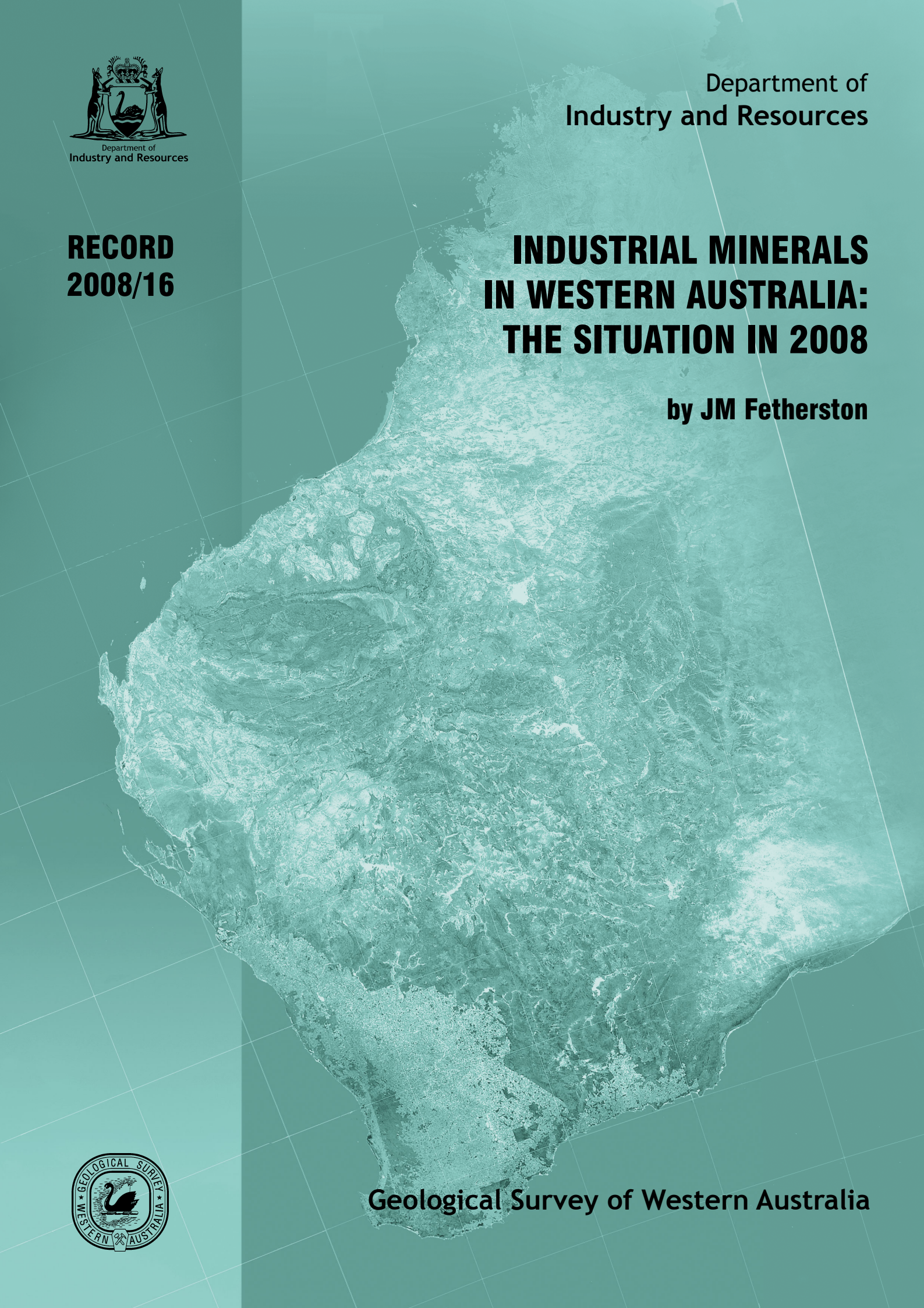

Department of
Industry and Resources

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2008/16

INDUSTRIAL MINERALS IN WESTERN AUSTRALIA: THE SITUATION IN 2008

by JM Fetherston

Geological Survey of Western Australia

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

Record 2008/16

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by
JM Fetherston

Perth 2008

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Frontispiece:
Created by German master craftsmen, this superbly carved fish (length approximately 25 cm) was crafted from the newly-discovered Waldburg variscite. The polished red eye is of hessonite, a variety of grossular garnet

