin (along the Whim Creek Belt), felsic and mafic volcanic rocks and sedimentary rocks of the Whim Creek Group were deposited at c. 3010 Ma. (The Whim Creek Belt is fault-bounded against the metasedimentary rocks of the Mallina Basin.) Within the main part of the basin, at about 3000–2940 Ma, turbidite sequences of the Mallina Formation were deposited, with coarse clastic sequences (Constantine Sandstone) accumulating in the centre and along the southeastern edge of the basin. In the southeast, the basin lies unconformably on chert, banded iron-formation and felsic volcanic sequences equivalent to the Cleaverville Formation (c. 3015 Ma) of the west component: this is seen in the area of Nunyerry Gap. In the southeast (on SATIRIST) the basin is variously fault-bounded against mafic–ultramafic volcanic rocks of the Warrawoona Group (part of the east component), unconformable on the Warrawoona Group, and elsewhere unconformable on the Cleaverville Formation. The relationship between the various rock units in the central component is shown schematically in Figure 4.

The main structures in the basin are northeasterly trending folds (Whim Creek Anticline, Croydon Anticline, and Wohler Anticline) that were produced during a deformation event, between 3000 Ma and 2940 Ma, associated with reactivation and dextral movement along the Sholl Shear Zone. Development of the east-northeasterly trending Mallina Shear and the northeasterly trending Wohler Shear also occurred during this event. Between 2950 Ma and c. 2925 Ma there were successive magmatic events with the emplacement of granitoids and the layered-mafic intrusions.

Layered-mafic intrusions (Archaean)

The west Pilbara area is characterized by a number of large, layered mafic–ultramafic intrusions, some of which have isotopic ages of c. 2925 Ma, which have been emplaced into the earlier rocks of the granite–greenstone terrane. The intrusions are listed below (ordered roughly from west to east) and their distribution is shown on Figure 5 and Plate 1 (map codes on Plate 1 and in the digital dataset are also shown below):

AaU	Munni Munni Intrusion
AaI	Maitland Intrusion
AaR	Radio Hill Intrusion
AaN	North Whundo Intrusion
AaD	Dingo Intrusion
AaH	Mount Sholl Intrusion
AaB	Bullock Hide Intrusion
AaA	Andover Intrusion
AaS	Sherlock Intrusion
AaO	Opaline Well Intrusion
AaM	Millindinna Intrusion (Satirist, Mount Dove, mouth Yule River, Langenbeck)

The intrusions in the west (Munni Munni to Andover in the list above) tend to occupy a northeasterly trending corridor, which is parallel to a prominent magnetic lineament, but oblique to the shear zone (Fig. 5). The lineament was recognized initially by Mathison and Marshall (1981). A detailed study of the petrogenesis and platinum-group element mineralization potential of layered-mafic intrusions located on DAMPIER, PINDERI HILLS, and ROEBOURNE was carried out by AGSO (formerly called the Bureau of Mineral Resources) between 1983 and 1989 (Hoatson et al., 1992).

Hamersley Basin (Archaean–Palaeoproterozoic)

The volcanic and sedimentary rocks of the Hamersley Basin unconformably overlie the North Pilbara granite–greenstone terrane. The rocks are assigned to three groups,

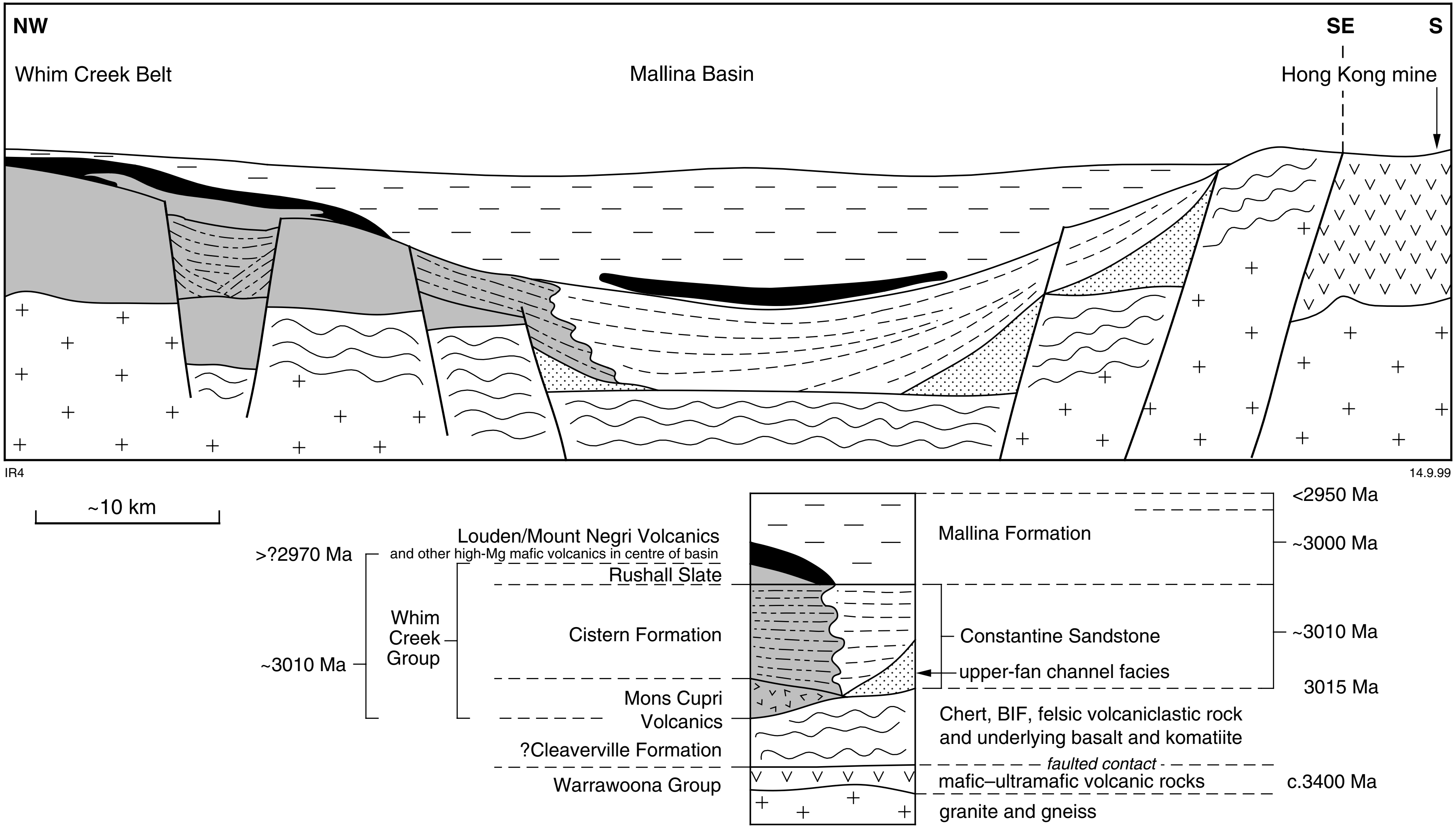

Figure 4. Schematic cross section through the central component of the North Pilbara granite–greenstone terrane, showing the proposed relationship between the rocks of the Whim Creek Group, Louden Volcanics, Mallina Formation, Constantine Sandstone, and ?Cleaverville Formation (modified after Smithies et al., 1999)

in ascending order, the Fortescue, Hamersley, and Turee Creek Groups, which are collectively known as the Mount Bruce Supergroup (Trendall, 1990). The Turee Creek Group does not occur in the west Pilbara area. Geochronological data indicate that basin development occurred between the late Archaean and the Palaeoproterozoic, with the arbitrary boundary between the two eras, at 2500 Ma, located in the lower part of the Brockman Iron Formation of the Hamersley Group (Trendall, 1990).

Fortescue Group (Archaean)

The Fortescue Group forms most of the southern half of the area, consisting of mafic and intermediate lavas and subordinate mafic to felsic tuffs, felsic lava, mafic intrusive rocks, and siliciclastic and carbonate sedimentary rocks. Trendall (1990) and Thorne and Trendall (in prep.) have proposed a six-fold subdivision of the succession into lower, middle, and upper volcanic and sedimentary units. These are listed below, in ascending order, together with map symbols that appear on Plate 1 and in the digital dataset.

AFr	Mount Roe Basalt (c. 2772 Ma)
AFh	Hardey Formation
AFk	Kylena Formation
AFt	Tumbiana Formation
AFm	Maddina Formation
AFj	Jeerinah Formation (c. 2687 Ma)

The lower Fortescue Group rocks (Mount Roe Basalt and Hardey Formation) were deposited on the granite–greenstone terrane in three north-northeasterly trending sedimentary basins, known as the west Pilbara, the Marble Bar, and the east Pilbara basins (Blake, 1984). The basins were initiated under a regional tensional regime that produced north-northeasterly trending tensional fractures. Only the west Pilbara basin occurs in the west Pilbara area of this report, and here Blake (1984) recognized three sub-basins: west, central, and east.

The Fortescue Group rocks are intruded by two large intrusions: the Cooya Pooya Dolerite (in the central part of the west Pilbara) and the Gidley Granophyre (in the northwest of the area). The Cooya Pooya Dolerite is an extensive mafic-sill complex that intrudes the volcano-sedimentary rocks of the Hardey Formation. The sill complex is up to 100 m thick and consists mainly of dolerite with a lower ultramafic unit and some granophyre (Hickman and Smithies, in prep.). In the vicinity of Mount Wohler the dolerite may pass into lava (Kriewaldt and Ryan, 1967), and in some areas, e.g. south of Copper Bore (McIntyre, 1988) the basal sections of the complex consist of olivine cumulate.

The Gidley Granophyre is a thick sheet of granophyre with a basal gabbro, which is intruded along the basal unconformity of the Fortescue Group. It outcrops on the Dampier Archipelago and Burrup Peninsula and is estimated to have a total thickness of 3000 m and a gentle dip to the north-northwest. Kriewaldt and Ryan (1967) suggested that the Gidley Granophyre may be correlated with the Cooya Pooya Dolerite.

Hamersley Group (Late Archaean–Palaeoproterozoic)

The Hamersley Group conformably overlies the Fortescue Group in the west and extreme south of the west Pilbara. The group consists of five important banded iron-formations separated by mudstones, carbonates, dolerites, and felsic volcanic rocks (Trendall and Blockley, 1970; Trendall, 1990). The group is subdivided into eight units that are listed below, in ascending order, together with map symbols that appear on Plate 1 and in the digital dataset.

AHm	Marra Mamba Iron Formation
AHd	Wittenoom Formation
AHs	Mount McRae Shale and Mount Sylvia Formation
ⱣHb	Brockman Iron Formation
ⱣHj	Weeli Wolli Formation
ⱣHw	Woongarra Rhyolite
ⱣHo	Boolgeeda Iron Formation

Mafic dyke swarms

Archaean to Neoproterozoic mafic dyke swarms intrude rocks of the Pilbara Craton, and Tyler (1990) has recognized three main groups: those that pre-date deformation of the greenstone belts; those that post-date deformation of the greenstone belts, but pre-date development of the Hamersley Basin; and those that developed during and after the Capricorn Orogeny (c. 2.0 to 1.8 Ga). At least ten separate swarms may be distinguished.

Ashburton Basin

The Ashburton Basin unconformably overlies the Hamersley Basin, and is itself unconformably overlain by Proterozoic rocks of the small Mount Minnie Basin and Phanerozoic rocks of the Carnarvon Basin. In the west Pilbara, the Ashburton Basin flanks the western margin of the Pilbara Craton and contains sedimentary and volcanic rocks of the Wyloo Group (Thorne and Seymour, 1991).

Wyloo Group

The units exposed are, in stratigraphic order: Mount McGrath Formation; Duck Creek Dolomite; June Hill Volcanics; and Ashburton Formation.

Mount Minnie Basin

The Mount Minnie Basin is a small basin that unconformably overlies the northwestern part of the Ashburton Basin.

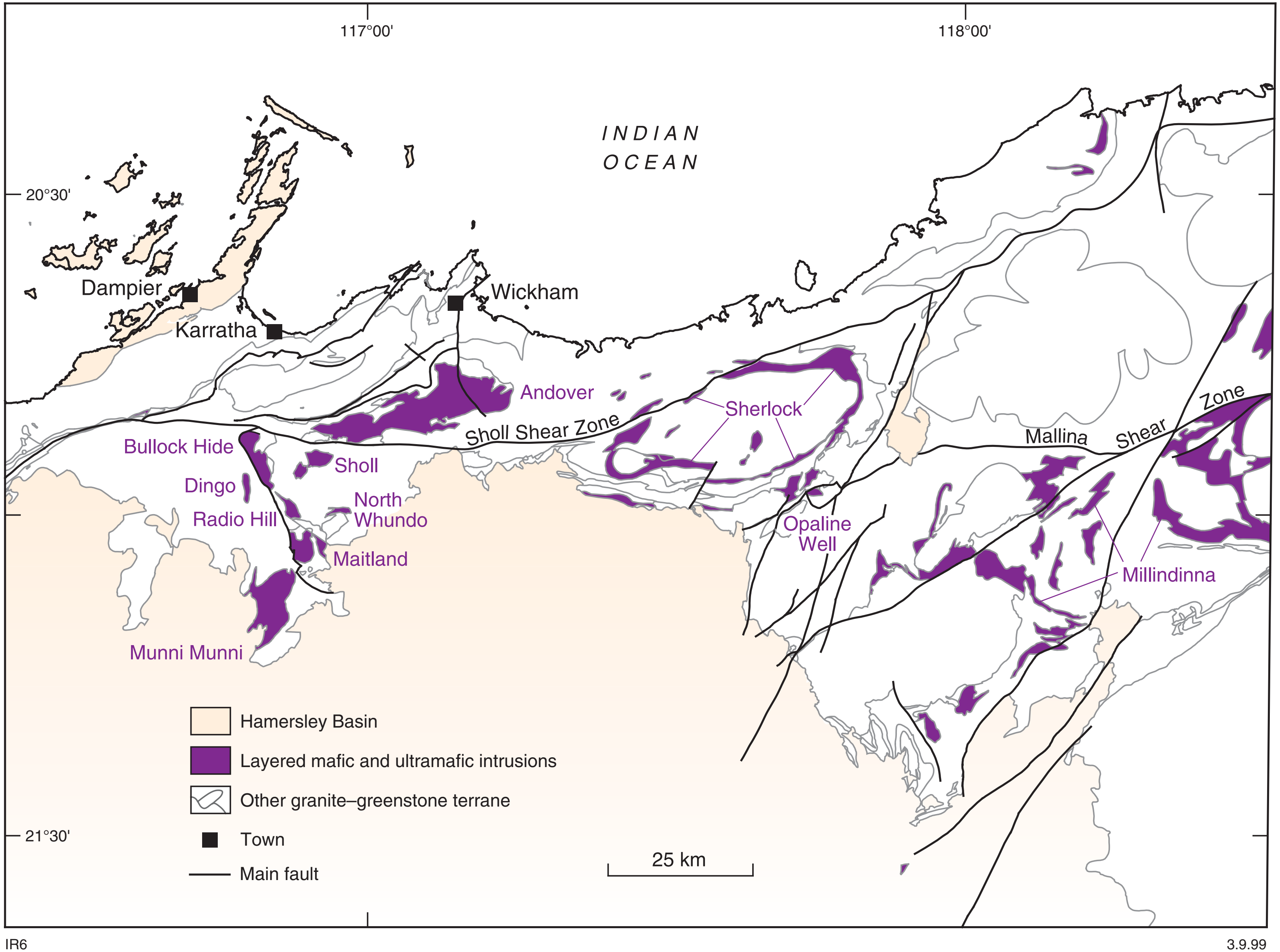

Figure 5. Map showing the distribution of Archaean layered-mafic intrusions in the granite–greenstone terrane of the west Pilbara

Mount Minnie Group

The Mount Minnie Group is about 1600 m thick and consists of silicified conglomerate and sandstone with mudstone (Thorne and Seymour, 1991).

Carnarvon Basin

Early Cretaceous

The Early Cretaceous in the west Pilbara is represented by a thin sequence (up to 45 m) of fluvial to tidal sandstone, siltstone and conglomerate, marking the eastern margin of the Peedamullah Shelf of the Carnarvon Basin (Hocking et al., 1987; Commander, 1994a,b). The stratigraphic units representing the sequence are the Nanutarra Formation and the Yarraloola Conglomerate (Williams, 1968).

Regolith

Cainozoic regolith materials form surficial cover over most of the area, and were developed as the products of weathering, mass wasting, erosion, and transport. On the accompanying 1:500 000-scale map (Plate 1) the regolith is divided into relict, depositional, and the Robe Pisolite. These three units are subdivided further on the digitized geology (on the accompanying CD-ROM) and described below (map codes are those shown on the CD-ROM).

Duricrust *(Czx)* — residual

The oldest units are residual ferruginous duricrust and related siliceous cap rocks that formed in the early Tertiary, and are typically seen in upland areas over mafic volcanic and banded iron-formation rocks of the Hamersley Basin and along strike ridges over some of the ultramafic and arenaceous rocks of the North Pilbara granite–greenstone terrane.

Pisolite (*Czp*) — Robe Pisolite

Unique iron-rich alluvial deposits were developed in palaeochannels of ancient drainage systems throughout the Hamersley area, particularly in those of the Robe River and Fortescue River, with the iron derived from Precambrian iron formations. The palaeochannels were filled by limonitic and pisolitic goethite together with fragments of fossil wood and seams of clay during the Eocene (Backhouse, 1979). These iron-rich deposits in the southwest of the area are referred to as Robe Pisolite, which now forms prominent mesas and elevated valley benches with local subcropping valley fill. The deposits reach their maximum development and are best exposed along the course of the ancient Robe River valley, where the deposits are from 5 to 30 m thick, with some locally reaching over 50 m. Other occurrences are known in the western Fortescue valley, where groundwater exploration has shown that the Robe Pisolite lies under thick overburden (Barnett and Commander, 1986). Outside the west Pilbara other major occurrences are in the palaeodrainages of Yandicoogina and Marillana Creeks (in the eastern Hamersley Range), and there are significant deposits south of Robe River in the areas of the Cane River, Duck Creek, and Boolgeeda Creek. The Robe Pisolite is regarded as equivalent to the Poondano Formation of the east Pilbara (east of Port Hedland).

Calcrete (included in *Qx* and *Qa*) — depositional

Calcrete deposits form in valley floors and along old drainage channels in the broad coastal plains. Calcrete also develops as residual cover over mafic igneous rocks and some metasedimentary rocks of greenstone sequences (e.g. Mallina Formation). Extensive calcrete deposits occur in the Fortescue valley where they are an important aquifer: the Millstream bore field supplies water to the towns of Dampier, Karratha, Wickham, and Cape Lambert.

Colluvium *(Qx)* — depositional

Older colluvium deposits, consisting of scree, gravel, sand, and silt, form dissected talus and sheetwash aprons that flank elevated areas of exposed rock. Younger colluvial and alluvial material forms extensive areas of floodplain near the north and west coasts.

Alluvium *(Qa)* — depositional

Alluvial deposits occupy the present drainage channels, and form the floodplains and deltas of major rivers. The deposits consist of unconsolidated or partly consolidated clay, silt, sand, and gravel. In many floodplain areas clayey silt forms an irregular rough surface called ‘gilgai’ (or crabhole) country, which is characterized by numerous cracks and small sinkholes. Alluvial gravels and sands provide important sources of water for towns, mines, and pastoral stations in the region. A large borefield near the mouth of the Turner River supplies water for Port Hedland. In the west, testing of the gravels below the Ashburton Plain has shown that there are significant groundwater resources yet to be utilized (Commander, 1994a,b).

Coastal deposits *(Qm)* — depositional

Coastal deposits include tidal, intertidal, and supratidal muds and silts (with mangroves), with shelly sand in coastal dunes and old beach lines. In some areas coastal limestone (lime-cemented shelly sand) has been deposited, and this is a source of lime (Abeysinghe, 1998).

Exploration and mining

1870–1920 — the age of discovery and early mining

The west Pilbara features some of the early mineral discoveries in Western Australia, made soon after white settlement of Roebourne and Cossack and surrounding pastoral leases in the middle to late 1860s. In 1872 copper was discovered (by J. Cooper) southwest of Roebourne at Glenroebourne (Carlow Castle and Fortune mines) and, in the same year, lead and silver were found south of the town at the Andover mine; small quantities of copper and lead–silver ores were said to have been shipped from Cossack in 1873. According to Maitland (1909), gold was reported from quartz reefs (yielding 5 ounces per ton) west of Roebourne in 1877, and, in 1882, a Mr A. McRae found a 14 pennyweight nugget* between Cossack and Roebourne (Woodward, 1911; Taylor, 1987). However, these gold finds did not spark much interest in the area at the time.

The main gold rush started in 1888 with discoveries at Mallina, Egina, and Pilbara Creek, and this led to the proclamation of the Pilbara Goldfield on 1st October the same year. Also in 1888 a rich copper lode was reported at Whim Creek (Woodward, 1890), reputedly found in 1882 by Phillip Saunders†. However, news of gold discoveries to the southeast, first in 1886 at Nullagine (with further finds from 1888 onward), caused many prospectors and miners to move away from the west Pilbara. Interest in the area was rekindled by further gold discoveries at Nickol River (1890), Croydon (1895), Hong Kong (1895), Toweranna (1895), Weerianna (1896), and Station Peak (1897) (Woodward, 1890; Maitland, 1909).

During this early period, much of the gold obtained from the area was unfortunately not reported, so it is impossible to make a complete assessment of the gold production from various mining centres. In particular, there is no record of production from the reputedly rich alluvial field at Egina, and production from the Pilbara mining centre appears grossly understated. It is likely that many thousands of ounces were not declared to avoid payment of a gold tax of 2/6d per ounce, as happened in the East Kimberley gold rush from 1886 to 1888 (Playford and Ruddock, 1985). Total recorded gold production for the period from 1897 to 1983 is shown in Appendix 3.1.

During these early years the government was quick to recognize the economic importance of the emerging mineral-rich area of the west Pilbara and the need to provide some geological assistance for the private companies that had been responsible for the developments at that time. So the west Pilbara was amongst the first areas to be visited by the new Government Geologist, Harry Woodward, in 1887 (Woodward, 1890, 1895) and it was later the subject of more detailed field investigations during the period 1904 to 1909, and in 1912. The publications based on these later surveys made important contributions to the early knowledge of the geology and mineral potential of the State (Montgomery, 1907; Maitland, 1906, 1908, 1909; Woodward, 1911; Blatchford, 1913).

In addition to gold, further copper discoveries were made at Mons Cupri (1897), Egina (1897), and Croydon (1898). In 1907 copper production started at Weerianna, Red Hill, and Yarraloola. Whundo was found in 1911, and production started at nearby Yannery in 1913.

In terms of the State's mineral wealth in the early 20th century the west Pilbara was a relatively small contributor of gold — mainly from the Station Peak and Weerianna mines, with smaller amounts from mines at Hong Kong, Lower Nickol, Toweranna, Mallina, and Carlow Castle. But the area was an important source of copper, mainly from the rich lodes of the Whim Creek mine (Fig. 6) with peak production in 1912 and 1913 (Appendix 3.2). Smaller amounts of copper were produced from mines at Carlow Castle (with some silver), Croydon, Whundo, Yannery, Weerianna, and Fortune (Appendix 3.2). In addition there was small sporadic production of antimony from Peawah, Mallina, Sherlock Crossing, and the Star mine east of Balla Balla (Appendix 3.5).

1920–1960 — the quiet years

The west Pilbara was a quiet backwater with little new development until the 1960s, when the era of modern mineral exploration began and when the GSWA commenced its regional 1:250 000-scale mapping program in the area. There was, however, a notable exception in the late 1930s when field investigations were undertaken by the Aerial Geological and Geophysical Survey of Northern Australia (AGGSNA), an organization established by the Commonwealth Government to invigorate mining with surveys of areas promising for mineral discoveries. AGGSNA was a forerunner to the Bureau of Mineral Resources (BMR), which in turn became AGSO. AGGSNA issued a number of reports on gold, copper, antimony, and chrysotile at various centres in the west Pilbara (Finucane, 1937; Finucane and Sullivan, 1939; Finucane and Telford, 1939a,b; Finucane, Jones, and Telford, 1939; Finucane, Sullivan, and Telford, 1939; Telford, 1939a,b).

At Whim Creek, where copper mining continued intermittently until 1964, there was some exploratory drilling by the Department of Mines in 1941–42, and by North Broken Hill Limited in 1952–53 (Low, 1963). In the 1950s and 1960s cupreous ore (the term used for copper ore for agricultural use as a soil conditioner) was obtained from copper mines at Whim Creek, Croydon, and Carlow Castle.

During the period between 1930 and 1950 some small production of gold was recorded from the Station Peak and Weerianna mines. Also, between 1925 and 1937, chrysotile asbestos was produced from mines at Nunyerry and Sherlock.

In the late 1950s some general reconnaissance was undertaken for base metals in the area by CRA, Mount Isa Mines and Westfield Minerals, prior to the enormous

* A typographic error shows 14 ounces (435g) instead of 14 pennyweights (22g) in another part of Woodward's (1911) account. This error was perpetuated in Maitland's publication (1909) and more recently in Hickman's publication (1983). If a 14-ounce nugget had been found, this would surely have caused a major rush to the Roebourne area in 1882 and changed the course of mining history.

† There is some doubt about this. In the description of his journey to the Kimberley in 1882, when he found gold in the Halls Creek area (Clement and Bridge, 1991), Saunders said he found copper between Roebourne and the Yule River, but he was not impressed because he could not discover any defined lodes. This does not match with descriptions of the Whim Creek lodes by Woodward (1890).

Figure 6. Photograph of Whim Creek copper mine taken in about 1900, looking toward the southwest. The Whim Creek gossan is along the top of the ridge in the right background; the photograph in Figure 16 was taken from this ridge. Black and white photograph courtesy of Dominion Mining Ltd

upsurge in exploration activity throughout the Pilbara that took place in the 1960s.

1960 onward — the age of mineral exploration

The most important phase of minerals development in the Pilbara commenced after the lifting of the Commonwealth embargo on iron ore exports in December 1960 and the lifting of State restrictions on iron ore exploration in early 1961. Following the initial 'boom' in iron ore exploration, a number of North American companies commenced vigorous exploration programs for base metals throughout the North Pilbara granite–greenstone terrane in the middle to late 1960s. The area was considered to have similar potential to known base metal regions in the Archaean Superior Province in eastern Canada where a number of significant discoveries had been made in the early 1960s. The initial focus was on copper–lead–zinc targets, based on exploration models of volcanogenic massive sulfides (VMS) but, by 1968 at the start of the 'nickel boom', this was broadened to include nickel–copper targets in layered mafic–ultramafic intrusions and in mafic–ultramafic volcanic sequences.

At the same time, the GSWA was completing its program of 1:250 000-scale mapping of the west Pilbara. As new maps were released, they provided industry with valuable information on which to make regional assessments of areas with potential for a variety of mineral commodities.

Exploration was at its height in the west Pilbara during the period from 1968 to 1975, spurred on by several successful programs where geophysical and geochemical surveys had delineated significant anomalous zones. During follow-up drilling of these zones a number of nickel–copper deposits were discovered in 1970 to the south of Karratha at Mount Sholl and Ruth Well and to the northwest of Whim Creek at Sherlock Bay. Further drilling and exploration at the old mining centres of Whundo, Mons Cupri, and Whim Creek outlined resources of copper and copper–zinc (with some silver) and confirmed these deposits as having a volcanogenic exhalative origin, which provided further stimulus for intensive exploration for base metals in felsic volcanic sequences of the Whim Creek Belt and Sholl Belt.

Since that period the intensity of exploration has diminished, although continuing activity in the area resulted in the discovery of the copper–zinc–silver deposits at Salt Creek (northwest of Whim Creek) in 1977, the PGE (platinum-group elements) deposit at Munni Munni and the nickel–copper deposit at Radio Hill in 1984, the silver deposit at Elizabeth Hill in 1987 (the latter three south of Karratha) and, most recently, the gold deposits at Indee (east of Whim Creek) in 1997.

The following details of the exploration history and mine development in the west Pilbara (since 1960) have been summarized from open-file data in the Department's WAMEX database and various Geological Survey publications; these are outlined below under the sub-headings for various commodity groups.

Iron ore

From mid-1961 to the end of 1962 there was intensive exploration for iron ore throughout the area of the Hamersley Basin in which two main types of ore were targeted: pisolitic ore (formed in palaeochannels of major drainage systems); and hematite and hematite–goethite enrichment ore (supergene-enriched banded iron-formation). In the west Pilbara the iron ore target was pisolitic ore (‘Robe Pisolite’), and several deposits, with inferred resources of about 3500 Mt, were discovered by BHP Co. Ltd and Basic Materials Pty Ltd in three areas known as Lower, Middle, and Upper Robe River (MacLeod et al., 1963).

The pisolitic ores were the first of the ore types to be recognized in the Hamersley region of the Pilbara (MacLeod, 1966). Maitland (1909) recorded the occurrence of bedded ironstone at Chalyarn Pool (near the eastern tip of Deposit F, see below) during his reconnaissance survey of the west Pilbara and the Ashburton areas. In the mid-1950s geologists from BHP Co. Ltd noted the extensive mesa cappings of pisolitic iron at Robe River during regional exploration for manganese. However, there had been a Commonwealth embargo on iron ore export since 1938 and this stifled any exploration until the embargo was lifted in 1960 (Blockley et al., 1990). A boom in iron ore exploration occurred from 1961 onward, when the State Government made tenements available for this purpose. Within two years exploration had revealed that the Hamersley region contained resources of about 8000 Mt of material at a grade exceeding 50% Fe. This made it one of the largest iron provinces in the world and it became known as the Hamersley Iron Province. GSWA commenced a program of regional mapping of the entire province in 1962, culminating in a bulletin on the geology of the iron deposits in 1966 (MacLeod, 1966).

It was soon found that the pisolitic ores were widespread in palaeochannels, and occurred in almost every drainage system that had drained very large areas of the Brockman Iron Formation and Marra Mamba Iron Formation (the original sources of the iron in the secondary accumulations of pisolitic ores). The most extensive development of these ores was seen to be on the western side of the iron province in the Robe River and Duck Creek drainage systems (Plate 1).

The Robe River pisolites were explored by BHP Co. Ltd in the Lower Robe River area, between Warramboo and Deepdale Homesteads, where the largest mesa deposits occur. Fourteen major outcropping deposits were recognized, and these were labelled alphabetically from ‘A’ to ‘N’ proceeding upstream (Harms and Morgan, 1964). Since the early 1970s the Lower Robe deposits have been referred to as Deepdale deposits (A to K) and Eastern Deepdale deposits (L to N). In the Middle and Upper Robe River areas, exploration was carried out by Basic Materials Pty Ltd and joint venture partner Cleveland Cliffs Iron Co. of the USA (Cleveland Cliffs subsequently acquired the entire interest). The Middle Robe deposits, in the area of Pannawonica and Mount Enid, are represented by relatively smaller mesas downstream of the Hamersley Range scarp and their exploration has been described by Adair (1975). The Upper Robe deposits (‘gorge deposits’) occur in the Robe River and Kumina Creek upstream of the Hamersley Range scarp. The deposits are quite numerous and are scattered throughout the gorges: a detailed account of the deposits was given by Zimmerman et al. (1973).

Mining of pisolite ore commenced in 1972, when Cliffs Robe River Iron Associates* commenced operations at Middle Robe River, and continued until 1982 when the deposits were mostly worked out. Under an agreement with BHP, Cliffs Robe River then began mining at Eastern Deepdale. In 1987 BHP sold its interests in Eastern Deepdale and Deepdale to the current owner Robe River Iron Associates† (this group now holds all of the Robe deposits, except for some of the Upper Robe deposits). Mining production since 1982 has moved progressively from the Eastern Deepdale deposits (Mesas L to N; Fig. 7A, B, C) to Deepdale Mesa K deposit (in 1987) and to the current operation at Deepdale Mesa J deposit. Robe River Iron Associates is Australia’s third largest iron ore producer, and the world’s fourth largest seaborne trader in iron ore (Department of Resources Development, 1998).

Iron ore exploration for pisolitic ore continued elsewhere in the Robe River area. In 1972–73 BHP Co. Ltd located a large concealed deposit at Bungaroo Creek, lying below alluvial cover (Robe River Iron Associates now own the deposit). Numerous small resources of low-grade pisolitic ore have also been defined elsewhere in the west Pilbara, but companies have considered these too small for development.

In 1977 Australian Hanna commenced exploration for taconite iron deposits (low-grade, magnetite–quartz, unenriched banded iron-formation) on the Balmoral–Bilanoo project areas. Exploration for this additional type of iron ore, in the Joffre and Dales Gorge Members of Brockman Iron Formation, suggested deposits in three areas containing an order of magnitude estimate of 3780 Mt of ‘crude ore’ with a potential to yield 1320.5 Mt of magnetite concentrate. The deposits and surrounding exploration tenements are now held by Mineralogy Pty Ltd.

* Cliffs Robe River Iron Associates was a consortium of United States, Japanese and Australian interests that included Cliffs International Inc., Mitsui Iron Ore Development Pty Ltd, Robe River Limited, and Mount Enid Iron Co. Pty Ltd; Cliffs International Inc. managed the Robe River project until 1986.

† Robe River Iron Associates includes North Limited (53%), Mitsui Iron Ore Development Pty Ltd (33%), Nippon Steel Corporation (10.5%), and Sumitomo Corporation (3.5%); North Limited manages the project.

Vanadium and titanium

During 1961–62 Mangore (Australia) Pty Ltd (a subsidiary of Union Carbide) assessed the vanadium–titanium potential of titaniferous magnetite layers in layered-mafic intrusions at Andover and Balla Balla. Although the deposits at Andover were considered to be too small and discontinuous for further work, geophysical exploration and drilling was carried out by Garrick Agnew Pty Ltd during the mid-1960s at Balla Balla and to the west at Don Well. Drilling in outcrop areas and in areas of strong magnetic anomalies revealed extensive zones of primary and oxidized ore within three separate deposits at Balla Balla and another large deposit to the west at Don Well.

Texasgulf Australia carried out further drilling and metallurgical assessment in 1975 after it was found that there were metallurgical treatment problems with the ore material, which consists of very fine intergrowths of ilmenite in vanadiferous magnetite. Feasibility studies by Texasgulf concluded that prohibitively high costs would be involved in separating the ore into vanadium-rich and titanium-rich products. Since 1998 there has been a renewed interest in recovering vanadium from the Balla Balla deposit using recently developed beneficiation methods. Plans are in hand to develop the deposits (Tanganyika Gold NL, Quarterly report for September 1998).

The small deposits at Andover (known as Gregory West) have recently been exploited as a source of heavyweight aggregate for submarine natural gas pipelines on the Northwest Shelf.

Base metals (copper, lead, zinc, and silver)

Initially, base metal exploration was undertaken at the sites of old copper mines. During the 1960s two associated companies, Westfield Minerals (WA) NL and Whim Creek Consolidated NL (and their joint-venture partners), carried out exploration to extend resources of supergene copper and copper–zinc sulfides at Whundo–Yannery and at Whim Creek – Mons Cupri.

Westfield undertook initial evaluation, including drilling, at Whundo–Yannery in the period from 1964 to 1966, and during 1970–71 further drilling was carried out by joint venture partner Consolidated Goldfields Australia Ltd (Collins and Marshall, 1999b). A drill-indicated resource for Whundo was estimated at 1.16 Mt averaging 2.08% Cu, 1.33% Zn, 11 g/t Ag. Following a feasibility study in 1975, openpit mining by Whim Creek Consolidated NL in 1976 yielded 6200 t of supergene oxide ore at 26.98% Cu.

Noranda Australia Limited carried out further exploration (as joint venture partner) in 1982–83 to test for down-dip extensions of ore at Whundo, and did further drilling in 1989. In 1991 Noranda withdrew from the joint venture, and management was undertaken by Dominion Mining (who had recently taken over Westfield Minerals and Whim Creek Consolidated). Dominion planned to transport the remaining resources of oxide copper (at Whundo and Whundo West) to a heap leach operation at Whim Creek (see below), but in 1998 the company sold its interests in the deposits to Straits Resources Ltd.

Whim Creek Consolidated NL took over the Whim Creek mine in 1964 from Dowa Mining Co. Ltd of Japan who had carried out diamond drilling between 1962 and 1964. Whim Creek continued drilling from 1965 to 1975 and estimated resources of 2.916 Mt at 1.63% Cu, 0.6% Zn, 0.3% Pb and 9 g/t Ag (total oxide and sulfide mineralization using a cutoff grade of 0.3% Cu). Various metallurgical and feasibility studies have been carried out since 1970 mainly to assess the treatment of the copper material.

Exploration at Mons Cupri from 1968 (Fig. 8) was undertaken by Whim Creek's joint venture partner Australian Inland Exploration Company Inc. (a subsidiary of Texasgulf Inc. of U.S.A.). By 1972 the latter company had established a significant resource of copper–lead–zinc–silver and proposed a volcanogenic model for the origin of the deposit (Miller and Gair, 1975).

Dominion Mining took over in 1991 and planned a processing facility at Whim Creek to heap leach copper ore from Whim Creek, Mons Cupri and Whundo. In 1994 Matlock Mining took an option to undertake this development but withdrew in 1995 after detailed evaluation. Straits Resources Ltd took a further option in 1996, and purchased Whim Creek and Mons Cupri in 1997.

At Carlow Castle some early work was done by Westfield, followed by Consolidated Gold Mining Areas in 1968. A more extensive program was carried out by AMAX between 1969 and 1972 to test for further copper mineralization in the Carlow Castle lodes and to test mafic–ultramafic units in the surrounding area for nickel–copper potential. Although the program did not locate any substantial deposits, drilling did reveal an interesting intersection of 5% zinc over 3 m in pyritic chert to the northeast of Carlow Castle. At Weerianna, Westfield Minerals also made a broad assessment of base metal potential in 1972.

From 1967 to 1980, encouraged by its success at Mons Cupri, Australian Inland Exploration (later called Texasgulf Australia) carried out an extensive exploration program for volcanogenic copper–zinc deposits in the greenstone sequence flanking the northern and eastern margins of the Caines Well Granitoid Complex (Collins and Marshall, 1999a). The discovery of the copper–lead–zinc–silver deposit at Salt Creek in 1977 and the smaller base metal discoveries at Balla Balla in 1979–80 confirmed the regional extent of the mineralized Whim Creek Belt. (Utah Development Company also explored parts of this belt between 1967 and 1974, but did not obtain encouraging results.)

From 1969 onward the volcano-sedimentary sequence of the Mons Cupri – Mount Fraser area (south of the Caines Well Granitoid Complex) has continued to be the focus of systematic VMS exploration by a number of companies: Utah Development Company (1969–1973),

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A.

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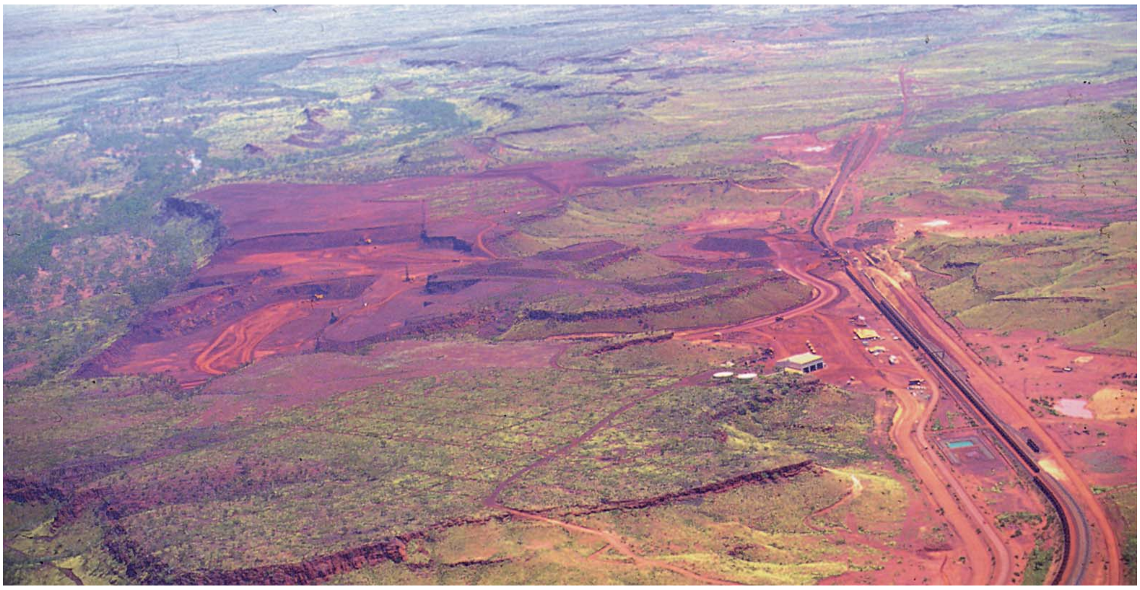
B.



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C.

Figure 7A. Photograph of Eastern Deepdale iron deposits, showing mesas L, M, and N, looking northwest. Mesa N is in the foreground. Phototgraph taken from the air during the production period between 1982 and 1986

B. Photograph of Eastern Deepdale iron deposits, showing mesa N, looking southeastward to Pannawonica Hill. Photograph taken from the air during the production period between 1982 and 1986

C. Photograph of Eastern Deepdale iron deposits, looking to the southwest, showing mesas L and M and the Eastern Deepdale loadout facility. Photograph taken from the air during the production period between 1982 and 1986

Photographs A, B, and C courtesy of Robe River Iron Associates

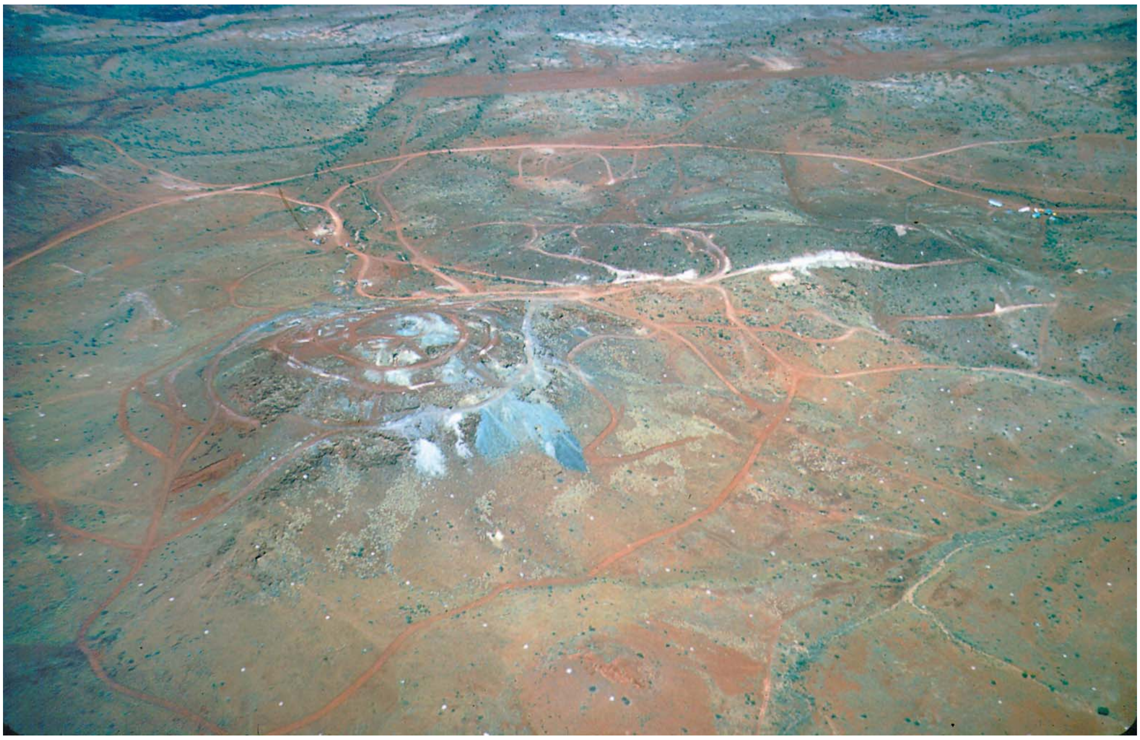

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Figure 8. Photograph of Mons Cupri, looking west, taken from the air on 26 October 1969 at the peak of the diamond drilling program by Australian Inland Exploration Inc. Photograph courtesy of M. E. Smith

Mallina Mining (1969–1970), Westfield Minerals (1970), Texasgulf (1977), Esso (1980), WMC (1981), Duval–Picon (1982–1984), Geopeko (1986–1990), Dominion Mining (1988–1991), and Pilbara Mines (1993 onward). A number of 'gossan' occurrences and geophysical anomalies have been tested by drilling, but to date no significant sulfide intersections have been made in this highly prospective area.

Between 1968 and 1974 base metal exploration by both Westfield Minerals and U.S. Steel Corporation extended over most of the greenstone sequences on either side of the Sholl Shear Zone (south of Dampier–Roebourne) from Mornong Well to Mount Regal to Bardies Well. Westfield discovered significant nickel–copper deposits at Mount Sholl and Ruth Well in 1969–1970 (discussed later), plus a number of minor occurrences of copper–nickel, zinc–lead, copper–silver, and gold. Data from the work by U.S Steel were never fully reported to the Department: a detailed base metal assessment report for the whole Pilbara and numerous sample assay sheets were submitted, but without maps or plans.