Contents

Appendix

Plates (in back pocket)

Figures

Tables

Industrial minerals in Western Australia: the situation in 2008

by

JM Fetherston

Abstract

In 2006–07, about 7% ($2558 million) of the value of mineral production (excluding petroleum) in Western Australia was derived from industrial minerals, mainly titanium and zircon mineral sands, industrial diamond, salt, manganese, tantalite, speciality aluminas, spodumene, garnet, and gypsum. In 2007, Western Australia was the world's largest producer by weight of tantalite (61%), zircon (25%), and the titanium mineral, rutile (22%). The State was also the second-largest world producer of the lithium mineral, spodumene (22%), industrial diamonds (21%), and the titanium mineral, ilmenite (13%). Another key industrial mineral was salt (sixth-largest world producer at 4%).

In the northern half of the State, industrial mineral production is centred largely around industrial diamonds, salt, manganese, tantalite, and gypsum. In the southwest of the State, titanium minerals and zircon predominate, with tantalite, hydrated and calcined alumina, spodumene, garnet, limestone and limesand, silicon metal and silica sand, and talc occupying important market sectors.

Geologically, the State has major untapped potential for industrial minerals in a variety of settings and a number of identified deposits are targets for current and future development. Currently, Bemax Resources' Gwindinup and Happy Valley mineral sand operations in the Bunbury area are ramping up initial production. A number of significant projects coming into production include Lynas Corporation's Mount Weld rare earth element (REE) deposit near Laverton, and Windimurra Vanadium's recommissioning of the Windimurra vanadium deposit. South of Shark Bay, Gunson Resources' zircon-rich Coburn mineral sands project is in final feasibility stage. Other projects currently under consideration include two solar salt projects at Onslow and Yannerie on the Pilbara coast, the Ant Hill and Sunday Hill manganese deposits in the east Pilbara, the Mount Cattlin tantalum deposit at Ravensthorpe, and mineral sand deposits at Cataby and the Hyperion deposit at Cooljarloo North in the mid-west coastal plain.

Recent major exploration projects have included the Cyclone mineral sands deposit in the Eucla Basin, the Cummins Range rare earth carbonatite deposit in the east Kimberley region, and vanadium deposits at Balla Balla in the West Pilbara and Barrambie and Gabanintha in the Yilgarn Craton. Other projects included the discovery of diamonds at the Blacktop kimberlite dyke south of Karratha, potash evaporites at Lake Disappointment in the central desert region, and a reappraisal of phosphate mineralization at Cardabia south of Onslow.

Recently upgraded port handling facilities and road networks, together with the provision of natural gas to industry in key mining and processing areas, have enhanced value-adding processes employed by many advanced technology companies. This, coupled with the successful identification of niche markets, should place Western Australia in a favourable position to service South East Asian and other world markets with reliable, high-quality industrial minerals and downstream products.

KEYWORDS: Industrial minerals, titanium minerals, zircon, industrial diamond, salt, tantalite, manganese, alumina, gypsum, spodumene, limestone and limesand, vanadium, talc, garnet, silica, rare earth elements, value-added processing, bulk handling, export, Western Australia.

Introduction

This Record is a revision and update of Fetherston and Searston (2004) 'Industrial minerals in Western Australia: the situation in 2004'. This new Record discusses the industrial mineral potential and describes the main industrial mineral commodities currently produced in Western Australia in order of economic importance from mineral sands (mainly titanium minerals and zircon) to semiprecious stones, and other minerals (Table 1). Because Christmas Island is administered by Western Australia, a short section is also included on phosphate rock mined on the island. A discussion on minerals currently under development follows, including the Mount Weld rare earth element project and the recommissioning of the Windimurra vanadium mine. Current industrial mineral exploration programs in Western Australian, development proposals, and progress of more advanced exploration projects are then discussed.