Noranda examined the area again in the early 1980s, concentrating mainly around Whundo and the East Well area where a minor gold occurrence was tested during drilling.

Since 1993 Dragon Resources Ltd has conducted an exploration program over a large region, between Radio Hill and Mount Fraser, and this met with some early success in 1994–95 at Orpheus (23 km southeast of Karratha) where drilling located zinc with copper, silver, and gold.

Esso carried out copper–zinc exploration southeast of Roebourne at the Woodbrook prospect (Bob Well gossans) in 1974–75, but withdrew after obtaining discouraging results from induced polarization surveys.

In the far west, Arimco NL explored the Devil Creek greenstone belt for stratiform lead–zinc–silver between 1988 and 1990, and drilled a small prospect at Shepherds Well. During stream-sediment sampling the company also identified low-order PGE anomalies (discussed later). Between 1993 and 1996 CRA also explored for base metals and gold here and at other prospects along strike to the northeast, but no substantial deposits were located.

In the Mallina Basin, around the old copper mines at Evelyn and Quamby, Bell Brothers explored for base metals (and uranium) between 1969 and 1971. Aquitaine Australia carried out further exploration here from 1976 to 1978. In 1991, MIM Exploration assessed the potential for Whim Creek-style copper–zinc mineralization around Mallina and Peawah, using the concept that rocks of the Mallina Formation correlated with the Rushall Slate at Whim Creek.

CRA explored for base metals and gold in the Ashburton Basin around the Yarraloola mine area, 130 km southwest of Karratha, from 1992 to 1997 with Giralia Resources NL – Stan McDonald. CRA also explored the Katanga prospect (sedimentary and volcanic rocks) to the north of Yarraloola (this work also included a search for diamonds).

Nickel and copper

During 1970 significant nickel–copper discoveries were made by Whim Creek Consolidated NL near Mount Sholl south of Karratha — at Sholl A1, B1, and B2, and at Ruth Well. The company located disseminated nickel–copper sulfides at the northern edge of the Radio Hill intrusion in 1972 (but it was not until 1983 that AGIP discovered the Radio Hill deposit, as discussed below). The company also located minor nickel mineralization during 1970–71 at prospects known as Sullam, Cunig, Munni Munni North, Cadgerina Dyke, and Whundo South; minor copper mineralization was located in 1972 at North Whundo.

In 1983 AGIP and SAMIM discovered the nickel–copper deposit at Radio Hill, following drilling of geophysical anomalies that indicated a body of sulfide mineralization (Peters and de Angelis, 1987; de Angelis et al., 1987a,b), and AGIP later estimated a resource of 1.1 Mt at 2.53% Ni and 1.80% Cu. Underground trial mining began and a concentrator and smelter were built at the site (at a cost of about $45 million), but the operation was closed down in 1992 and placed on care-and-maintenance in the face of ore-treatment problems and a drop in nickel prices. In 1994 Resolute Limited took over the project (which included the Sholl and Ruth Well deposits) and carried out additional exploration until the company sold the project in 1997 to Titan Resources NL. Titan reopened the Radio Hill mine and commenced production in April 1998 (Fig. 9). Under an agreement with WMC, Titan is sending nickel and copper concentrates to Kalgoorlie for smelting.

Australian Inland Exploration discovered the nickel gossan at Sherlock Bay, east of Roebourne, in 1970 during exploration for VMS mineralization. Geochemical and geophysical surveys defined an east-northeasterly trending anomalous zone about 2 km long, and between 1970 and 1973 drilling delineated a large low-grade nickel–copper resource that the company estimated to be 75 Mt at 0.5% Ni and 0.1% Cu (Miller and Smith, 1975). The company had also commissioned an airborne magnetic survey over the coastal plain between Roebourne and Balla Balla that outlined a number of prominent magnetic anomalies. A number of these were drilled (in addition to Sherlock Bay) and were confirmed as concealed layered mafic–ultramafic intrusions (at prospects called George–Sherlock, Dumbalena, Padthureena, Triple, and Elbow). Although there was considerable enthusiasm in 1973 to proceed with the development of Sherlock Bay, depressed metal markets in the middle to late 1970s meant that this low-grade large-tonnage deposit did not warrant development at that time. Since 1989 further surface exploration over the Sherlock Bay area has been undertaken by Dragon Resources (with joint venture partner Poseidon Australia from 1991 to 1993, and with Outokumpu since 1998).

Regional exploration for nickel–copper continued east of the Sherlock area, testing Mg-rich mafic units in the

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Figure 9. Photograph of Radio Hill nickel mine and treatment plant, taken from the summit of Radio Hill looking northward

Mount Negri Volcanics (to the north and northeast of Mount Negri). Consolidated Goldfields first explored this area for copper–lead–zinc between 1968 and 1973, but Texasgulf also looked for nickel–copper between 1971 and 1975.

To the southeast of Whim Creek, Mallina Mining and Utah explored for nickel–copper in layered-mafic intrusive bodies (parts of the Millindinna Intrusion) in the Mallina Basin. From 1972 to 1975, to the south of this area, Utah undertook extensive nickel–copper exploration, including diamond drilling, at the Teichman project in the area of mafic to ultramafic rocks (Warrawoona Group) between Empress mine, Kangan Syncline and the Pilbara mining centre.

Between 1988 and 1992 Dominion and Newmont tested the area of an aeromagnetic anomaly south of Karratha (called Baynton) for possible nickel–copper and PGE potential. The anomaly may have represented a westward extension of the Dingo layered-mafic intrusion; however, results were inconclusive.

The core-shed disasters of the mid-1980s at Ruth Well, Sherlock Bay, and Mons Cupri caused major setbacks to mineral exploration and research on base metals and nickel mineralization in the west Pilbara. Drillcore racks were vandalized when unknown persons took away all of the metal core trays and left the drillcore tipped into heaps. As a result, any new information from physical examination of the scrambled diamond core (from Ruth Well, Sholl A1, Sholl B1, Sholl B2, Sullam, Sherlock Bay, Salt Creek, and Mons Cupri) is scanty. The only information now available are the old records in drill logs, assay sheets, and drill cross sections in mineral exploration reports. It is estimated that it would cost several million dollars (in today's currency) to repeat the previous drilling programs.

Gold

Various gold exploration programs have been undertaken since 1968 at the old gold mining centres of Carlow Castle, Lower Nickol River, Croydon, Toweranna, Womerina, Weerianna, Mallina–Peawah, and Station Peak. In addition, prospecting and small-scale mining have continued on an intermittent basis at these centres and at a number of smaller gold prospects throughout the west Pilbara. There has been little systematic regional exploration for gold except for work by Western Mining Corporation in the central part of the Mallina Basin (from 1981 to 1983) and current work by Resolute Resources in the same area (since 1996). There was also regional exploration, targeting the basal Hardey Sandstone for Witwatersrand-type conglomerate-hosted gold, by Carpentaria Exploration during 1981–82 and by CRA Exploration from 1990 to 1992.

Openpit Mining assessed the near-surface gold potential of the Carlow Castle, Fortune, and Good Luck vein deposits between 1984 and 1988, but concluded that there was limited potential for an openpit resource. These deposits are currently being explored by Legend Mining NL.

In the lower Nickol River area Samantha Exploration NL carried out brief exploration for lode and alluvial gold during 1983–84. In 1983 the Commonwealth Scientific and Industrial Research Organisation (CSIRO) identified and studied samples of alluvial platinoids (osmiridium grains) found in alluvial gold deposits in the east of the area (Hudson and Horwitz, 1983). Sir Samuel Mines carried out more detailed work from 1984 to 1991, in which lode gold in a series of twelve east-northeasterly trending 'mylonite zones' in mafic to ultramafic meta-volcanic rocks was explored; alluvial gold and PGE potential were also assessed. From 1984 to 1989 Callina–Minsaco explored for gold and PGE in an area between Nickol River and Wickham.

At Croydon, West Coast Holdings tested the alluvial potential between 1980 and 1983, and this work was followed by more-detailed assessment by Golden Valley Mines from 1984 to 1988, and Tracer Mining from 1988 to 1992. (The area was also briefly explored for gold during nickel–copper and copper–zinc exploration by Utah and Mallina Mining & Exploration NL between 1967 and 1973.)

The vein deposits at Toweranna were explored by Texasgulf Australia between 1974 and 1976. Further work, including drilling, was undertaken by Taurus Resources between 1983 and 1987. Results from both programs indicated that there was only a small resource available.

The Womerina area was briefly examined by Utah in 1972 and Esso in 1979. More-detailed sampling and pitting of alluvial and eluvial deposits between 1983 and 1986 were undertaken by Rosses Point Pty Ltd. During the period from 1981 to 1992 Zymron Pty Ltd carrried out futher assessment, and a medium-scale mining operation produced 1459 oz (45 380 g) of alluvial gold in 1987–88. The company planned further evaluation of alluvial potential and bedrock potential but this was never undertaken.

The Weerianna vein deposits have been explored and mined since 1978 by Noranda (this company later became Pioneer Minerals then Plutonic Gold, which was taken over by Homestake Mining in 1998). Some exploration was also carried out by Extract Holdings between 1987 and 1989.

The Mallina–Peawah and Station Creek areas were briefly explored for gold during nickel–copper exploration between 1968 and 1972 by Mallina Mining & Exploration NL and West Pilbara Antimony Pty Ltd. Arsenic anomalism (and gold potential) was noted in laterite samples at the contacts between small mafic–ultramafic intrusions and the Mallina Formation near Peawah. Between 1981 and 1983 Western Mining carried out a comprehensive regional mapping and geochemical sampling program in the central Mallina Basin, in the area of Mallina – Mount Langenbeck – Indee. Although some gold and arsenic anomalies were delineated in areas of sheared and silicified metasedimentary rocks, the company considered that these were of a fairly low order so no follow-up work was recommended. Resolute Resources re-assessed this open-file exploration data in 1996 and decided to carry out further geochemical sampling and drilling (on what is known as the Indee project).

Resolute have had encouraging results from drilling geochemical anomalies occurring over a large area, and the southwesterly trending Mallina Basin is shaping up to be a new turbidite-hosted gold province. This type of mesothermal gold mineralization appears to have received little attention in Western Australia, despite the fact that turbidite-hosted gold is a significant source of gold elsewhere in Australia and the world, for example Ballarat–Bendigo in Victoria, Hodgkinson Basin in North Queensland, Nova Scotia, Canada, Yellowknife district, NWT, Canada.

Antimony

During the period from 1968 to 1972 Mallina Mining & Exploration NL evaluated old antimony deposits in the Mallina–Peawah area and at Sherlock Crossing. To the north of Whim Creek exploration was carried out by Goldstream Mining in 1986–87 for antimony–gold in hydrothermal veins cutting Mount Negri Volcanics. Dominion Mining also explored this area for base metals and epithermal antimony–gold between 1988 and 1990.

Platinum-group elements

In the early 1980s Hunter Resources commenced a program of platinum-group element (PGE) exploration that targeted all known areas of layered-mafic intrusions in the west Pilbara. Hunter focused initially on the Munni Munni Intrusion to explore the mafic–ultramafic contact areas, using the Bushveld and Stillwater models of PGE mineralization. This followed petrological research at Munni Munni by Donaldson (1974), who compared the intrusion with the layered-mafic complexes at Skaergaard, Bushveld and Stillwater. Investigations by the BMR at Munni Munni commenced in 1983 as part of an assessment of PGE potential in layered-mafic intrusions of the west Pilbara (Hoatson et al., 1992; Hoatson, 1994). Hunter located the Munni Munni reef (or Hunter's reef) in 1984 by surface sampling and trenching. Follow-up drilling between 1985 and 1988 delineated a subeconomic PGE resource in the central zone of the reef (about 700 m in strike length); the reef extends for about 7.5 km along the contact zone.

Minor PGE occurrences were also located at Munni Munni South, 'J' reef (northeast Munni Munni), and at Dingo Intrusion. During the late 1980s Hunter extended exploration to the east of Roebourne to assess the PGE potential of layered mafic–ultramafic sills (comprising the Sherlock and Millindinna Intrusions) between the George and Yule Rivers.

A PGE occurrence at the base of the Cooya Pooya Dolerite, south of Coppermine Well, was located in 1984 by Duval Mining and followed up between 1986 and 1988 by Hunter Resources, who reported the host rock as a differentiated olivine cumulate, and sampled gossanous outcrops within it. Hunter recommended further work and reported the construction of a drill pad. Although a percussion drillhole was noted during field validation of this occurrence by the author in 1997, no drilling results have been reported to the Department.

From 1986 to 1988 Greater Pacific Investments (John Ferguson) explored for PGE in the Andover Intrusion along the contact between the ultramafic zone and gabbroic zone. Results were not considered encouraging for further work.

In the eastern part of the Nickol River goldfield, CSIRO and Sir Samuel Mines investigated alluvial occurrences of osmiridium grains, but the source of this PGE material remains unknown.

During base metal exploration in the Shepherds Well area of the Devil Creek greenstone belt, between 1988 and 1990, Arimco NL identified a large number of Pt–Pd anomalies in stream sediments in drainages occurring along the unconformity between the greenstone sequence and the overlying Hamersley Group mafic volcanic rocks. The source of this PGE material is also unknown.

Silver

In the area south of Radio Hill, AGIP discovered significant silver mineralization in 1987 in the northern part of the Munni Munni Intrusion close to the northerly trending Munni Munni Fault. AGIP did not consider the prospect to be big enough to warrant follow-up work. In 1996 East Coast Minerals and Legend Mining carried out drilling that outlined a small, but very rich, silver deposit now known as Elizabeth Hill. The companies have since undertaken feasibility studies and trial mining commenced in April 1999 (East Coast Minerals NL, Quarterly report for 30 June 1999).

Heavy mineral sands (HMS)

Exploration was first carried out by VAM Limited between 1968 and 1971 along the coast between Dampier and Onslow. This work defined a number of iron-rich strandline deposits, with low Ti and Zr content, and Ti-rich deposits at the mouths of the Fortescue River and Robe River. Between 1988 and 1991, Geopeko identified thin palaeoshorelines at Regnard Bay, but with little HMS content.

Aztec Mining undertook exploration for heavy minerals in palaeochannels of drainages across the coastal plain between the Yule and Peawah Rivers, but results were discouraging.

Uranium

Exploration by Cominco in the early 1970s tested the uranium potential of the basal Hardey Sandstone (on PYRAMID) for pyritic quartz-pebble conglomerate-type deposits, similar to those of Witwatersrand (South Africa) and Elliot Lake (Canada). Inco also tested this style of mineralization in conglomerates to the south of Croydon mining centre in 1970–71, and Marathon Petroleum carried out further work between 1980 and 1982. Results from drilling showed weakly uraniferous units in the Hardey Sandstone.

In the northern Carnarvon Basin in the late 1970s, Newmont and CRA Exploration explored for sandstone-type uranium in palaeochannel facies of the Cretaceous Nanutarra Formation and Yarraloola Conglomerate. Although redox roll-fronts were identified, no anomalous uranium was detected (Carter, 1981).

Diamond

Since 1992 systematic regional diamond exploration has been carried out throughout the west Pilbara by Stockdale, CRA, Livre Holdings, Diamond Ventures, Rudall Resources, and Southern Ventures. The main targets for exploration are discrete bull's-eye aeromagnetic anomalies with the potential to be small, intrusive pipelike bodies of diamondiferous kimberlitic or lamproitic rocks. The selection of target areas has been greatly assisted by detailed airborne surveys undertaken in 1995 by AGSO, the results of which are available to explorationists.

Mineralization

The 435 mineral occurrences in the west Pilbara are shown on Figure 10 and on Plate 1. The mineral occurrences on Plate 1 are grouped by mineral commodity and mineralization style. Symbol colours on the Plate are used to distinguish commodity groups and symbol shapes are used to distinguish mineralization styles. For the convenience of description in the section below, mineralization style is used as a main heading followed by each of the commodity groups under various sub-headings. Mineral occurrences referred to below are also identified by the WAMIN ‘deposit number’ shown thus: Radio Hill *(2958)*. Almost all of the occurrences are in the Archaean granite–greenstone terrane, except for the pisolitic iron ore deposits in Cainozoic palaeochannels.

Orthomagmatic mafic and ultramafic mineralization

Mineralization in layered-mafic intrusions

There are three commodity groups in this mineralization style:

- Steel-industry metals — nickel, cobalt, vanadium, titanium, and chromium
- Base metals — copper
- Precious metals — platinum-group elements (PGE), gold, and silver

Layered-mafic intrusions are a characteristic feature of the west Pilbara granite–greenstone terrane (Fig. 5). The main intrusions have an isotopic age of c. 2925 Ma and they are hosts to several deposits of nickel–copper, PGE,

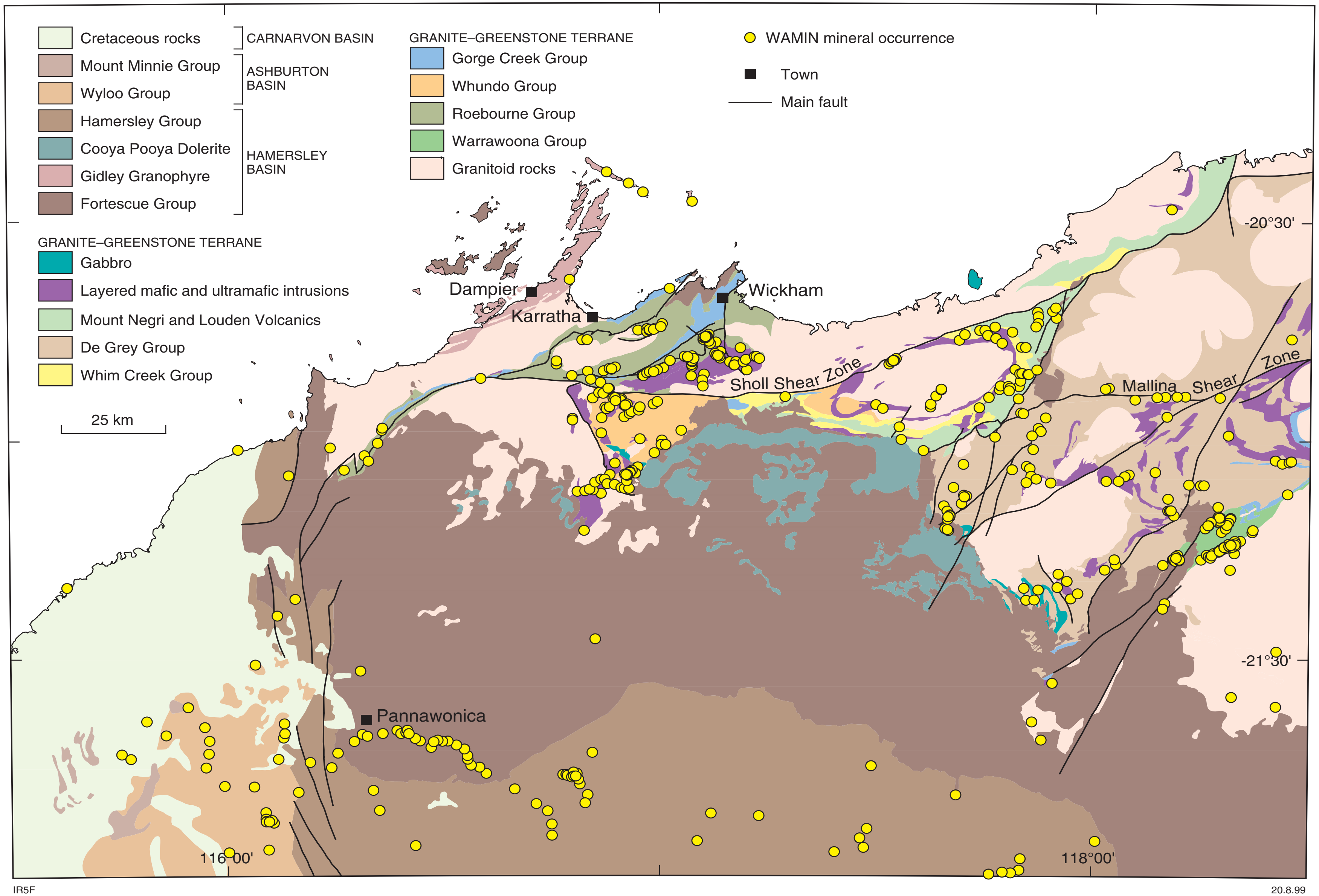

Figure 10. Distribution of 435 WAMIN occurrences in the west Pilbara

and vanadium–titanium. Since the late 1960s these intrusions have attracted substantial exploration interest for these commodities, as well as chromium and gold. The intrusions are listed below showing the mineral commodities that have been reported from them, and the distribution of the mineral occurrences is shown on Figure 11.

Munni Munni Intrusion: PGE, Ni, Cu, Cr, Au (Ag)

Maitland Intrusion: Cu

Radio Hill Intrusion: Ni, Cu, PGE, Au

Mount Sholl Intrusion: Ni, Cu, PGE

Dingo Intrusion: PGE

Andover Intrusion: V, Ti

North Whundo Intrusion: Ni

Bullock Hide Intrusion: none identified

Sherlock Intrusion: Ni, Cu, V, Ti, Cr

Opaline Well Intrusion: none identified

Millindinna Intrusion (Satirist, Mount Dove, mouth of Yule River, Langenbeck): none identified

A detailed petrogenetic study of layered intrusions on DAMPIER, PINDERI HILLS, and ROEBOURNE was carried out by BMR (and AGSO) between 1983 and 1989 (Hoatson et al., 1992). The main emphasis of that study is on the PGE potential of the first five intrusions listed above, and it includes 1:20 000-scale geological mapping, petrology, whole-rock and mineral geochemistry, geochronology, geophysics, and remote sensing. This comprehensive publication also includes information on deposits and occurrences of nickel–copper, copper, vanadium–titanium, chromium, and gold, and it is an essential reference for assessing the mineral potential of layered intrusions in the west Pilbara.

In addition to the above layered intrusions there are two younger intrusions of Fortescue Group age, one of which has shown some potential for PGE mineralization:

Cooya Pooya Dolerite (layered basal units): PGE

Gidley Granophyre: none identified

Nickel, copper (cobalt)

Deposits of nickel–copper sulfides were discovered in the Mount Sholl Intrusion (Sholl A1, B1, and B2) by Whim Creek Consolidated NL in 1970, in the Sherlock Bay Intrusion by Australian Inland Exploration Company in 1970, and in the Radio Hill Intrusion by AGIP–SAMIM in 1983. Minor occurrences have also been found in the lower part of the ultramafic zone in the Munni Munni Intrusion. A mine is now operating at Radio Hill (Figs 9 and 11) and there are plans to develop deposits B1 and B2 at Mount Sholl (see below), but the deposits at Sholl A1 and Sherlock Bay are still considered to be sub-economic.