Localities for industrial mineral commodities listed in this publication are given in Appendix 1, and are also included in the Department of Industry and Resources' database of mines and mineral deposits (MINEDEX) at www.doir.wa.gov.au. Most localities are also shown on Plates 1 and 2 (in the pocket at the back of this Record).

In the past, industrial minerals (generally non-metallic minerals) have had a variety of definitions commonly based on mineral classification. In recent times, there has been a shift in the definition to reflect the industrial mineral's end-use in industry. Accordingly, a number of metallic minerals, including tantalum, manganese, and vanadium, with substantial non-metallic end-uses are today classed as industrial minerals in those applications. In this publication, the definition of an industrial mineral has been adopted from the World Bank 1988 definition that states that industrial minerals are *'…all non-metallic, non-fuel minerals extracted and processed for industrial end-uses with the addition of that proportion of metal ores consumed in non-metallic applications'* (Noestaller, 1988).

Western Australia is the nation's most resource-rich State, with a diversity of significant mineral output that is almost unequalled in the world marketplace. In 2006–07, the State's industrial mineral production was valued at approximately $2558 million. This represents about 7% of the value of total mineral production (excluding petroleum) for the State in that year (Fig. 1).

Western Australia is a leading world producer of many industrial minerals. For example, in 2007, it was the world's largest producer by weight of tantalite (61%), zircon (25%) and the titanium mineral, rutile (22%). The State was also the second-largest world producer of the lithium mineral, spodumene (22%), industrial diamonds (21%), and the titanium mineral, ilmenite (13%). Another key industrial mineral was salt (sixth-largest world producer at 4%).

In the northern half of the State, industrial mineral production is centred largely around industrial diamonds, salt, manganese, tantalite, and gypsum. In the southwest of the State, titanium minerals and zircon predominate,

Table 1. Production and value of industrial minerals in Western Australia, 2006–2007

Commodity	*Production (t)* [(a)]	*Value (A$ million)*
MINERAL SANDS (EXCLUDING GARNET)		
Titanium minerals		
Ilmenite	926 027	101.51
Synthetic rutile	643 297	342.23
Leucoxene	52 257	19.67
Rutile	122 230	76.09
Other minerals		
Zircon	379 893	360.40
Staurolite	*7 000*	*1.04*
MINERAL SANDS SUBTOTAL	2 130 704	900.94
DIAMOND (ct)	18 222 045	na
SALT	10 051 102	228.04
MANGANESE	902 052	134.50
TANTALITE	674	na
ALUMINA, hydrated/calcined	*270 000*	*85.00*
SPODUMENE	290 432	na
GARNET	258 891	na
GYPSUM	1 494 849	28.40
BASIC RAW MATERIALS[(b)] (includes sand, clay, aggregate and limestone for construction purposes)	5 898 886	54.45
LIMESTONE AND LIMESAND[(b)] (includes an est. 406 000 t of limestone for the dimension stone industry)	3 791 742	23.24
SILICA AND SILICA SAND	630 537	6.02
DIMENSION STONE (includes sandstone, granite and marble but not an est. 406 000 t limestone building block material)	*17 226*	*2.99*
CLAY MINERALS (includes attapulgite, saponite, kaolin, and common clays)	na	1.50
SEMIPRECIOUS STONES (kg)	325 489	0.25
OTHER MINERALS (includes feldspar, red oxide pigment, spongolite, and talc)	na	448.74

NOTES: (a) tonnes, unless otherwise stated
(b) production figures are as reported to the Department of Industry and Resources (actual production is likely to be much higher as it often includes production from private land controlled by local government) figures in italics are estimates based on trends in production and/or value
na not available