Radio Hill and Mount Sholl Intrusions

Whim Creek Consolidated NL located three deposits around the Mount Sholl area in 1970, during drilling to test anomalous results from geochemical and geophysical surveys obtained in the late 1960s. The deposits are known as Sholl A1 (2942*), Sholl B1 (2943), and Sholl B2 (2944). Westfield also drilled magnetic and geochemical anomalies at Radio Hill (2958) and intersected minor nickel–copper mineralization in 1972. However, it was not until more-detailed geophysical surveys were completed by AGIP in 1983 that an EM target was highlighted for drilling, and mineralization intersected in 1984 (Peters and de Angelis, 1987; de Angelis et al., 1987a,b). Mining of the deposit by its new owners, Titan Resources NL, commenced in April 1998 (Appendix 3.8). The measured and indicated resources of massive sulfides at Radio Hill have been estimated to be 0.976 Mt at 2.58% Ni, 1.28% Cu, and 0.11% Co (Titan Resources NL, 1998). Additional indicated resources of disseminated sulfides have been estimated to be 1.2 Mt at 0.77% Ni, 1.07% Cu, and 0.04% Co (Titan Resources NL, 1997).

At the three Sholl deposits inferred resources have been estimated (Titan Resources NL, Quarterly report to 30 June 1999) as follows:

Sholl A1:	500 000 t at 0.60% Ni and 0.90% Cu;
Sholl B1:	462 000 t at 0.66% Ni and 0.80% Cu;
Sholl B2:	3 800 000 t at 0.74% Ni and 0.88% Cu.

Titan Resources has recently announced plans to undertake trial mining and bacterial heap leaching of deposits at Sholl B1 and Sholl B2 to produce nickel, copper, and cobalt (announcement to the Australian Stock Exchange, 23 September 1999 by Titan Resources NL).

At the Radio Hill and Sholl deposits nickel–copper mineralization (pentlandite, pyrrhotite, chalcopyrite) is predominantly within gabbroic material at the margin of the intrusions, lying structurally below mafic–ultramafic units of the main layered sequence. For the mineralization at Radio Hill, de Angelis et al. (1987a,b) suggested that the sulfides were initially disseminated within the layered gabbros, pyroxenites and peridotites and were later remobilized into stringer networks and massive lenses during a second phase of gabbro intrusion. Such a remobilization process is similar to that for nickel–copper sulfides within the Narndee layered ultramafic intrusion in the southeastern Murchison Province (Ahmat and Ruddock, 1990) although here the second intrusive phase of gabbroic material forms bodies that crosscut the central part, rather than the basal part, of the main layered sequence and the sulfide stringers and massive lenses are within ultramafic rocks at the contacts with these later gabbroic bodies.

For the Sholl deposits, Mathison and Marshall (1981) proposed a different process in which the host gabbro represented a chilled margin into which disseminated sulfides had sunk by gravitational settling following their separation from the adjacent parent peridotitic magma. This is somewhat similar to the process proposed by Thornett (1981) for the formation of the Sally Malay

* Unique number in WAMIN database, used on Plate 1 and in CD-ROM dataset

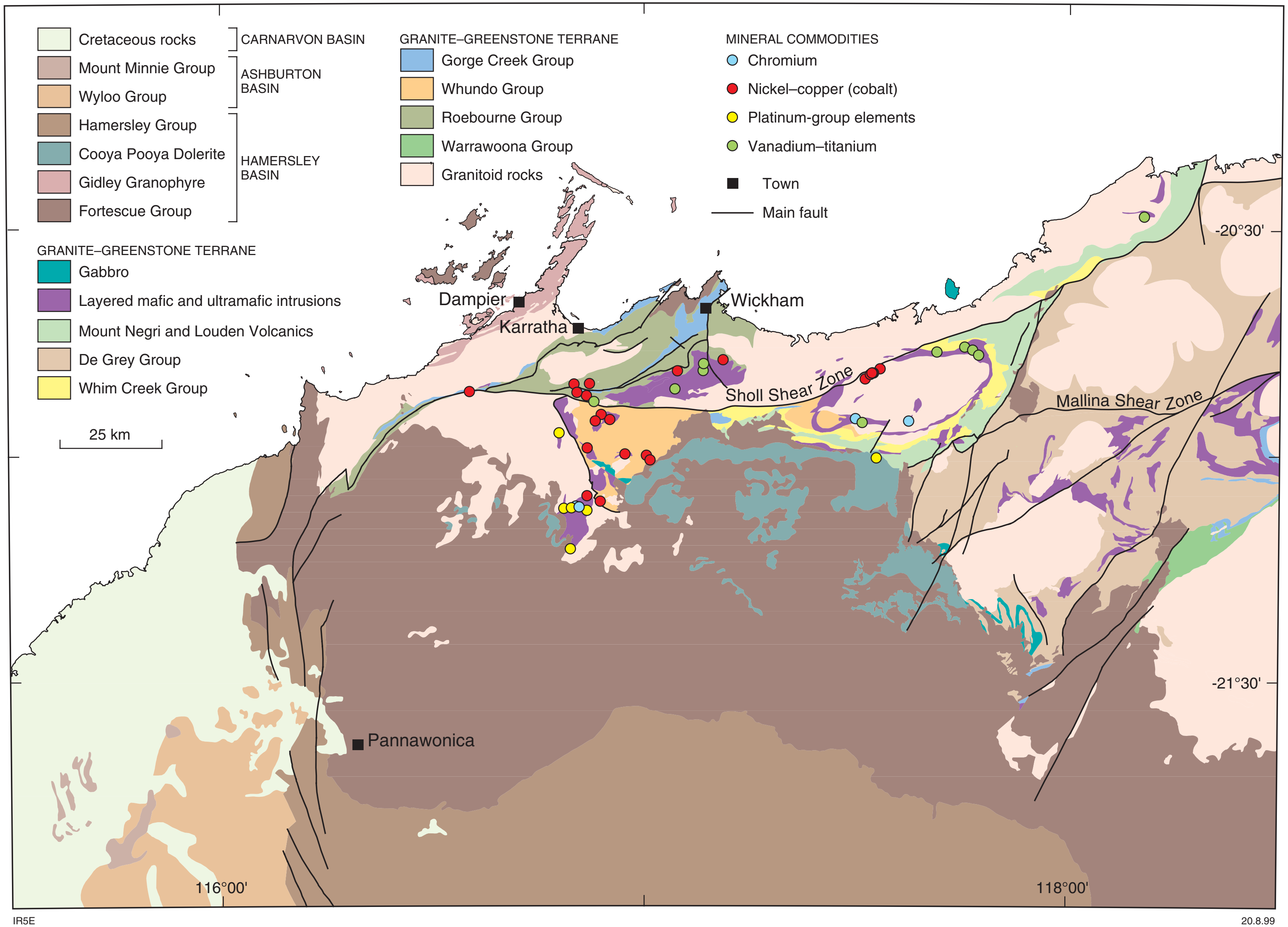

Figure 11. Distribution of nickel, copper (cobalt), vanadium, titanium, chromium, and platinum-group element occurrences in the west Pilbara

deposit in the East Kimberley. According to Thornett (1981) the host norite represented a marginal chilled phase of the layered mafic–ultramafic intrusion, where contamination of the original magma by felsic country rocks could have induced sulfide separation.

Sherlock Bay Intrusion

The presence of nickel was first detected in gossan sampling by Australian Inland Exploration Company during exploration for volcanogenic copper–lead–zinc in 1970. Follow-up geochemical and geophysical surveys led to a diamond-drilling program in 1972–73, which showed that nickel–copper mineralization extended for about 1.5 km in two east-northeasterly striking zones and persisted to a depth of at least 1000 m. Mineralization extends for a further 1.3 km to the west as separate zones of copper-rich material. The large low-grade nickel–copper deposit, known as Sherlock Bay (929), is marked by a strong linear magnetic anomaly that reflects the high magnetite content of the mineralized zone. It was initially estimated to contain a resource of 75 Mt at average grades of 0.5% Ni and 0.1% Cu (Miller and Smith, 1975) but this cannot be regarded as a resource under the Joint Ore Reserves Committee (JORC) (1999) code, because of the widely spaced nature of drilling in the deeper parts of the deposit. More recent estimates, in compliance with the JORC code, have been made for the uppermost part of the deposit: an inferred resource was estimated to be 16 Mt at 0.75% Ni and 0.9% Cu, of which 1.0 Mt would be amenable to openpit mining to a depth of 90 m (Dragon Resources Ltd, Quarterly report for December 1990).

Sherlock Bay may be interpreted as an intrusive-dunite type that has been involved in regional shearing. The mineralized horizon is a banded quartz–magnetite–amphibole–sulfide schist (Miller and Smith, 1975) that appears in outcrop as a banded ferruginous chert (Fig. 12). Mineralization occurs in the Sholl Shear Zone, in which the nickel–copper sulfides have been separated from their presumed ultramafic parent rock and emplaced in a partly mylonitized shear-zone sequence of volcano-sedimentary rocks and mafic–ultramafic intrusive rocks. The formation of the deposit may share some similarities with the emplacement of nickel sulfide bodies in the Thompson nickel belt in Manitoba, where sulfides were remobilized from host ultramafic rocks into gneissic and metasedimentary country rocks during a long and complex tectonic period (Peredery et al., 1982). Other interpretations have classified the Sherlock Bay deposit as a unique type of sedimentary-associated nickel deposit that formed by hydrothermal volcanic-exhalative processes (Groves et al., 1978; Marston, 1984).

Munni Munni Intrusion

Minor low-grade nickel–copper occurrences (3644) have been located in drillholes and costeans in the basal ultramafic units along the northern edge of the intrusion.

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Figure 12. Photograph of chert outcrop ('gossan'), which is the surface expression of the No. 1 zone at the Sherlock Bay nickel deposit, looking to the southwest

Vanadium, titanium

Significant deposits of vanadiferous titanomagnetite (Fig. 11) were delineated by Mangore (Union Carbide) and Garrick Agnew in the 1960s in the Andover Intrusion at Andover (344), and in the Sherlock Intrusion at Balla Balla (287, 288, 289) and Don Well (290). Before then, two of these deposits were known for their iron content. In the early 1900s oxidized titaniferous magnetite material was extracted from quarries and shafts at Balla Balla for use as a flux in the treatment of copper ore at Whim Creek mine, and lenses of iron-rich material at Andover were examined and assessed for their iron content by AGGSNA in 1938 (Finucane and Telford, 1939b) and by GSWA in the late 1950s (Connolly, 1959). The titaniferous magnetite horizons occur at the contact between a lower differentiated sequence of gabbros and pyroxenites and an upper sequence of leucogabbro and granophyre.

At Andover, Garrick Agnew estimated about 0.48 Mt of V–Ti material. Further work was undertaken by Mangore (Union Carbide) at Balla Balla, where drilling of magnetic anomalies delineated substantial resources of V and Ti in three separate deposits. In 1975 Texasgulf estimated tonnages of non-oxidized material to be 24.2 Mt for Balla Balla East, 56.8 Mt for Balla Balla Central, and 58.2 Mt for Balla Balla West. More recently Tanganyika Gold NL has carried out further drilling and has estimated total inferred resources for the three deposits at Balla Balla as 117 Mt of oxide and primary ore at an average grade of 0.70% V_2O_5, calculated to a vertical depth of 120 m (Tanganyika Gold NL, Quarterly report for September 1998).

In 1965, another large deposit was located by Garrick Agnew at Don Well (west of Balla Balla) as a result of drilling a strong magnetic anomaly. In 1975–76 Texasgulf Australia drilled the titaniferous horizon along strike for 5 km and reported a 'resource', to a vertical depth of 50 m, as 17. 3 Mt of 0.59% V_2O_5 and 12.95% TiO_2. More-recent drilling has indicated that the deposit contains an inferred resource, to a vertical depth of 50 m, of 40.8 Mt of 0.57% V_2O_5 and 12.30% TiO_2 (Dominion Mining Ltd, Quarterly report for March 1999).

Titanium-rich magnetite material, occurring in lenses in layered gabbro, was also identified east of Mount Fisher (4428) during PGE exploration by Hunter Resources in 1985.

Chromium

Minor occurrences of chromite (Fig. 11) have been noted during exploration for PGE, the most significant being those located north of (structurally below) the Munni Munni PGE horizon (4009, 4011). Other localities were identified by Hunter Resources in fine layers in a serpentinite body close to Sherlock Homestead (2873) and in discontinuous magnetite-rich lenses in layered pyroxenite east of Mount Fisher (4433).

Platinum-group elements

The main occurrences (Fig. 11) are at Munni Munni, with minor occurrences at two other localities: Dingo Intrusion and Cooya Pooya Dolerite (south of Mount Fraser).

Munni Munni Intrusion

Munni Munni (2961) is the most significant PGE deposit located to date in Australia. Between 1985 and 1988 Hunter Resources Ltd drilled 66 diamond holes to test the mineralized porphyritic websterite horizon that occurs as a persistent layer (typically 2–5 m thick) over a strike length of 7.5 km at the boundary between the 'ultramafic zone' and the overlying 'gabbroic zone' of the Munni Munni Intrusion (Barnes et al., 1990, 1991, 1992; Hoatson and Keays, 1987; Hoatson et al., 1992; Williams et al., 1990). The PGE mineralization has developed near the base of a zone of disseminated nickel–copper sulfides (5–15 m thick) that is commonly between 0 and 15 m below the gabbro–ultramafic rock contact.

Average grades intersected were 2.9 g/t Pt–Pd–Au, 0.3% Cu, and 0.2% Ni; higher grades of 5–7 g/t total PGE and gold exist in the central part of the drilled area. The deposit has been drilled to a depth of about 550 m below surface and it remains open along strike and at depth. While drilling has been too widely spaced to enable a resource to be calculated in accordance with the JORC (1999) code, a figure of 20–30 Mt of potentially mineralized material has been quoted (Williams et al., 1990).

Another PGE zone, called 'J' reef (3643) has been located in drillholes and costeans within the basal ultramafic rocks along the northeastern edge of the intrusion. Other PGE occurrences were drilled by Hunter Resources along the southeastern edge of the intrusion at Munni Munni south, near the Zebra Hill dyke (720) in a websterite zone believed to be a southern extension of the main PGE deposit.

The Munni Munni Intrusion has been compared to the Great Dyke of Zimbabwe in terms of its geometry, structure, sequence of rock types, and distribution of PGE mineralization (Barnes et al., 1990, 1992). Barnes et al. (1990) suggested that the northerly striking Cadgerina Dyke on the northwest side of the intrusion could be a feeder dyke to the layered intrusion.

Other layered intrusions

PGE (and gold) are associated with nickel–copper sulfides of the Radio Hill and Sholl deposits (Hoatson et al., 1992). A minor occurrence of PGE was discovered by Hunter Resources during exploration of the Dingo Intrusion (719).

Cooya Pooya Dolerite

At the base of the Cooya Pooya Dolerite, south of Mount Fraser, Duval Mining and Hunter Resources located minor PGE in 1985 in a basal olivine cumulate unit (2844).

Mineralization in komatiite and high-Mg basalt

Nickel, copper

Ruth Well prospect

The nickel–copper deposit at Ruth Well (2955) has been assigned to this mineralization style in the sheared thick komatiitic sequence of the Ruth Well Formation (Tomich, 1974; Nisbet and Chinner, 1981; Marston, 1984) and it is often referred to as the only komatiite-type deposit in the Pilbara Craton (Fig. 11). However, it may be interpreted as a layered-mafic intrusive style, whereby part of a mineralized layered-mafic body has been emplaced tectonically into the foliated komatiitic sequence (during movement along the Sholl Shear Zone). This was suggested during the relogging and petrographic examination of drillcore from the prospect by AGIP–SAMIM (1985–86) when it was observed that textures of the sulfides and peridotite–pyroxenite host rock did not show a foliation, in contrast to the adjacent komatiites (Hoyle, M. W. H., 1998, pers. comm.). The Ruth Well area lies to the north of the Sholl Shear Zone, where there is a complex series of fault slices consisting of mafic and ultramafic metavolcanic rocks, granitoid, and intrusive gabbros and ultramafic rocks. If these intrusive gabbros and ultramafic rocks represent a western extension of the Andover Intrusion, then this may be where the sulfides at Ruth Well were initially formed.

Mineralization undivided

Nickel, copper

Three prospects were discovered by Westfield Minerals between 1970 and 1972 at Cunig, Sullam, and North Whundo (Fig. 11). Mineralization is in mafic volcanic rocks of the Nallana Formation near the contacts with layered-mafic intrusions; it is presumed that mineralization was introduced during the process of intrusion. At Cunig (4297) nickel–copper sulfides occur in a shear zone in metabasalt near the contact with gabbro. Copper mineralization at North Whundo (3301) occurs in metabasalt at the contact with gabbro of the North Whundo Intrusion. At Sullam (18) nickel mineralization is in metabasalt near a gabbro contact, and pyrite is the main sulfide with minor bravoite, violarite, and millerite. On the surface there is gossan material in an area of chert outcrop showing colloform texture in places, which suggests that the nickel mineralization may be an unusual epithermal occurrence (Marshall, A. E., 1998, pers. comm.).

Stratabound volcanic and sedimentary (VMS) mineralization

Volcanic massive sulfide (VMS) deposits occur in calc-alkaline volcanic-dominated marine successions and are often referred to as volcanogenic exhalative deposits. The deposits have formed from hydrothermal fluids (as syngenetic accumulations of sulfide and sulfate minerals) that were most probably generated by magmatic (subvolcanic) heat sources. Recent reviews of these deposits have been made by Large (1992), Franklin (1993), Pirajno (1994), and Solomon and Groves (1994). The deposits of the west Pilbara have been recently reviewed by Barley (1992), Downes et al. (1998), Collins and Marshall (1999a,b), and Ferguson (1999).

The VMS deposits of the west Pilbara (Fig. 13) occur in two zones of Archaean felsic and mafic metavolcanic rocks referred to as the Whim Creek Belt in the east and the Sholl Belt in the west (Collins and Marshall, 1999a,b). As a result of recent GSWA mapping and geochronological studies, the rocks of these belts have been assigned to the Whim Creek Group and the Whundo Group respectively (Hickman, 1997b). In the Whim Creek Belt there are three main VMS deposits at Whim Creek, Mons Cupri, and Salt Creek, with smaller prospects at Croydon Road, Western pits, Salt Creek east, and Balla Balla. In the Sholl Belt there are three VMS deposits at Whundo, Whundo West, and Yannery. Deposits in the two belts are discussed in detail by Miller and Gair (1975), Reynolds et al. (1975), Marston (1979), Nickel (1982), Barley (1992), Downes et al. (1998), and Collins and Marshall, (1999a,b), and only brief descriptions are given in this report. Elsewhere in the west Pilbara other probable VMS deposits in Archaean rocks are in the area of Shepherd Well and in Proterozoic rocks at Yarraloola.

For the purposes of classification in the WAMIN database (Appendix 1), the VMS deposits are considered below under the subheadings volcanic-hosted sulfide and sedimentary-hosted sulfide. Also, a number of base metal veins, genetically related to the VMS deposits of the Whim Creek Belt and Sholl Belt, are discussed later in the section on **Vein and hydrothermal mineralization**.

Volcanic-hosted sulfide

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

Mons Cupri

Mons Cupri is a copper–lead–zinc–silver sulfide deposit (2932) in two parts: an upper stratiform siliceous zone of lead–zinc(–copper–silver) mineralization and, underlying this, a discordant, funnel-shaped chloritic zone containing mainly disseminated and stockwork copper (–zinc–silver) mineralization (Miller and Gair, 1975; Tanner, 1990; Collins and Marshall, 1999a). Host rocks are felsic agglomerates and fragmental tuffs of the Mons Cupri Volcanics. The stratiform zone is 5–10 m thick in tuffaceous sedimentary rocks of the Cistern Formation and contains massive to semi-massive galena, sphalerite, chalcopyrite, and pyrite. The chloritic hydrothermal feeder zone is deeply oxidized and is now exposed as the prominent hill of Mons Cupri (Figs 8 and 14). Mineralization is mainly within a stockwork of chalcedony–siderite veins in which chalcopyrite is predominant over pyrite, with minor galena and sphalerite.

About 600 m northwest of Mons Cupri there is a small stratabound copper deposit at Western Pits (4074) in chloritized tuffaceous metasedimentary rocks.

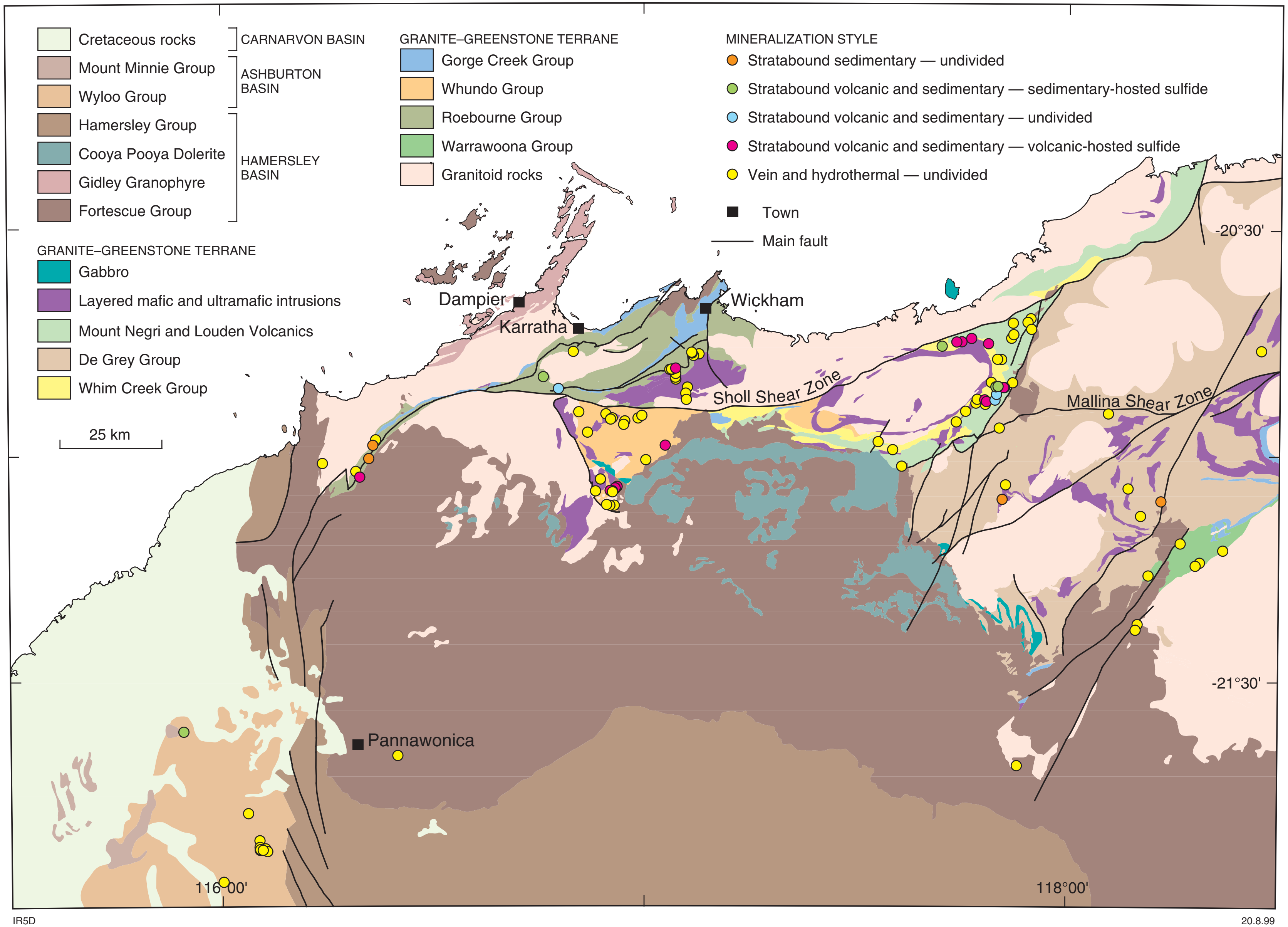

Figure 13. Distribution of base metal occurrences in the west Pilbara showing mineralization styles of stratabound VMS, stratabound sedimentary (undivided), and vein and hydrothermal

Figure 14. Photograph of Mons Cupri Hill taken from the southwest. Old lead–silver workings known as Comstock are located on the low ridge on the far left

Total production from Mons Cupri between 1899 and 1917 was 2428.12 t of copper ore and concentrates; in 1961, 209.46 t of cupreous ore was produced (Appendix 3.2). An estimate of 'in situ ore resources' at Mons Cupri in 1978 has been quoted as 1.51 Mt of oxide ore at 1.13% Cu, and 1.38 Mt of sulfide ore at 1.74% Cu, 2.48% Zn, 1.13% Pb, 46 g/t Ag, and 0.49 g/t Au (Collins and Marshall, 1999a). More recently, ore reserves of copper (leachable openpit proved and probable reserves of oxide and supergene material) were estimated to be 4.1 Mt at 0.75% Cu (Straits Resources Ltd, 1997).

Whundo

At Whundo (3366; Collins and Marshall, 1999b), stratabound copper–zinc mineralization is in chlorite–muscovite–quartz schist near the contact between mafic volcanic rocks of the Nallana Formation and felsic volcanic rocks of the Tozer Formation (Kojan and Hickman, in prep.). The Whundo mine consists of two deposits, Whundo and Whundo West, which are 350 m apart. Roberts (1974) recognized three types of sulfide mineralization: layered pyrite, sphalerite, and chalcopyrite; massive pyrite and pyrrhotite with minor sphalerite and chalcopyrite; and pyrite plus chalcopyrite in veins, layers, and stringers. Supergene and oxidized ore contains malachite, azurite, cuprite, and chalcocite. Whundo was found in 1911 (when it was first called Trouble copper mine) and there was some early production until 1920. Cupreous ore (for agriculture) was extracted in the 1950s. Extensive exploration was undertaken in the 1960s and early 1970s by Westfield Minerals and Consolidated Goldfields, which led to resource definition at both Whundo and the smaller deposit at Whundo West. There was no development until Whim Creek Consolidated NL undertook openpit mining of supergene ore at Whundo in 1976 to obtain copper for shipment (Fig. 15). Zinc-rich material remains in stockpiles on site and the small resource at Whundo West remains undeveloped.

Total production from Whundo has been 7358.74 t of copper ore and concentrates, plus 1066.92 t of cupreous ore (further details are in Appendix 3.2). At Whundo – Whundo West resource figures (not in accordance with the JORC Code) have been quoted as 2 Mt of sulfides at an average grade of 2% Cu, 1.3% Zn, and 11 g/t Ag (Davies and Blockley, 1990).

Two small zinc and copper occurrences were found close to the Whundo mine in felsic volcanic rocks during exploration in the 1960s and 1970s at Zinc gossan (3834) and Nicks gossan (3835).

Yannery

The Yannery stratabound deposit (3367; Collins and Marshall, 1999b) contains secondary mineralization including malachite, chalcocite, and cuprite. Mineralization is in quartz–chlorite–sericite schist (altered felsic metavolcanic rocks of the Tozer Formation) formed in the trough of a northwesterly plunging synform. The mine opened in 1913 and 476.76 t of copper ore and concentrates was produced until 1920. In the 1950s and 1960s a total of 1911.8 t of cupreous ore was extracted (Appendix 3.2).

About 600 m northeast of Yannery there is a small copper–zinc prospect at Chinamans Grave (3368) where gossans have developed at the unconformity between

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Figure 15. Photograph of Whundo openpit copper mine, looking toward the east, taken from the air in 1976 during mining of supergene ore. Photograph courtesy of Dominion Mining Ltd

schists of the Tozer Formation and overlying Hardey Sandstone. Drilling by Consolidated Goldfields in 1971 did not intersect any significant mineralization.

Shepherd Well

In the westernmost greenstone sequence low-grade volcanic-hosted base metal mineralization is found in the Nickol River Formation at Shepherd Well (291), where exploration drilling intersected lead, zinc, and silver in epiclastic tuffs and cherts. Further base metal sulfides were also located along strike to the north-northeast at Devil Creek (3756).

Sedimentary-hosted sulfide

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

Whim Creek

The Whim Creek copper–zinc deposit (2933) is a stratabound sediment-hosted volcanogenic deposit in strongly cleaved rocks of the Rushall Slate, a sequence of argillites, siltstones, and turbiditic greywackes. Thin sills of andesite lie above and below the mineralized horizon. The Rushall Slate overlies felsic rocks of the Mons Cupri Volcanics and is, in turn, overlain by the mafic Mount Negri Volcanics (Fig. 16). The sulfides accumulated from volcanic-exhalative fluids in more distal (basinal) facies compared to the proximal facies at Mons Cupri. The mineralized horizon is 150–200 m above the base of the Rushall Slate and can be traced for about 5 km around a circular basin that Collins and Marshall (1999a) interpreted as part of a caldera structure. The horizon is 1.5–3 m thick along most of its strike, but it thickens to 10–15 m in the mine area where the mineralization occupies the trough of a northeasterly plunging syncline lying between two northeasterly trending faults about 400 m apart. The primary sulfide mineralization occurs as discontinuous lenses and disseminations, and consists (in decreasing order of abundance) of cobalt-rich pyrite, pyrrhotite, chalcopyrite, and sphalerite, with minor galena, magnetite, and arsenopyrite. The supergene mineralization, which has accounted for all copper production from the mine, consists mainly of malachite, azurite, cuprite, and chrysocolla (chalcocite was recorded as important in Montgomery, 1907; Woodward, 1911; and Blatchford, 1921). In addition the supergene zone contains an abundance of other secondary minerals that have been described by Nickel (1982) and Downes et al. (1998).

Whim Creek has been one of the main producers of copper in the State. Since 1891 its production has been 74 489.68 t of copper ore and concentrates plus 12 098.3 t of cupreous ore (further details are in Appendix 3.2). An estimate of 'in situ ore resources' at Whim Creek in 1978 has been quoted as 1.37 Mt of oxide ore at 1.59% Cu, and 1.04 Mt of sulfide ore at 1.59% Cu, 1.3% Zn, 0.2% Pb, 8.6 g/t Ag (Collins and Marshall, 1999a). More recently, ore reserves of copper (leachable openpit proved and probable reserves of oxide and supergene material) were

Figure 16. Photograph of old workings at Whim Creek taken from the gossan ridge looking to the northeast. Mount Negri is in the background on the left

estimated to be 2.53 Mt at 1.34% Cu (Straits Resources Ltd, 1997).

Salt Creek

The Salt Creek copper–lead–zinc–silver sulfide deposit (301) is a small stratabound epiclastic-hosted deposit (Collins and Marshall, 1999a), which occurs in pyritic, tuffaceous siltstones that may be part of the Cistern Formation (Smithies, 1998a). These rocks are located south of the Sholl Shear Zone and overlie felsic volcanic rocks and volcaniclastic sedimentary rocks that may be part of the Mons Cupri Volcanics. The deposit appears to represent distal exhalative mineralization, which has accumulated at a slightly lower stratigraphic level than distal sulfides at the Whim Creek deposit. Mineralization is interbedded with the siltstones and consists of thin layers of massive and banded sulfides together with extensive sulfide stringer veins. The sulfides are pyrite, sphalerite, chalcopyrite, and galena, with minor magnetite. The tabular deposit has a strike length of about 200 m and is faulted into two lenses: A (west) and B (east); lens A is not exposed. Inferred resources for Salt Creek (lens A) have been estimated as 0.5 Mt at an average grade of 1.20% Cu, 3.0% Pb, 8.4% Zn, and 43g/t Ag (Pilbara Mines NL, 1994).

Further stratabound base metal sulfide layers occur in tuffaceous rocks about 3.5 km along strike to the east at Salt Creek east (302). East of the latter, at Balla Balla and West Balla (3800, 3801), a number of base metal occurrences have been located during exploration.

Yarraloola

At Yarraloola (3734) copper–lead–zinc mineralization is probably of distal volcanogenic origin. Mineralization occurs in basalt, felsic pyroclastic rocks, volcaniclastic sedimentary rocks, and chert of the Wyloo Group. Production of cupreous ore in 1963 was 2.75 t (Appendix 3.2). Exploration by WMC and Great Boulder Mines, between 1970 and 1980, revealed low-grade base metal mineralization. Further exploration at the prospect by Noranda (1983–84), and Renison Goldfields Corporation (1991) was not encouraging.

Stratabound sedimentary mineralization — undivided

Base metal — copper, lead, zinc (silver)

Egina

The Egina copper mine (3458) is in the southern part of the Mallina Basin, where stratabound mineralization appears to have become remobilized and concentrated in fold hinges of clastic metasedimentary rocks of the Mallina Formation (Marston, 1979). Recent work by Smithies (1997b) and Huston et al. (in prep.) proposed that metasedimentary rocks in the Mallina Formation may be correlated with the Rushall Slate of the Whim Creek Group, and it may be that base metal mineralization at Egina is related to distal hydrothermal activity. If such is the case, then Egina may be regarded as a volcanogenic sedimentary-hosted deposit.

Total production from Egina was 550.67 t of copper ore and concentrates, plus 29.05 t of cupreous ore (further details are in Appendix 3.2).

Croydon (Evelyn)

At the Evelyn copper (zinc, lead, silver) mine (3451) mineralization is in north-northeasterly trending shoots (probable shears) in folded tremolite schist and tremolite–chlorite schist that is close to the contact with medium- to coarse-grained clastic sedimentary rocks (Constantine Sandstone) in the core of the Croydon Anticline. The tremolitic schists have been included as part of the Millindinna Intrusion by Smithies (1998a). As at Egina, it appears that lower grade stratabound mineralization has been remobilized and concentrated into fold hinges (Marston, 1979), and it may be that Evelyn is a volcanogenic sedimentary-hosted deposit related to distal hydrothermal activity (Smithies, 1997; Huston et al., in prep.). A total of 598.42 t copper ore and concentrates was obtained from the mine from 1898 to 1909 (increasing sphalerite at depth discouraged further mining); 104.24 t of cupreous ore was taken out in 1952 and between 1959 and 1963 (Appendix 3.2).

Uranium, gold

Exploration since the late 1960s has tested the basal Hardey Formation in clastic sedimentary basins of the Fortescue Group for occurrences similar to those of the Witwatersrand in South Africa. Two occurrences of very low-grade uranium were located during drilling south of Croydon mining centre (3754, 3755).

Sedimentary — banded iron-formation (taconite) mineralization

Iron

The term taconite is used strictly as an economic term for unenriched banded iron-formation, which can be viably extracted and beneficiated after fine grinding (Trendall, 1983; Blockley, 1990). It represents a fourth category of iron ore in the Hamersley Iron Province, which at present is not economically exploited. The other three types of ore (that form the main orebodies of the province) are: pisolitic ore, supergene enrichment ore, and detrital ore. For the purposes of classification in the WAMIN database, these three types are considered under two mineralization styles and are discussed later under the headings **Regolith — alluvial to beach placers** and **Regolith — residual and supergene.**

The main occurrences of taconite in the west Pilbara are at Balmoral (3418), Bilanoo (3419), and Southwest Fortescue (3442).

Vein and hydrothermal mineralization — undivided

Precious metal — gold (antimony)

Structurally controlled vein and hydrothermal occurrences (also known as mesothermal or epigenetic lode occurrences) show two distinct areas of distribution (Fig. 17): a western area (west of Roebourne), and an eastern area (east of Whim Creek). Mineralization in both areas is in massive, brecciated and laminated quartz, forming single veins, multiple veins, and stockwork veins. Nearly all of the vein occurrences are surrounded by quite extensive alluvial ‘patches’, where substantial gold nuggets and large amounts of finer alluvial gold have been derived from the lodes.

In the western area the host rocks are mainly mafic–ultramafic metavolcanic sequences in the Roebourne Group, gabbros of the Andover Intrusion, and mafic–ultramafic and felsic metavolcanic rocks in the Whundo Group. The main structural control on mineralization is the east-northeasterly trending Sholl Shear Zone, or splays from this, and other main shears parallel to this zone (Plate 1 and digital geology on CD-ROM).

In the eastern area, turbidite-hosted (‘slate belt’) gold and gold–antimony deposits are in the Mallina Basin in clastic metasedimentary rocks of the Mallina Formation and in ?overlying mafic metavolcanic rocks of the Louden – Mount Negri Volcanics. The main structural controls are the east-northeasterly trending Mallina Shear Zone and the northeasterly trending Wohler Shear Zone or splays from these (Plate 1 and digital geology on CD-ROM). In addition, gold mineralization has accumulated at the contacts (and within) gabbro bodies and porphyry bodies that intrude the metasedimentary rocks in the central and southern parts of the basin.

Although there has been minimal research on mesothermal gold occurrences in the west Pilbara, it may be presumed that they have features in common with those of other Archaean greenstone sequences in the world. Since the late 1980s a very large number of research papers have considered this class of deposit, and there have been recent reviews by Groves (1993), Hodgson (1993), Solomon and Groves (1994), Pirajno (1994), Kerrich and Cassidy (1994), Groves et al. (1995), Witt and Vanderhor (1996), and McCuaig and Kerrich (1998). Common characteristics of the deposits, which also apply to those in the west Pilbara, are:

- they are late orogenic, and occur in metamorphic terranes;
- they are associated with major fault zones, or second or higher order splays, that have focused the flow of large volumes of metamorphic and igneous fluids;
- they occur in a wide range of brittle and brittle–ductile structures;
- they have developed in domains of lower strain where rock dilation has enabled mineralization to accumulate;
- the host rocks generally exhibit greenschist facies metamorphism.

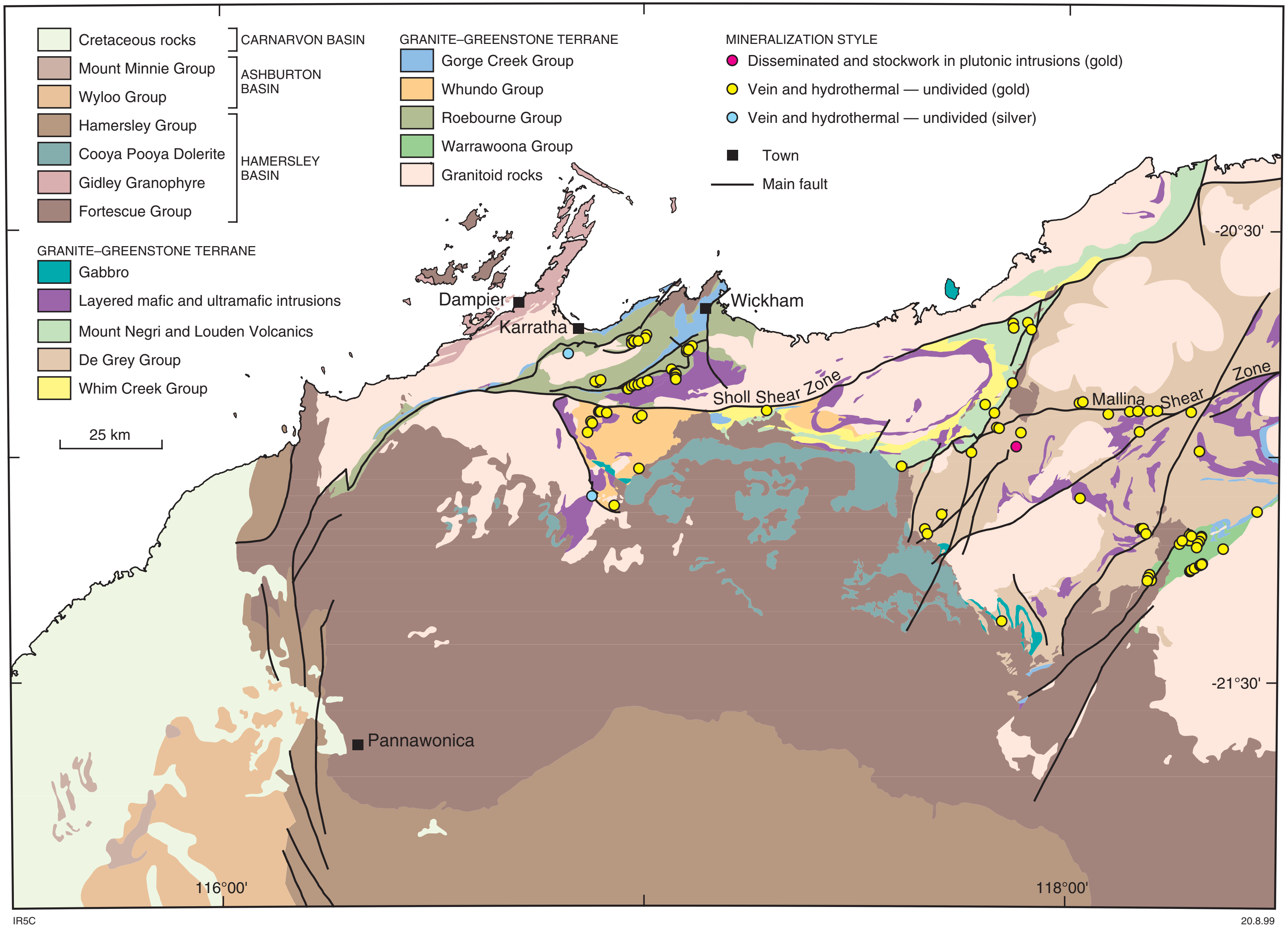

Figure 17. Distribution of mesothermal gold (vein and hydrothermal) occurrences, gold occurrences in stockwork veins in felsic plutons, and vein and hydrothermal silver occurrences in the west Pilbara

Gold production was significant in the late 19th century and early 20th century (Appendix 3.1). There are no producing gold mines in the area at present, apart from intermittent small-scale mining activity, but since 1997 there has been active and successful exploration in the Mallina Basin where Resolute Resources has an advanced project known as Indee.

In rocks of the Roebourne Group, the most significant mesothermal deposits are at Lower Nickol (3243, 3244, 3245, 3246, 3363), Weerianna (3254, 3255, 3256, 3257, 3630), and Carlow Castle (1975). Mineralization at Weerianna and Carlow Castle occurs in veins that are close to a main northeasterly trending sinuous, silicified, tectonized zone, appearing as a prominent 'chert' ridge (Hickman, in prep.). A number of smaller vein-hosted deposits, west of Carlow Castle, have been worked in the area of Sing Well (3248, 3249, 3250, 3251) and Six Mile Well (4006, 4008, 4010). Vein mineralization occurs in gabbros of the Andover Intrusion south-southeast of Carlow Castle, where there has been production from the small copper–gold mines at Fortune (1977, 1978) and Good Luck (3237). In the Whundo Group the main occurrences are to the west of the Sholl Intrusion at Radleys Find (2956, 3279) and the Four Ounce show (3283). Smaller occurrences are to the east of the intrusion at Sholl Northeast (3281) and south of this at East Well (3779, 3780).

The turbidite-hosted mesothermal gold occurrences in the Mallina Basin are historically important — it was the gold discovery at Mallina (725) that triggered the Pilbara gold rush in 1888. Other lode gold and alluvial gold discoveries were made in the basin at Egina (3460), Croydon (3454, 3455), and Station Peak (2889). Large amounts of gold were said to have been obtained from Egina and Croydon in the early years, but there are no official records of this early production.

The Station Peak centre has been the largest producer in the west Pilbara, and the gold veins occur in an altered gabbro body intruding metasedimentary rocks of the Mallina Formation; quartz porphyry dykes also occur along the contact of the intrusion (Finucane, 1937). Total mined gold production was 366.895 kg, plus 6.257 kg of alluvial and dollied gold (further details are in Appendix 3.1).

Characteristically, turbidite-hosted gold occurs in shears and stockworks with outcropping alteration zones of silicates, carbonates, iron oxides and iron sulfides. Elements associated with the gold are arsenic, antimony, tungsten, copper, lead, and zinc. In the Mallina Basin the gold–antimony association is common, as at Mallina (725) and Peawah (1997), with antimony more predominant in the northwestern part of the basin where veins occur in Negri Volcanics (1238, 1239, 1240, 1262, 1266, 3377).

In the southern part of the basin, scheelite was reported in stream sediments during exploration by Western Mining Corporation around Mount Satirist (3814, 3815, 3816) and minor copper–zinc–lead was recorded by Mallina Mining NL (during nickel–copper exploration) near Mount Satirist (6173) and Youlingoorina Hill (6175), where sulfides occur in quartz veins in Mallina Formation, close to contacts with layered-mafic sills of the Millindinna Intrusion. A galena vein was also reported near Station Peak gold mine although its exact location is not known (Montgomery, 1907; Blockley, 1971). Gold is predominant in the deposits at Croydon (3454, 3455), Station Peak (2889), Withnell (3651), Camel 1 and 2 (3652, 4012), Becher (3653), Withnell East (5841), Calvert (5844), Geemas (5847), and Charity (5849).