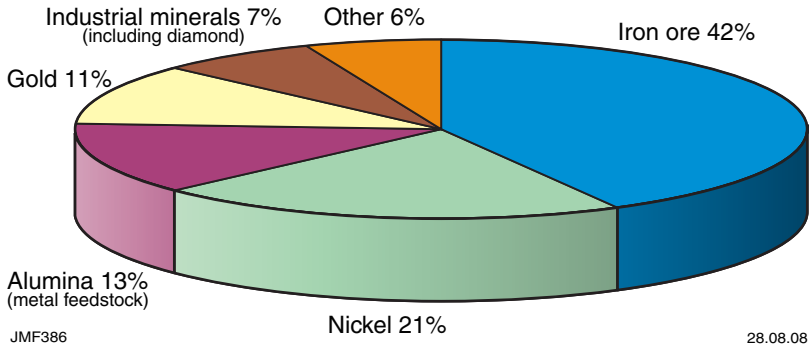

Figure 1. Industrial minerals as a percentage of total value of mineral production (other than petroleum) in Western Australia in 2006–07. Total value of industrial minerals was approximately $2558M

with tantalite, hydrated and calcined alumina, spodumene, garnet, limestone and limesand, silicon metal, silica sand, and talc occupying important market sectors.

Geologically, the State has major untapped potential for industrial minerals in a variety of settings and a number of identified deposits are targets for current and future development. Currently, Bemax Resources' Gwindinup and Happy Valley mineral sand operations in the Bunbury area are ramping up initial production. A number of significant projects coming into production include Lynas Corporation's Mount Weld rare earths deposit near Laverton with total resources (ore) of around 15 Mt rare earth oxides. Mining has recently commenced at the Mount Weld site and, in full production, this operation should make Western Australia the world's second-largest producer of rare earth oxides. Also, Windimurra Vanadium's long-awaited recommissioning of the Windimurra vanadium deposit is due for start-up, possibly towards the end of 2008. South of Shark Bay, Gunson Resources' zircon-rich Coburn mineral sands project is in final feasibility stage. Other projects currently under consideration include the Ant Hill and Sunday Hill manganese deposits (HiTech Energy Ltd), the Mount Cattlin tantalum deposit at Ravensthorpe (Galaxy Resources Ltd), and mineral sand deposits at Cataby (Illuka Resources), and the Hyperion deposit at Cooljarloo North (Image Resources NL).

Major operational projects include major mineral sands operations for titanium minerals and zircon along the Swan Coastal Plain from Eneabba in the north, south to Cooljarloo, and numerous operations in the Pinjarra, Bunbury, and Busselton regions in the far south. These operations produce almost 1.75 Mt of titanium minerals and 0.38 Mt of zircon each year, valued at over $900 million, most of which is exported to China, Europe, and North America.

In the Kimberley region, the Argyle and Ellendale diamond mines extract around 16 Mct of industrial diamonds per annum, particularly from the Argyle operation. Along the Pilbara coast and farther south at Shark Bay, five major salt evaporators produce over 10 Mtpa of salt for export, principally to South East Asia and also to the Middle East.

Western Australia's only operating manganese mine, located at Woodie Woodie in the East Pilbara region, produced over 0.9 Mt in 2006–07. Although 90% of the high-grade manganese is destined for the steelmaking industry, the remaining 10% finds non-metallic applications mainly in the manganese chemical industry, especially in the production of electrolytic manganese dioxide (EMD).

Other major industrial mineral projects include tantalite, one of the principal sources of tantalum metal. Western Australia currently has the world's largest tantalum operation with most ore sourced from the Wodgina mine in the west Pilbara. At the Greenbushes mine in the southwest of the State, spodumene, an important ore of lithium is extracted from an extensive pegmatite deposit, acknowledged as the world's largest hard-rock lithium resource. North of Geraldton, at Port Gregory, there are extensive deposits of garnet-rich mineral sands. At this site, almost 0.26 Mt were mined in 2007–08 and the resulting garnet concentrate was destined mainly for the water-jet cutting and abrasive industries. Western Australia has about 180 gypsum deposits with a total resource of potentially economic gypsum of about 1.5 Gt, although by far the largest is the extensive barred basin deposit at Lake MacLeod situated on the northwest coast. The Lake MacLeod operation can produce up to 1.5 Mtpa of high-quality gypsum, most of which is exported to Japan mainly for the plasterboard industry. South of Perth, at Kwinana, Alcoa World Alumina Australia diverts about 0.27 Mt of its alumina production to non-metallic applications in the form of hydrated and calcined alumina, valued at an estimated $85 M in 2006–07, for the production of a diverse array of aluminium chemicals, industrial abrasive and refractory products.