Significant gold mineralization occurs in a sequence of mafic to ultramafic (and minor felsic) metavolcanic rocks of the Warrawoona Group to the south of the Mallina Basin. There has been no modern regional assessment of gold potential in this area (although there was a major exploration program for nickel and base metals by Utah in the period between 1973 and 1975), and nearly all of the descriptive details are contained in the earliest GSWA reports of Montgomery (1907), Maitland (1909), Woodward (1911), and Blatchford (1913). Further information is contained in the AGGSNA reports of Finucane (1937) and Sullivan (1939). This area of Warrawoona Group rocks lies within the Yandeyarra Aboriginal Reserve and, following the completion of Utah's exploration program in 1975, access has been restricted for large-scale mineral exploration; only occasional prospecting and small-scale mining have been allowed by the local community.

The main old mining centres are at Pilbara (3526, 3528, 3529, 3538, 3539), Hong Kong (3482, 3488), Empress (3479, 3491, 3492), and Teichman (3468, 3469, 3464, 3466). The Pilbara centre is historically one of the richest nugget fields in an area where gold veins intersect an east-northeasterly trending belt of schistose mafic metavolcanic and gneissic rocks extending for about 12 km along the northwestern contact of the Yule Granitoid Complex. At Hong Kong there is a line of workings extending for about 850 m along a northeasterly trending zone of auriferous veins intersecting mafic metavolcanic rocks. About 2 km northeast of this zone there are other old workings at Princess May (3481) and Princess May East (3483) where mineralization occurs in quartz veins and associated pyritic quartz porphyry dykes cutting mafic metavolcanic rocks. At Empress and at Teichman a number of quartz vein deposits occur in mafic metavolcanic rocks. About 1.5 km southwest of Teichman, at Mountain Maid (3467), there is a vein deposit that has developed in both Warrawoona Group mafic rocks and unconformably overlying mafic rocks of the Fortescue Group. The official records of gold production unfortunately give a poor impression of the large amounts of gold taken from this area in the period between 1888 and 1920 (Appendix 3.1).

Precious metal — silver

The Elizabeth Hill silver deposit (721), located in veins adjacent to the northerly trending Munni Munni Fault, lies at the basal contact (northern edge) of the ultramafic zone of the Munni Munni Intrusion with an underlying granitoid body. Mineralization may be similar to deposits of silver (and cobalt) associated with gabbroic intrusions in the Cobalt district of Ontario, Canada.

Figure 18. Photograph of hand specimen of high-grade silver–calcite ore material from stockwork veins in the Elizabeth Hill deposit. Base of specimen is 10 cm. Photograph courtesy of East Coast Minerals NL and Legend Mining NL

High-grade silver was discovered during nickel–copper exploration by AGIP in 1987. Further exploration of the prospect since 1994 by East Coast Minerals NL – Legend Mining NL has revealed a very rich, but small, silver deposit. Mineralization is in a series of rich pods formed in a shear structure that links to the Munni Munni Fault lying immediately to the west (Barnes, 1995). Native silver and lesser amounts of silver sulfide minerals occur as both fine and coarse grains within a coarse-grained calcite vein stockwork (Fig. 18). Barnes (1995) considered that the mineralization is primary and could be related either to differentiation in the layered-mafic intrusion or to assimilation of country rock by mafic magma.

East Coast Minerals NL announced an indicated resource estimate for the deposit as 0.028 Mt at an average grade of 1% Ag* (announcement to the Australian Stock Exchange on 14 August 1998). Underground trial mining of the deposit commenced in April 1999, and the joint venture companies announced that the first trial shipment of 4 t of silver concentrate, containing 808 kg (26 000 oz) of silver, was made in June (East Coast Minerals NL, Quarterly report for 30 June 1999).

* East Coast Minerals NL have pointed out that prediction of the average grade is very difficult due to the 'nugget effect' caused by extremely rich silver veins and local erratic concentrations of native silver.

Base metal — copper, lead, zinc (cobalt, silver, gold)

Base metals in hydrothermal veins are common in faults and shears in all lithologies in greenstone sequences of the west Pilbara (Fig.13), and occurrences of this mineralization style were the first to be discovered near Roebourne in 1872. Hydrothermal base metal occurrences are described below under the subheadings of three types of host rocks.

Hydrothermal veins in mafic rocks

The Carlow Castle mine (1975) is believed to have been the site of the first copper discovery in the west Pilbara in 1872, when it was called Glenroebourne. It has been a producer of both copper and gold, as well as some silver; the ore is also cobaltiferous. Mineralization lies in seven northerly trending, steeply dipping veins in mafic metavolcanic rocks of the Ruth Well Formation, close to a main northeasterly trending tectonized silicified zone (Hickman, in prep.). Total production was 1041.03 t of copper ore and concentrates, plus 25.94 t of cupreous ore; some 7.87 kg of silver was also produced (further details are in Appendices 3.2 and 3.4).

The Fortune and Good Luck copper–gold mines are located about 1.5 to 2 km south-southeast of Carlow Castle. Mineralized quartz veins occur in shears in gabbro of the Andover Intrusion. Total production from the


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Figure 19. Photograph of old workings at the Andover lead–silver mine looking toward the north

Fortune workings (1977) between 1901 and 1919 was 418.99 t of copper ore and concentrates; in 1963–64, 16.88 t of cupreous ore was produced (Appendix 3.2). Production of copper ore from the Good Luck workings (3237) in 1917–18 was 5.29 t (Appendix 3.2).

The old lead–silver mine at Andover (2957) south of Roebourne was another of the first discoveries in 1872. A northerly trending vein (about 500 m long) intersects granitoid in the south and gabbro (Andover Intrusion) in the north (Fig. 19). Mineralization is galena, sphalerite, smithsonite, and malachite. The vein is pegmatitic in the south (at the main underlay) but becomes quartz rich to the north. Historical production was recorded only between 1948 and 1952, when 67.91 t of ore was produced (Appendix 3.3) yielding 44.17 t of lead and 14.213 kg of silver (Appendices 3.3 and 3.4).

At Croydon, also called Quamby (3452), to the north of the Evelyn mine, a narrow copper-rich quartz vein occurs in folded tremolite schists (Millindinna Intrusion) and metasedimentary rocks (Constantine Sandstone). In 1907 production was 15.24 t of copper ore and concentrates (Appendix 3.2).

Two small copper mines occur at Lilly Blanche (3258) and Ena (3259) to the west of Roebourne townsite. Copper-rich veins trend northeasterly in gabbro (Andover Intrusion) and metabasalt. Production from Lilly Blanche in 1907 and from 1915 to 1918 was 1057.17 t of copper ore (Appendix 3.2).

At Tom Well (3239), just south of Karratha, copper (–silver) mineralization occurs in an easterly trending vein in mafic to ultramafic metavolcanic rocks of the Regal Formation, lying about 50 m north of the contact with the Karratha Granodiorite. A number of old pits and shafts have been sunk along the vein over 140 m but there is no recorded production. There is further copper–silver mineralization in small quartz veins to the west of the old workings.

South of the Maitland Intrusion, the Maitland copper mine (3240) lies in sheared mafic metavolcanic rocks of the Nallana Formation. The shearing is associated with the Maitland Shear Zone just to the south. Production of cupreous ore was 37.99 t in the period between 1963 and 1969 (Appendix 3.2).

At Orpheus (3384) a copper–zinc(–silver–gold) prospect was discovered in 1995 during gossan sampling and follow-up drilling by Dragon Resources (Dragon Mining NL, Quarterly report for December 1995; Ferguson, 1999). Mineralized quartz veins occur in an area about 200 m wide and 1 km along strike in mafic metavolcanic rocks of the Bradley Basalt.

At South Whundo, east of the Maitland mine, the same zone of mineralized shears may be traced as a series of small copper pits (3242) in sheared ultramafic metavolcanic rocks of the Nallana Formation. In the easternmost workings gold is also associated with the copper (3772).

At Twin Table small copper workings occur in veins in sheared mafic metavolcanic rocks of the Nallana Formation (3238).

At Nickol River Hill (17) a northerly trending gossanous quartz vein has been tested by several small pits. Samples from the pits showed copper–lead–zinc–silver mineralization. The vein affects ultramafic metavolcanic rocks of Tozers Formation.

At Mount Negri small pits and shafts have been sunk on copper–lead veins in mafic metavolcanic rocks of the Mount Negri Volcanics, near the top of Mount Negri, and about 1 km further west of this (4102, 4436).

Mays Find (2931) is a prospect where gossanous quartz veins occur in sheared basalt of the Mount Negri Volcanics. Samples of gossan assayed up to 10.1% Pb, 0.45% Cu, and 230 g/t Ag (Collins and Marshall, 1999a). The basalt overlies a zone of mineralized felsic volcanic rocks and chert (Mons Cupri Volcanics) that contain gossans anomalous in copper, lead, and zinc.

Hydrothermal veins in felsic rocks

A northerly trending vein at Copper Bore (379) contains copper, lead, zinc, and silver mineralization. The vein intersects lithic tuffs of the Mons Cupri Volcanics and it represents the only base metal occurrence at the western end of the Whim Creek Belt.

The Comstock lead–silver lode (2934) lies along the crest of a low ridge about 500 m south of Mons Cupri hill. It is a northwesterly trending zone of intersecting mineralized quartz veins in the andesitic Comstock Member of the Rushall Slate. Total production of lead and silver between 1915 and 1917, and from 1950 to 1953 was 78.2 t of lead and 28.768 kg of silver (Appendices 3.3 and 3.4).

Small pits at Western Hill (3356) expose supergene copper mineralization in quartz veins cutting felsic volcanic rocks of the Mons Cupri Volcanics, near the contact with a gabbro body. In 1961, production of cupreous ore was 14.78 t (Appendix 3.2).

Bookingarra West (2930) is an exploration prospect where a galena-rich quartz vein occurs in a shear zone in rhyolitic rocks of the Mons Cupri Volcanics. A rock-chip sample from the vein contained 24% Pb and 400 g/t Ag.

The Canhams copper(–gold) prospect (2910) features prominently on the DAMPIER 1:250 000-scale topographic sheet, yet it is only a small pit 1.5 m deep. Copper mineralization is in a vein in felsic metavolcanic rocks of the Nallana Formation. A grab sample of material from the pit assayed 9.4% Cu, 4.6 g/t Au, and 70 g/t Ag (Dragon Resources, 1998, pers. comm.).

Lead–silver at the Nunyerry deposit (3475) occurs as mineralized quartz veins in a granitoid inlier in the Chichester Range north of Mount Florance Homestead. The deposit was discovered in 1957 by D. Hicks, who produced 1.17 t of lead and 0.381 kg of silver (Appendices 3.3 and 3.4).

Hydrothermal veins in sedimentary rocks

In the Ashburton Basin, copper veins intersect Duck Creek Dolomite at Red Hill (3794), where there has been a small amount of copper production (Marston, 1979).

Disseminated and stockwork mineralization in felsic plutonic intrusions

Precious metal — gold

At Toweranna gold mine (2890), northerly trending auriferous pyritic quartz veins lie within, and marginal to, a stock of coarse-grained feldspar porphyry, which is possibly related to the Peawah Granodiorite (Smithies, 1998b). The porphyry intrudes the Mallina Formation in the sheared axial region of the northeasterly plunging Croydon Anticline. Gold was discovered at Toweranna in 1895 and there was significant production between 1897 and 1901, and from 1913 to 1918 (Appendix 3.1; Telford, 1939b).

Thirteen kilometres south of Toweranna, Hickman (1983) noted that similar porphyry (with pyrite and magnetite) forms dykes in Mallina Formation in the axis of the anticline. The gold content of these dykes is not known.

Pegmatitic mineralization

Beryl, tantalum (tin)

A series of northeasterly trending pegmatites intrudes the ultramafic zone of the Andover Intrusion southeast of Roebourne (Ellis, 1962). Several pegmatite prospects have been worked for beryl(–tantalum–tin) in the Mount Hall area (3267, 3701, 3702, 3703).

In the Yule Granitoid Complex, beryl has been obtained from pegmatites at Corung Creek (3486), Mumbillina (3487), and south of Yule tin mine (3578).

Regolith — alluvial to beach placer mineralization

Pisolitic iron ore (Robe Pisolite)

For the purposes of classification in the WAMIN database these deposits are considered as a unique style of alluvial mineralization, in which the processes of physical and chemical weathering, transport, deposition, chemical concentration, and chemical precipitation have been involved. It would be misleading to refer to them as a supergene mineralization style, because they have not developed by secondary processes 'in situ' over primary

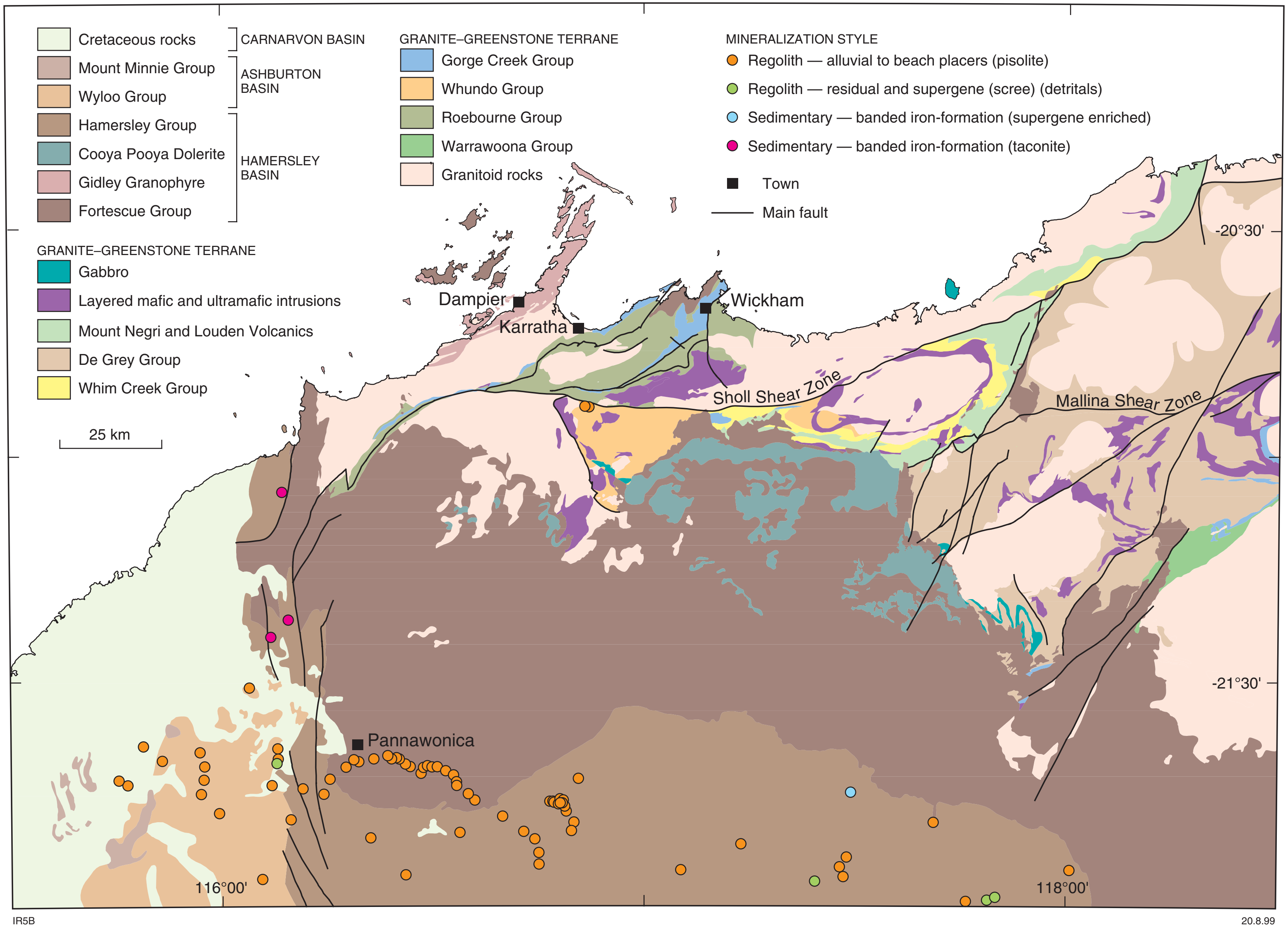

Figure 20. Distribution of iron ore occurrences in the west Pilbara

ore zones or, as in the case of supergene hematite and hematite–goethite ores of the Hamersley Basin, by enrichment processes in banded iron-formations.

The pisolitic ores are riverine palaeochannel deposits that consist of a mixture of hydrated oxides of iron and hematite (with some maghemite) forming cemented masses of concretionary spherulites. Detailed accounts of these deposits were provided by MacLeod et al. (1963), Harms and Morgan (1964), MacLeod (1966), Zimmerman et al. (1973), Adair (1975), and Butler (1976); an account of their geomorphological aspects was given by Twidale et al. (1985). The size of the spherulites (generally less than 2 mm) indicates that they should strictly be classified as ooliths, but MacLeod (1966) recommended use of the term 'pisolitic iron ore', to avoid confusion with 'oolitic iron ores of marine origin', and this became the accepted term until lately. As a result of recent industry-sponsored research it has been proposed that pisolitic iron ores should be called 'channel iron deposits' with the acronym 'CIDs' (Ramanaidou et al., 1991; Morris, 1994; Cudahy and Ramanaidou, 1997). However, this proposed nomenclature is not acceptable to all the iron ore producers.

It is generally agreed that the original source of the iron was the banded iron-formations of the Pilbara, but there is some contention over details of the mechanisms involved in the concentration of iron in the palaeochannels (Harms and Morgan, 1964; MacLeod, 1966; Butler, 1976; Hall and Kneeshaw, 1990). Notwithstanding these details, a simplified view is that the iron deposits formed in a forested mature landscape in swampy channels of broad meandering rivers. In the beds of the rivers there were accumulations of iron-rich fragments derived from the Hamersley banded iron-formations and overlying iron-rich laterite. These fragments acted as nucleii for the reprecipitation of dissolved iron (leached by acidic water from source rocks and laterite) so that alluvial muds and sands were gradually replaced to form thick channel-wide sheets of pisolitic iron ore.

These deposits can be traced in the drainage system of the Robe River for 160 km from Warramboo Station, on the North West Coastal Highway (Fig. 20), to the upper reaches of the river near Silver Grass Peak (just south of the southern boundary of Plate 1). In the Robe River valley the pisolite deposits were separated into three parts (for the purposes of exploration and initial development) known as the Upper, Middle and Lower Robe River areas. In the Upper Robe River area the pisolite forms benches along narrow valleys and gorges largely underlain by Brockman Iron Formation (Zimmerman et al., 1973). Downstream of the gorges the area of pisolite widens, in the Middle Robe River, where mesas with pisolite caps become prominent (Adair, 1975). In the Lower Robe River area the pisolitic mesa development is more extensive (Harms and Morgan, 1964). In the Lower and Middle Robe River areas the palaeochannels are incised into the underlying Early Cretaceous Yarraloola Conglomerate. In the westernmost Lower Robe River area, the channels become less defined and the pisolite is intercalated with sands and clays, suggesting a delta or coastal floodplain of the ancestral Robe River (MacLeod, 1966). As discussed earlier, since the early 1970s the Lower Robe River areas of pisolite ore have been referred to as the Deepdale and Eastern Deepdale deposits.

Robe River Iron Associates refers to the various pisolite deposits using an alphanumeric system for each mesa (Fig. 21). The Deepdale deposits are referred to as Mesas A to K (3421–3430). The Eastern Deepdale deposits are referred to as Mesas L to N (3431–3433). The Middle Robe River deposits are referred to as Mesas 2400A to G (6002–6004, 6006–6008, 6010–6011), Mesa 2401A (3854), Mesas 2402A to E (6012–6016), Mesas 2403A to E 6017–6021), and Mesa 2405A (6022). Total production from Robe River is 426 Mt of iron ore (further details are in Appendix 3.7).

Further upstream the 'gorge' deposits of Upper Robe River are numbered in the WAMIN database as 3704–3706, and 3717–3719. The Kumina Creek deposits are numbered 1, 2, and 3 (3623, 3720, 3721).

The large Bungaroo Creek deposit (3420), southeast of Mesa J deposit, is concealed below alluvium. Other small pisolite iron deposits are exposed at Jimmawurrada (3439), Dinner Camp (3732), Camp Pisolite (3782), Red Hill (3726), Peters Creek (3841), and Twin Table Hills (3817, 3818).

Precious metal — gold

The most important occurrences (Fig. 22) are those that were discovered between 1888 and 1892 at Pilbara (3536, 3544), Egina (3460, 3498), Lower Nickol (3253, 3364), Croydon (3453, 3454, 3455) and Womerina (3559, 3573, 3574). Although there are no complete official production figures from these mining centres, it is clear from early accounts of mining history that these were very rich areas for nuggets, slugs, and finer eluvial and alluvial gold. A substantial amount of alluvial gold has been extracted from the Friendly Creek alluvial tin operation (see below). Smaller areas of alluvial and eluvial material have been worked at Four Ounce Show (3283, 3380), Mount Sholl Northeast (3281, 3282), and in the area around the vein gold occurrences at Sing Well (3248) and Six Mile Well (4008).

Precious metal — platinum-group elements

Occurrences in the Nickol River alluvial gold workings (3241) were originally highlighted in exploration by Samantha Gold (Fig. 22) and followed up in research work by CSIRO (Horwitz and Hudson, 1983; Hudson and Horwitz, 1984). The source of the osmiridium was thought to be from an earlier palaeoplacer concentration. Horwitz (1990) reiterated that the source may be from either a palaeoplacer in the cherts of the Nickol River Formation or from fine-grained sediments low in the Gorge Creek Group (representing an old erosional surface) originally derived from an ophiolite sequence.