Bulk quantities of other key industrial minerals produced in in the State include limestone and limesand, silica and silica sand, and talc. There are also encouraging signs of a possible resurgence in the dimension stone industry as a result of a recent increase in exploration. This is in response to current interest shown by overseas and domestic processors in a number of the State's visually attractive, high-quality building stones for applications by the architectural industry.

The vast majority of the State's industrial mineral output is destined for the export market, particularly to South East Asia. Until recently, the less-developed manufacturing base on the west coast traditionally meant reduced local demand for industrial minerals than from the more populated eastern states. In the southwest, industry is well supplied with electricity largely generated from the extensive high-grade coal deposits at Collie, 60 km east of Bunbury, backed up by a number of natural gas power stations. Also, available energy resources have been supplemented by the extension of natural gas pipelines from the Northwest Shelf to key mining and processing centres in the Pilbara, Eastern Goldfields, and the southwest of the State.

The ready availability of energy, coupled with value-added processing by many advanced technology companies, as well as upgrades to many port facilities, has placed Western Australia in a favourable position to continue servicing South East Asian and other major export markets with reliable, high-quality industrial minerals and downstream products.

Abbreviations

A$	Australian dollars
ASX	Australian Securities Exchange
$CaCO_3$	calcium carbonate
CaF_2	calcium fluoride (the mineral fluorite)
CaO	quicklime
cpht	carats per hundred tonnes
ct	carat
DoIR	Department of Industry and Resources
Fe_2O_3	iron oxide
Gt	gigatonnes
g/t	grams per tonne
ha	hectare
JORC	Australasian Code for Reporting of Mineral Resources and Ore Reserves
K	potassium
K_2SO_4	sulfate of potash
kg	kilogram
lb	pound
Li	lithium
Li_2O	lithium oxide
MgO	magnesium oxide
Mm^3	million cubic metres
Mt	million tonnes
Mtpa	million tonnes per annum
MVA	apparent power (in megawatts)
µm	micrometre
Na	sodium
P_2O_5	phosphorus pentoxide
REE	rare earth elements
ROM	run of mine
SiO_2	silica
t	tonne
Ta_2O_5	tantalum pentoxide (the mineral tantalite)
TiO_2	titanium dioxide
tpa	tonnes per annum
tph	tonnes per hour
US	United States of America
US$	US dollars
¥	Japanese yen

Geological setting

In Western Australia, virtually all near-surface rocks have been affected to some degree by deep-weathering processes that have controlled landscape evolution since at least the end of the Permian. As a result, much of the State's fresh bedrock is covered by an unconsolidated to indurated regolith blanket of varying thickness containing a variety of transported and residual materials. Although some industrial mineral deposits, such as dimension stone, are found in relatively unweathered rocks that range in age from Archean to Phanerozoic, the majority are found in unconsolidated to indurated material that blankets these rocks.

Studies in Western Australia have demonstrated the important relationship between regolith development and the concentration of many industrial minerals in deeply weathered profiles. Examples of this may be seen in the deep weathering of the Mount Cassiterite and Mount Tinstone tantalite orebodies at Wodgina (Fetherston, 2004), and the Ockley–Wickepin kaolin deposits in the southwest of the State (Abeysinghe and Fetherston, 1999). This relationship is critical in understanding the distribution and structure of these deposits and will play a significant role in future exploration projects. In general, most of the State's industrial mineral deposits have evolved within the following three broad regolith types.

Residual or relict ferruginous duricrusts

Residual or relict ferruginous duricrusts are typified by examples where the deep weathering of granitic rocks in many areas, particularly the Archean Yilgarn Craton, has developed lateritic profiles in excess of 40 m containing high-grade, primary kaolin deposits such as those near Meckering, and Ockley–Wickepin in the southwest of the State.

Other examples from the Yilgarn Craton include the deep weathering of gabbroic rocks resulting in the concentration of rich vanadiferous horizons in places such as Windimurra. In the Darling Ranges to the east and southeast of Perth, lateritic bauxite profiles, with elevated alumina and reduced iron levels, have formed over granitic rocks and to a lesser extent mafic greenstones resulting in the development of extensive areas of high-grade bauxite.