Tin

The only significant alluvial tin deposits in the west Pilbara are those at Friendly Creek, a tributary of the Yule River (Fig. 22). The deposits (3535) are located about 3 km east

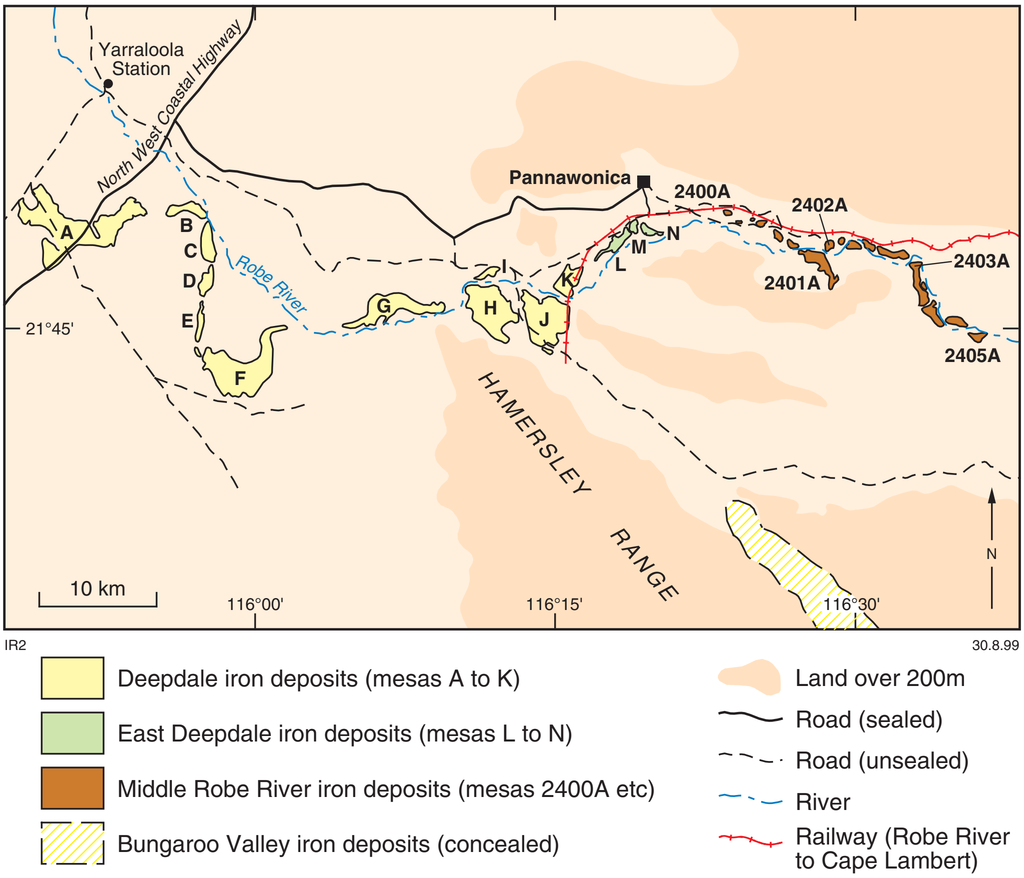

Figure 21. Map showing locations of Robe River iron deposits. Map redrawn from the original and published with permission of Robe River Iron Associates

of the Pilbara gold mining centre. They have been described in detail by Blockley (1980). The source for the cassiterite is considered by Blockley to be a series of aplite pegmatites of similar type to those at Moolyella and Shaw River in the east Pilbara. The pegmatites are probably related to a granite stock within the Yule Granitoid Complex. A substantial amount of tin concentrate (and gold) has been obtained from the Friendly Creek area (Appendices 3.1 and 3.6).

Heavy mineral sands

During exploration on the coastal plain in the west by Vam Limited, between 1969 and 1971, two sub-economic deposits (Fig. 22) were delineated at Robe River mouth (3863) and Fortescue River mouth (3865).

Regolith — residual and supergene mineralization

Iron

The supergene-enriched banded iron-formation ores are commercially the most important of the State's iron ore resources, and they occur in the Brockman Iron Formation and Marra Mamba Iron Formation of the Hamersley Group. The ores are referred to as supergene hematite and hematite–goethite ores, which have developed as a result of enrichment processes in banded iron-formations (Blockley, 1990). There is one occurrence of this type in the west Pilbara, in the southeast of the area (3665), but it is of low grade.

The category of iron ore deposits referred to by industry as 'detritals' represents iron-rich scree (talus) material that has developed adjacent to the supergene enrichment bedrock source of hematite and hematite–goethite deposits (Preston, 1998). For the purposes of classification in the WAMIN database these detrital ores are included with supergene enrichment ores. Deposits of detrital iron ore occur in the southeastern corner of the west Pilbara area (Fig. 20), at Mount Pyrton (3558), Mount Margaret (3556, 3557), and P5 (3566). There is also an isolated occurrence at Yeera Bluff 2 (3760), about 20 km west of Pannawonica.

Mineralization controls and exploration potential

In the west Pilbara most of the mineralization and exploration potential is within the relatively small area of the Archaean granite–greenstone terrane. Although small,

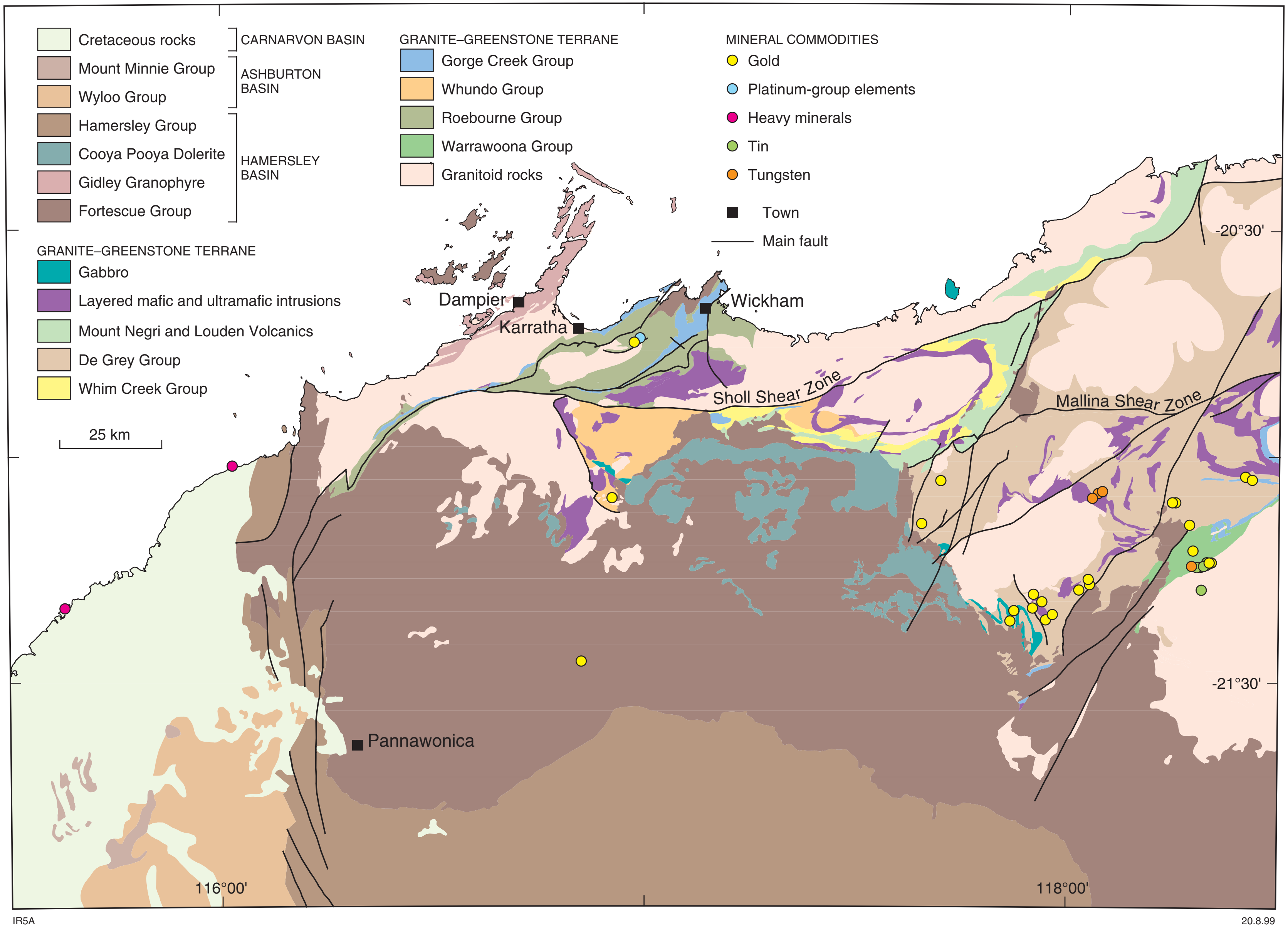

Figure 22. Distribution of alluvial to beach placer occurrences of gold, platinum-group elements, heavy mineral sands, tin, and tungsten in the west Pilbara

this area contains a wide variety of mineralization styles and exploration targets, many of which have been pursued since the late 1960s. While there was early success with nickel–copper and base metal discoveries, with the most prominent magnetic and geochemical anomalies being drilled, later exploration success was hampered by the limitations of geophysical and geochemical techniques available at the time. However, since the mid-1990s, the recently developed techniques of mobile metal ion (MMI) in geochemistry (Mann et al., 1998) and airborne 'GEOTEM deep' in geophysics (Peters, 1996) are being used to detect deeper zones of mineralization that were not responsive to older exploration methods in prospective areas of the west Pilbara. A recent review of the latest geophysical techniques in use in Western Australia, compiled by Dentith et al. (1994), includes examples from the west Pilbara. A multi-element geochemical method applicable to VMS mineralization in the west Pilbara has also been discussed by Rugless and Vanderplank (1995).

Orthomagmatic mafic and ultramafic mineralization

Nickel–copper

The main nickel sulfide deposits in the area are hosted by layered-mafic intrusions. Although the west Pilbara attracted early exploration interest for this style of nickel mineralization, the search for further deposits dwindled in the middle to late 1970s as commodity prices fell and there was a growing perception amongst exploration geologists that this mineralization style was typified by small low-grade deposits.

Since the discovery of the mammoth nickel deposits at Voisey's Bay in eastern Labrador in 1994 (Naldrett et al., 1996), however, attention has refocused on the potential of layered-mafic intrusions elsewhere in the world. As a consequence there has been a renewal of activity to explore the layered intrusions of the west Pilbara for similar occurrences to Voisey's Bay. In the exploration model for the latter, an important target area for sulfide accumulation is the feeder zone to the layered intrusion. Such a target area may be represented at the surface by a later stage of mafic intrusion, which may be expressed as a concentration of gabbroic sills and dykes.

There is also potential for nickel deposits, similar to those of the Thompson nickel belt in Canada, along the complex structural corridor of the Sholl Shear Zone.

Although only one komatiite-associated deposit has been found in the area, at Ruth Well (which could also be interpreted as a layered-mafic intrusive type), the discovery was made many years prior to the development of the new model for the segregation and accumulation of sulfides resulting from komatiitic volcanism (Hill et al., 1988, 1990, 1996). This model has been used successfully for nickel exploration in the eastern Yilgarn Craton, but there has been little attempt so far to apply it in the west Pilbara. The areas with the most potential are those having thick sequences of komatiite and high-Mg basalt, such as areas of the Ruth Well Formation in the west component and the Warrawoona Group in the east component of the North Pilbara granite–greenstone terrane.

Platinum-group elements

The main host rocks occur in layered-mafic intrusions in which the target horizon for PGE accumulations is located near the contact between the main ultramafic zone and the overlying mafic zone, as at the Munni Munni Intrusion (also the Bushveld Complex, the Great Dyke of Zimbabwe, and the Stillwater Complex). Other accumulations, similar to the 'J' reef at Munni Munni, may develop in the lower parts of the ultramafic zone. There is potential for PGE mineralization associated with nickel–copper deposits, as at Radio Hill and Sholl.

Exploration has identified PGE concentrations in an area of olivine cumulate rocks near the base of multiple intrusions of the Cooya Pooya Dolerite, south of Copper Bore, but as yet there has been no regional follow-up to test the potential for this target elsewhere in the west Pilbara.

Recent work in Canada has highlighted occurrences of disseminated PGE in thick (80–130 m) differentiated mafic–ultramafic flows in the Archaean Abitibi greenstone belt, Ontario (Stone et al., 1996). It is possible that such a style of PGE mineralization may be a source for the Nickol River alluvial osmiridium deposits (Horwitz and Hudson, 1983; Hudson and Horwitz, 1984). Most importantly, it appears to have been overlooked as an exploration target in the west Pilbara area, in particular in the thick komatiitic sequences of the Ruth Well Formation and the Warrawoona Group.

Vanadium, titanium, chromium

Deposits of vanadiferous titanomagnetite occur within the upper gabbro–leucogabbro zones of two layered-mafic intrusions (Sherlock and Andover). In areas lacking outcrop, these deposits have been located by drill-testing strong, positive, linear magnetic anomalies. While it is possible that other similar deposits, marked by magnetic anomalies, occur below thick alluvial cover of the coastal plain between Roebourne and Sherlock, they would not be an attractive exploration target because any openpit mining would involve removal of very thick overburden in an area subject to inundation.

To date only small pods of chromite-rich material have been located in outcrop at the Munni Munni and Sherlock Intrusions, near the contact between the ultramafic and mafic zones. It is possible that more continuous chromite-rich seams could occur in areas of this contact zone concealed beneath alluvial or colluvial cover.

Gold

Recent research in the Skaergaard Intrusion has highlighted the potential for gold in layered-mafic intrusions (Bird et al., 1991; Anderson et al., 1998). This style of gold mineralization does not yet appear to have attracted any exploration attention in the west Pilbara.

Stratabound volcanic and sedimentary mineralization (VMS)

Copper, zinc, lead (silver, gold)

The most prospective areas are those of calc-alkaline volcanic and volcanogenic sedimentary rocks of the Whim Creek Group (c. 3010 Ma) in the east and the Whundo Group (c. 3120 Ma) in the west. Another area of high prospectivity is in the far west along a corridor of the Roebourne Group, in particular the Nickol River Formation (c. 3270 Ma), that flanks the Sholl Shear Zone.

A major factor influencing further exploration in these prospective areas is the effectiveness of various geochemical and geophysical techniques in detecting anomalous zones that may represent base metal sulfide bodies. In the Whim Creek – Mount Fraser area various electromagnetic surveys have shown that the lithologies are highly resistive over prospects that may contain large, blind, moderately deep (>200 m) sulfide zones. In the Salt Creek – Sherlock Bay area, electromagnetic surveys are further hampered by near-surface saltwater intrusion along the coastal flats. Magnetic surveys have had limited effectiveness as an exploration tool for copper–zinc sulfides in the west Pilbara because the known deposits (Whim Creek, Mons Cupri, Salt Creek, and Whundo–Yannery) are not associated with large amounts of magnetite. Accordingly, they show only a weak magnetic response; although the weak magnetic anomaly associated with the Mons Cupri deposit has a rather distinctive ‘tadpole’ shape.

The base metal potential of the Mallina Basin is largely untested. Recent work by Smithies (1997) and Huston et al. (in prep.) has suggested close similarities between the stratigraphic and structural setting of mineralization in the Croydon and Egina areas (in the southern part of the basin) to the setting at Whim Creek.

The potential of the Fortescue Group for VMS mineralization has recently been highlighted by the work of the Geological Survey during mapping of PINDERI HILLS (Kojan and Hickman, 1998). Geochemical and petrographic studies suggest that felsic and intermediate volcanic rocks in the Kylena and Maddina Formations show evidence for a calc-alkaline fractionation trend, which may be interpreted as a change in tectonic setting to a subduction-related environment (at c. 2717 Ma) from a rift-related environment (at c. 2765 Ma) of the Mount Roe Basalt and Hardey Formation. This evidence points to a style of volcanism that may be associated with base metal mineralization.

Sedimentary (banded iron-formation) mineralization

Iron

In the west of the region, there is potential for possible future development of unenriched (taconite) material in the banded iron-formations in the Cleaverville Formation, the Marra Mamba Iron Formation and the Brockman Iron Formation.

Vein and hydrothermal mineralization

Gold

Turbidite sequences

Until quite recently, gold mineralization in turbidite sequences (also referred to as ‘slate belts’) appears to have been overlooked as an exploration target in the State, despite the fact that large gold deposits of this type are found in a number of places in Australia and around the world in rocks ranging in age from Archaean to Cainozoic (e.g. Bendigo–Ballarat, Victoria; Hodgkinson Basin, Queensland; Otago area, New Zealand; Nova Scotia, Canada; Slave Province, NWT, Canada; Juneau gold belt, Alaska). This type of deposit has been reviewed by Boyle (1986).

One of the recent successful exploration programs, by Resolute Resources, has been to test the potential for turbidite-hosted gold(–antimony–arsenic) deposits in the Mallina Formation in the east. Surprisingly, this area has not received much attention (since WMC’s exploration program in 1983–84) in the recent gold boom prior to Resolute’s work, even though historical records show that rocks of the Mallina Formation (emplaced within mafic intrusions) have been the source of significant gold: at Mallina, Croydon, Egina, and Station Peak. Nor has there been much attempt to explore for similar gold–antimony deposits in the adjacent (?overlying) mafic volcanics of the Mount Negri Volcanics in the northwest of the Mallina Basin.

The main structural control on mineralization within the Mallina Basin is the northeasterly trending Mallina Shear Zone and splays from this. In the northwest of the basin the main control is the east-northeasterly trending Sholl Shear Zone. Indications of mineralization may be seen at the surface as zones of silicification, carbonatization, chloritization, and (in areas near Mallina) tourmalinization. Recent exploration has been successful using drilling to test geochemical targets outlined by anomalous gold, arsenic, and antimony.

Mafic–ultramafic sequences

In the western area mesothermal mineralization is structurally controlled within mafic–ultramafic volcanic rocks of the Roebourne Group (as at Lower Nickol River, and Weerianna mining centres) and the Nallana Formation of the Whundo Group (Radleys Find and Four Ounce Show). The main control is the sinuous easterly to east-northeasterly trending Sholl Shear Zone and northeasterly trending splays from this. The exploration potential of gold lodes in the mafic–ultramafic volcanic rocks of the area has received little attention since the middle to late 1980s when a number of drilling programs tested the potential only for near-surface resources. Results from these tended to show that many lodes were discontinuous along strike and the various deposits were considered to be subeconomic for openpit development. However, there is potential for larger, more continuous zones of structurally controlled mineralization. To assess such potential, further exploration programs will need to identify structural corridors using the latest geoscientific data available from the 1:100 000-scale geological mapping program of the GSWA and the higher resolution airborne magnetic surveys completed by AGSO.

In the east there is significant potential for this type of gold target in mafic–ultramafic rocks of the Warrawoona Group in an area extending from the old mining centre at Hong Kong southward to the old centres at Teichman and Pilbara.

Silver

The silver occurrence at Elizabeth Hill, in hydrothermal veins at the northern contact of the Munni Munni layered-mafic intrusion, suggests similarities to silver deposits developed in the Cobalt district of Ontario. It has highlighted the potential for other occurrences of this mineralization style in all of the layered intrusions of the west Pilbara.

Copper, lead, zinc (silver, gold)

There is potential for epigenetic base metal mineralization associated with volcanic centres in areas of felsic volcanic rocks (Lyre Creek Member) of the Hardey Formation in the Fortescue Group, although there has not been any recorded exploration for this particular target (Witt et al., 1998).

Mineralization in kimberlite and lamproite intrusions

Diamond

The west Pilbara area has potential for the discovery of diamondiferous pipes and dykes of kimberlite and lamproite, associated with deep crustal fractures that affect both the North Pilbara granite–greenstone terrane and the overlying Hamersley Basin. Airborne magnetic surveys completed by AGSO in 1995 have provided industry with improved regional data for targeting areas of bull's-eye anomalies that may represent such intrusions.

Alluvial to beach placer mineralization

Pisolitic iron ore

There is significant potential for the discovery of large deposits of pisolitic ore concealed beneath alluvial cover in the Fortescue Valley. However, it is unlikely that exploration would commence for many years until the current inventory of pisolite resources has been developed and there is a need for further resources.

Gold (uranium)

Since 1968, several companies have tested the potential for gold and uranium in Archaean palaeoplacers in the Hardey Formation of the Fortescue Group. Although drilling results at a few prospects have not yielded encouraging results, there may still be significant potential for this 'Witwatersrand' type of deposit in clastic sedimentary basins of the Fortescue Group, given that suitable source rocks do exist: perhaps as earlier palaeoplacers in previously deposited Lower Fortescue rocks or as lode gold material from greenstone sequences (e.g. Mallina Basin rocks).

There is significant potential for Cainozoic alluvial gold deposits, particularly in the east, in the present drainages and in earlier palaeochannels that may contain material sourced from lode gold mineralization in rocks of the Mallina Basin.

Conclusion

The west Pilbara must still be considered as a most prospective underexplored part of the State for a broad range of commodities in a variety of mineralization styles. Many areas have been highlighted during past exploration as being prospective for volcanogenic base metal sulfides, nickel–copper sulfides, PGE, and gold. They have yet to be fully tested by the latest geochemical and geophysical exploration methods, and to be assessed in the light of new geological concepts arising from the mapping program and the airborne geophysical surveys of the current National Geoscience Mapping Accord.

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Appendix 1

WAMIN and EXACT databases

WAMIN database (mineral occurrences)

The WAMIN* 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 report only deals with mineral occurrences. These and other attributes were extracted either from open-file mineral exploration reports in WAMEX† or from the published literature.

Those elements of the database that were used to create the symbols for mineral occurrences and tabular information displayed in Plate 1 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); and
- mineralization style (symbol shape).

The elements of the database used for symbology in Plate 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, the north Eastern Goldfields, and the Bangemall Basin.

* WAMIN Western Australian Mineral Occurrence database
† WAMEX Western Australian Mineral Exploration database

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 Minerals and Energy (DME) mines and mineral deposits information database (Townsend et al., 1996). All occurrences in the WAMIN database are assigned with a unique, system-generated number (deposit number). The font style of this number (bold, italicized, and so on) is used as the coding to indicate operating status both on the face of the map and in the accompanying table. The system used in Plate 1 is:

- Mineral occurrence — any economic mineral exceeding an agreed concentration and size found in bedrock or regolith (italic serif numbers, e.g. *2905*).
- Prospect — any working or exploration activity area that has found subeconomic mineral occurrences, and from which there is no recorded production (italic serif numbers, e.g. *14*).
- Mineral deposit — economic minerals for which there is an established resource figure (serif numbers, e.g. 314).
- Abandoned mine — workings that are no longer operating, or are not on a care-and-maintenance basis, and for which there is recorded production, or where field evidence suggests that the workings were for more than prospecting purposes (bold–italic sans serif numbers, e.g. ***263***).
- Operating mine — workings that are operating, including on a care-and-maintenance basis, or that are in development leading to production (bold sans serif numbers, e.g. **1457**).

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). As some occurrences will not have been named in the past, these appear without names in the WAMIN database and in the table shown in Plate 1. That is, no attempt has been made to provide names where none are currently recognized. 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.

Table 1.1. WAMIN authority table for commodity groups

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

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. The commodity group, as listed in Table 1.1, determines the particular colour for the mineral occurrence symbols in Plate 1.

The commodity groupings are based on those published by the Mining Journal (1998) with modifications, as shown in Table 1.2, to suit the range of minerals and end-uses for the mineral output of Western Australia.

Mineralization style

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

Table 1.2. Modifications made to the Mining Journal Ltd (1998) commodity classification

Commodity group (Mining Journal Ltd, 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 1.3. WAMIN authority table for mineralization styles and groups

Mineralization style	*Typical commodities*	*Group symbol*[(a)]
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	▽

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

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 1.3).

To fully symbolize all the mineralization style groups would result in a system that is too complex. As the full details of the classification are preserved in the underlying WAMIN database, the chosen symbology has been reduced to nine shapes (Table 1.3).

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 1.4.

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, which has been developed by the 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

* 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 1.4. 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

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 (either AMG or latitude/longitude coordinates), the resulting search will produce all reports for the 1:100 000-scale sheet in which that single point is located. Hence, for example, it is not possible to restrict report selection to small areas of prospective ground of particular interest to the user. As a consequence these WAMEX searches are time consuming, and they have become more time consuming as the number of open-file reports has increased with continuing releases of data.

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

The spatial index consists of an attribute database, developed in Microsoft Access, which is linked to ArcView for spatial representation. In 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 Arc/Info, and then transferred into ArcView to enable an interactive display of EXACT. The positional data are digitized from hard-copy maps and plans in mineral exploration reports, using various published sources (geological maps, topographic maps, and TENGRAPH†) for georeference purposes. The types of exploration activity detailed are essentially those used in WAMEX, with some rationalization, and these are listed in Table 1.5. 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 analyzed (asterisk symbol (*) against elements for a rough guide to anomalism)
- metres of drilling and number of holes
- scales of presentation of data in reports.

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

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

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

† DME's electronic tenement-graphics system

Table 1.5 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 2

Description of digital datasets on CD-ROM

There are three principal components of this study, which are this report, Plate 1, 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 map and report, 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 report and on Plate 1 is described in Appendix 1. The dataset on the CD-ROM includes textual and numeric information on:

- location of the occurrences (AMG coordinates, latitude and longitude, geological province, location method, and accuracy);
- commodities and commodity group;
- mineralization classification and morphology;
- order of magnitude of resource tonnage and estimated grade;
- mineralogy of ore and gangue;
- details of host rocks;
- 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 report is described in Appendix 1. The dataset on CD-ROM contains spatial and textual information (derived from WAMEX open-file reports) defining the locations and descriptions of exploration activities in the area. EXACT, for the west Pilbara area, was compiled between 1996 and 1998, and contains information on types of mineral exploration activity such as statistics relating to:

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

Positional data were taken from hard-copy maps of various scales, from company reports (in WAMEX), located from coordinate and/or geographical information (from topographic maps or Landsat images), and then digitized. Table 1.5 (in Appendix 1) 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 exploration concept, activities, and a synopsis of results.

WAMEX

All relevant open-file company mineral exploration reports for the area, indexed in the Department of Minerals and Energy (DME) 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) has current information on all mines, process plants, and deposits, excluding petroleum and gas, for Western Australia. Mineral resources included in MINEDEX must conform to 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 (DME's electronic tenement-graphics system) shows the position of mining tenements 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.

Solid geology and regolith

The solid geology and regolith incorporates an interpretation of the study area, at 1:100 000 scale, based on a recent compilation of the Geological Survey of Western Australia (GSWA) mapping, aeromagnetics (TMI images), and Landsat TM imagery. The full details of the solid geology and regolith are held on the CD-ROM. The regolith on Plate 1 is a simplified version of the digital dataset on the CD-ROM, and uses two overprints to distinguish relict and depositional regimes. The CD-ROM also includes a large number of solid geology and regolith units that are smaller than 250 000 m^2 in area that were omitted from Plate 1 for simplicity.

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 Australian Geological Survey Organisation (AGSO) 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 AGSO.

Measurements of the background radiation using an airborne crystal usually took place concurrently with the AGSO 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 AGSO, 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 west Pilbara study. The raw data are available commercially through the Remote Sensing Services section of the Department of Land Administration (DOLA). Images are included in the digital package that preserve the original 25 m pixel size, but these cannot be reverse-engineered back to any bands or band ratios of the original 6-band dataset.

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

Cultural features

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

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

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Appendix 3

Tables of production figures for the commodities gold, copper, lead, silver, antimony, tin, iron ore, and nickel mined in the west Pilbara

Table 3.1. Historical gold production in the west Pilbara (1897–1983)

Mine group	*Period*	*Gold mined (kg)*	*Alluvial and dollied gold (kg)*
Station Peak	1902–1908	291.813	–
	1909–1911	58.688	6.037
	1913	0.303	0.22
	1915–1919	0.169	–
	1940–1950	14.654	–
	1950–1952	1.268	–
Total		**366.895**	**6.257**
Toweranna	1897	1.84	–
	1897–1901	55.896	–
	1913–1918	96.397	0.81
Total		**154.133**	**0.81**
Weerianna	1897	5.789	–
	1900	1.063	–
	1908–1911	31.322	–
	1911–1915	57.619	–
	1927	0.108	–
	1934–1937	4.08	–
	1938–1942	11.08	–
Total		**111.061**	**–**
Friendly Creek	1973–1975	1.439	4.082
	1980–1983	52.825	1.216
Total		**54.264**	**5.298**
Carlow Castle	1910–1913	17.85	–
	1919–1924	0.657	–
Total		**18.507**	**–**
Lower Nickol	1900	0.304	–
	1901–1910	11.608	0.34
	1961–1962	0.218	–
Total		**12.130**	**0.34**

Mine group	*Period*	*Gold mined (kg)*	*Alluvial and dollied gold (kg)*
Hong Kong	1899–1900	9.702	–
	1907	0.598	–
Total		**10.300**	**–**
John Bull	1897–1899	7.27	–
Total		**7.27**	**–**
Mallina	1897	0.225	–
	1897–1900	2.974	–
	1913	0.797	–
Total		**3.996**	**–**
Mountain Maid	1917	0.179	–
	1920–1921	3.559	–
Total		**3.738**	**–**
Empress	1897–1899	3.317	–
Total		**3.317**	**–**
Pilbara	1897	1.857	–
	1908	–	1.497
	1955	0.599	0.308
Total		**2.456**	**1.805**
Princess May	1897	0.743	–
Total		**0.743**	**–**
Nickol King (?Radleys Find)	1913	0.357	–
Total		**0.357**	**–**
Croydon	1898	0.69	–
Total		**0.69**	**–**
Good Fortune	1916–1920	0.123	–
Total		**0.123**	**–**

SOURCE: For all tables — Department of Minerals and Energy MINEDEX database

Table 3.2. Historical copper production in the west Pilbara (1897–1983)

Mine group	*Period*	*Copper ore and concentrates (t)*	*Cupreous ore and concentrates (t)*	*Average grade [(a)] (%)*	*Contained copper (t)*
Whim Creek	1891–1893	735.6	–	15	220.68
	1898–1901	9 242.6	–	16.59	1 533.65
	1906–1919	64 481	–	12.28	7 919.1
	1949–1958	–	10 856	5.78	588.84
	1963–1964	–	1 242.3	23.51	292.17
(Rushalls)	1899	20.32	–	15	3.05
(Stranger)	1899	10.16	–	25	2.54
Total		**74 489.68**	**12 098.3**	**12.19**	**10 560.03**
Mons Cupri	1899	374.9	–	12.99	48.74
	1899–1901	1 666.2	–	12.81	204.29
	1911–1917	387.02	–	11.95	34.29
	1961	–	209.46	7.82	16.39
(Western Hill)	1961	–	14.78	10.45	1.54
Total		**2 428.12**	**224.24**	**11.51**	**305.25**
Whundo	1911	23.58	–	26.8	6.32
	1915–1918	392.38	–	21.3	83.57
	1920	331.81	–	17.99	59.62
	1920–1921	410.97	–	21.54	88.53
	1953–1959	–	1 056	9.83	103.81
	1957(sundry)	–	10.92	4.75	0.52
	1976	6 200	–	26.98	1 673
Total		**7 358.74**	**1 066.92**	**23.92**	**2 015.37**
Yannery	1913–1920	476.76	–	24.25	115.63
	1951–1968	–	1 911.8	12.87	245.99
Total		**476.76**	**1 911.8**	**15.14**	**361.62**
Carlow Castle	1899	135.13	–	22.76	30.75
	1900	26.42	–	23.99	6.34
	1907	88.39	–	24.0	21.22
	1909–1913	421.82	–	18.46	58.2
	1914	22.79	–	15.56	3.55
	1916	70.1	–	11.3	7.92
	1917–1928	170.13	–	14.78	25.15
	1956–1957	–	25.94	8.12	2.1
	1957	106.25	–	9.79	10.4
Total		**1 041.03**	**25.94**	**15.52**	**165.63**
Fortune	1901	22.35	–	20.46	4.57
	1908–1910	51.89	–	22.87	11.87
	1912–1919	344.75	–	18.54	63.92
	1963	–	2.8	10.3	0.28
	1963–1964	–	14.08	12.99	1.83
Total		**418.99**	**16.88**	**18.92**	**82.47**
Good Luck	1917–1918	5.29	–	19.4	1.03
Total		**5.29**	**–**	**19.4**	**1.03**
Weerianna	1907	1 019.6	–	18.71	190.76
(Lilly Blanche)	1908	20.32	–	14.37	2.92
	1915–1916	17.25	–	17.49	3.02
Total		**1 057.17**	**–**	**18.60**	**196.7**
Croydon	1899	176.78	–	15.23	26.93
(Evelyn)	1900–1909	421.64	–	18.99	80.06
	1952	–	93.18	6.95	6.48
	1959–1960	–	7.83	9.34	0.73
	1963	–	3.23	19.9	0.64
Total		**598.42**	**104.24**	**16.34**	**114.84**
Croydon (Quamby)	1907	15.24	–	26.97	4.11
Total		**15.24**	**–**	**26.97**	**4.11**
Egina	1899–1907	550.67	–	19.19	105.69
	1955	–	29.05	11.68	3.39
Total		**550.67**	**29.05**	**18.82**	**109.08**
Maitland	1963–1969	–	37.99	8.08	3.07
Total		**–**	**37.99**	**8.08**	**3.07**
Yarraloola	1963	–	2.75	14.6	0.40
Total		**–**	**2.75**	**14.6**	**0.40**

NOTES: (a) Overall average grade for copper and cupreous ore and concentrates combined

Table 3.3. Historical lead production in the west Pilbara (1897–1983)

Mine group	*Period*	*Ore* (*t*)	*Average grade* %	*Contained lead* (*t*)
Comstock	1915–1917	187.05	40.83	76.37
	1950	1.14	46.34	0.53
	1953	3.34	38.89	1.3
Total		**191.53**	**40.83**	**78.20**
Andover	1948–1950	18.20	50.88	9.26
	1951–1952	49.71	70.23	34.91
Total		**67.91**	**65.04**	**44.17**
Nunyerry	1957	1.66	70.39	1.17
Total		**1.66**	**70.39**	**1.17**
Balmoral	1949	0.6	54.49	0.31
Total		**0.6**	**54.49**	**0.31**

Table 3.4. Historical silver production in the west Pilbara (1897–1983)

Mine group	*Period*	*Silver mined* (*kg*)
Comstock	1915–1917	27.492
	1950	0.397
	1953	0.879
Total		**28.768**
Andover	1948–1950	1.982
	1951–1952	12.231
Total		**14.213**
Carlow Castle	1909–1913	7.25
	1957	0.62
Total		**7.87**
Nunyerry	1957	0.381
Total		**0.381**
Balmoral	1949	0.065
Total		**0.065**

Table 3.5. Historical antimony production in the west Pilbara (1897–1983)

Mine group	*Period*	*Ore* (*concentrate*) (*t*)	*Contained antimony* (*t*)
Mallina	1903	22.36	na
	1907	7.22	2.61
	1947	4.00	1.42
Total		**33.58**	**4.03**
Star	1914–1916	22.64 (conc)	12.36
Total		**22.64**	**12.36**
Peawah	19?	5.9	3.38
	1916	15.2	8.39
Total		**21.1**	**11.77**
Sherlock	1916	na	11.03
Total		**na**	**11.03**

NOTES: na not available

Table 3.6. Historical tin production in the west Pilbara (1897–1983)

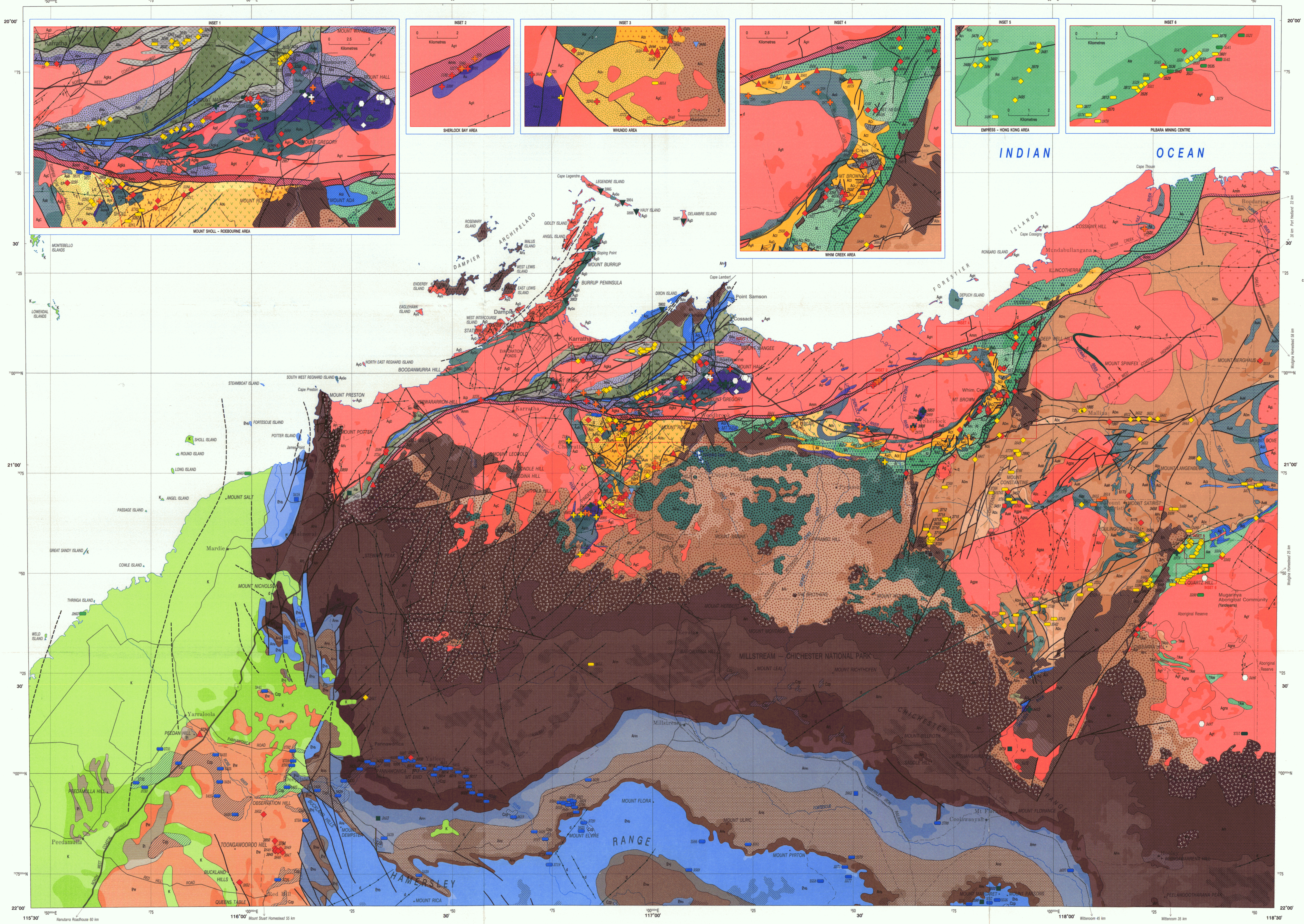
Mine group	*Period*	*Tin concentrate (t)*	*Contained tin (t)*
Friendly Creek – Yule River	1969–1970	14.65	10.26
	1971–1982	152.32	104.89
Total		**166.97**	**115.15**

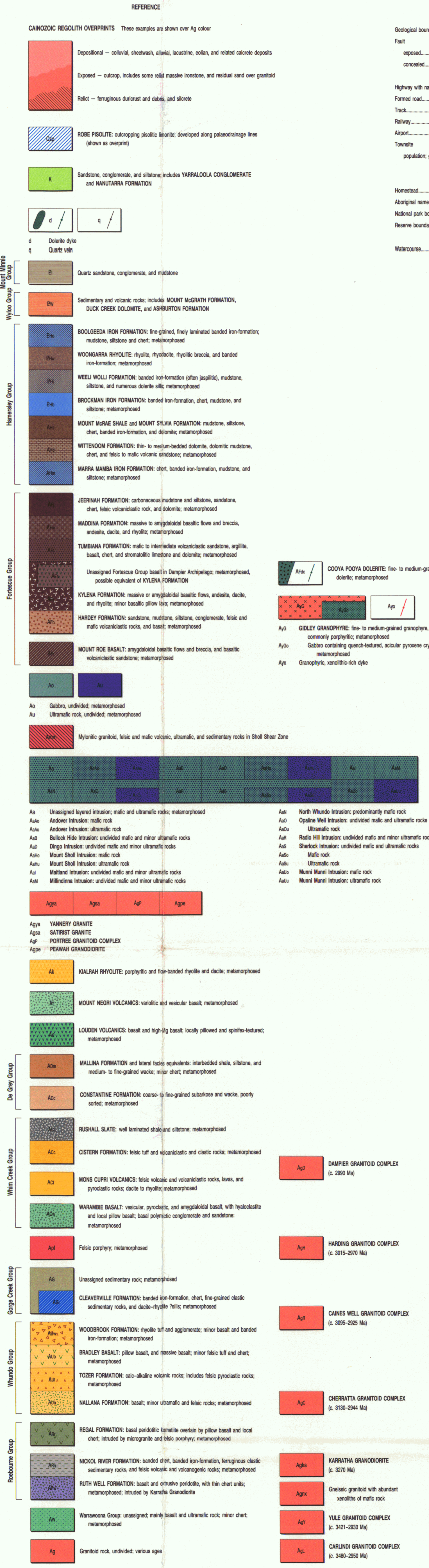
Table 3.7. Iron ore production in the west Pilbara (1972–1998)

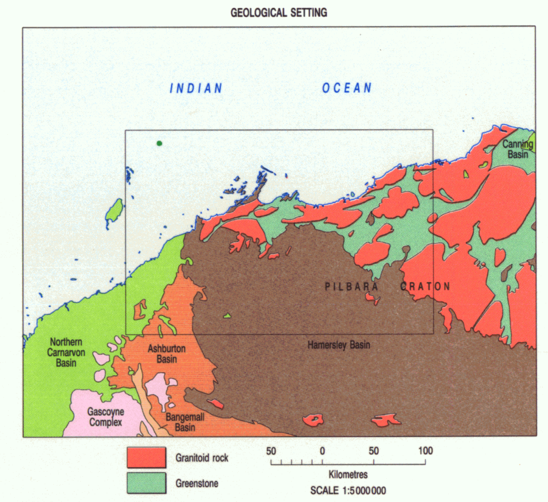
Mine group	*Period*	*Iron ore (dry) (Mt)*
Robe River		
Middle Robe	1972–1982	119
Eastern Deepdale	1982–1987	69
Deepdale	1987–1998	230
Total		**418**

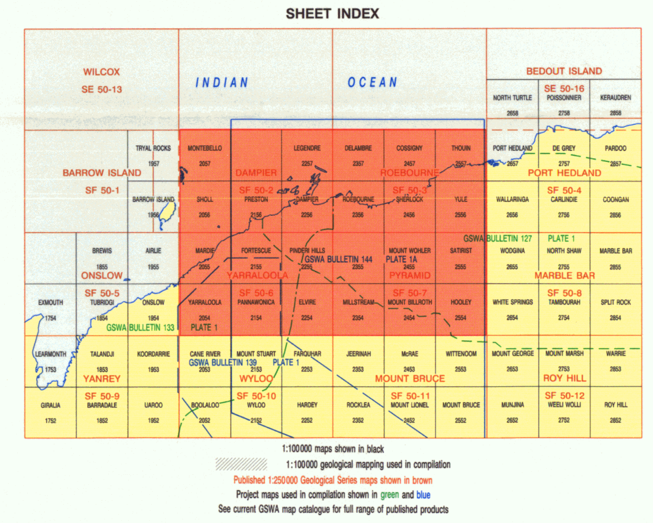
Table 3.8. Nickel production in the west Pilbara (1997–1999)

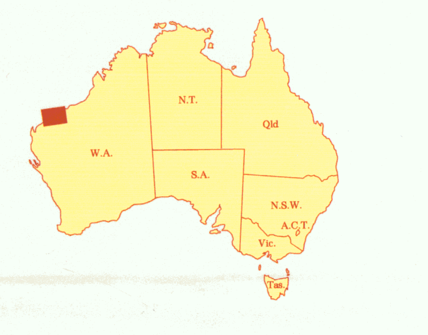
Mine	*Period*	*Nickel concentrate (t)*	*Contained nickel (t)*
Radio Hill	1997–98	4 690	474
	1998–99	38 837	3 924
Total		**43 527**	**4 398**











[illegible]

Mineral occurrence data compiled by I. Ruddock, R. W. Cooper, E. P. Peiris, and K. M. Ferguson 1999

Geology compiled by L. Y. Hassan, A. H. Hickman, C. A. Strong, and R. H. Smithies 1998–99, using GSWA maps (see sheet index)

Edited by C. Strong and C. Brien

Cartography by J. Kirk, S. Coldicutt, S. Collopy, and B. Williams

Mineralization information on this map is largely derived from non-confidential data held in the WAMIN database, GSWA May 1999

Topography from the Department of Land Administration Sheets SF 50-2, -3, -6, -7

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Data on this map are available in digital form

Printed by the Sands Print Group, Western Australia

The recommended reference for this map is:
HASSAN, L. Y., RUDDOCK, I., COOPER, R. W., PEIRIS, E. P., HICKMAN, A. H., STRONG, C. A., and SMITHIES, R. H., 1999, Mineralization and geology of the west Pilbara (1:500 000 scale), *in* Mineral occurrences and exploration potential of the west Pilbara *by* I. RUDDOCK: Western Australia Geological Survey, Report 70, Plate 1

DEPARTMENT OF MINERALS AND ENERGY
L. C. RANFORD, DIRECTOR GENERAL

GOVERNMENT OF WESTERN AUSTRALIA
HON. NORMAN MOORE, M.L.C.
MINISTER FOR MINES

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
DAVID BLIGHT, DIRECTOR

SCALE 1:500 000

5000 0 5 10 15 20 25 30 35 40 45 50
Metres Kilometres

TRANSVERSE MERCATOR PROJECTION
HORIZONTAL DATUM: AUSTRALIAN GEODETIC DATUM 1984
VERTICAL DATUM: AUSTRALIAN HEIGHT DATUM

Grid lines indicate 5000 metre interval of the Australian Map Grid Zone 50

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

REPORT 70 PLATE 1

MINERALIZATION AND GEOLOGY OF THE WEST PILBARA