In the northwestern Kimberley region, thick, lateritic bauxite profiles have formed at Cape Bougainville and Mitchell Plateau. In this area, up to 8.6 m of bauxite has developed over Proterozoic basalt.

Alluvial/fluvial and lacustrine paleodrainage deposits

These deposits are products of continuous chemical and mechanical weathering during prolonged landscape evolution in the interior of the State. Weathered materials

have been transported and subsequently deposited in paleochannels and playa lakes. In these environments, aluminium-, magnesium-, and calcium-rich weathering products may react and precipitate in quiescent conditions, often over long periods, to form thick deposits of attapulgite (Lake Nerramyne), bentonite (Watheroo), and secondary kaolin (Swan Valley). Many of these processes continue today in ephemeral lake systems. Other playa lake deposits derived from weathering, include gypsum, salt, potash, secondary magnesite, and diatomite.

Coastal regolith

Cenozoic sediments in the Perth and Southern Carnarvon Basins, and overlying the Albany–Fraser Orogen along the south coast, consist mainly of semi-consolidated and consolidated eolian quartzose and calcareous dunes. Along the west coast, numerous sets of parallel, quartzose dunes form prominent strandlines representing stillstands in sea levels during the Quaternary. Many strandlines from the Busselton–Augusta region in the south to Shark Bay in the north contain rich deposits of titanium minerals and zircon concentrated by wind and wave action. At Port Gregory, north of Geraldton, strandlines contain rich concentrations of garnet. Recently, concentrations rich in titanium minerals and zircon have been discovered in strandlines bordering the paleoshoreline of the Eucla Basin in the southeast of the State.

Semi-consolidated to consolidated calcareous dunes along the west and south coasts comprise the Pleistocene Tamala Limestone and equivalent units. Combined with unconsolidated Holocene limesands, these materials provide a valuable source of limestone and quicklime for industry. Substantial deposits are mostly located in the Perth metropolitan area and numerous locations north to Dongara.

Inland from the coast, the action of acidified rainwater on quartzose dunes has resulted in the removal of soluble ions, especially iron. These were transported to the watertable beneath where they were precipitated, leaving the upper depleted horizon as high-grade silica sand. Deposits of this type occur in the Gnangara and Canning Vale areas outside Perth, and in the south at Kemerton and Mindijup in the Bunbury and Albany areas respectively.

At Shark Bay, numerous interdunal playas (birridas) commonly form linear chains roughly parallel to the coast. These probably developed as deflation hollows, during the Pleistocene, at times of low sea level and strong winds, During these periods, eolian clay, silt, sand, and evaporites were deposited in these depressions. As sea levels rose again, some birridas were subject to flooding. When sea levels eventually fell, salinity levels increased and a substantial thickness of gypsum was deposited. More recently, playa gypsum has been deflated by strong winds and redeposited as gypsiferous dunes in the centres of some playas. Deposits of playa gypsum are also present at Cliff Head and Dooka, about 80 km south of Geraldton.

Further reading on the evolution, geomorphic history, and classification of regolith materials in Western Australia may be found in Hocking et al. (2007).

Projects with current and past production

Titanium mineral sands, zircon, and staurolite

Production

The titanium mineral sands industry (frequently referred to as heavy mineral sands) is the most important sector of the industrial minerals suite in Western Australia. In 2006–07, the estimated value of production of the titanium-rich minerals ilmenite, synthetic rutile (upgraded ilmenite), leucoxene and rutile, together with zircon and staurolite mineral sands, but excluding garnet, was $901 million for an estimated production of 2.14 Mt. This represents a return to the high values achieved at the beginning of the decade ($905 million in 2000–01) despite an overall decline in the value of production in the interim period that reached almost 20% in 2003–04.

The current recovery in production and dollar values is reflected in increases for ilmenite, rutile, and synthetic rutile in 2006–07 and is shown in Figure 2. Also, the value of production for zircon has sharply increased by 40% over three years since 2003–04 despite declining zircon grades, especially in the mid-west coastal plain around Eneabba. Leucoxene is the only mineral sand going against the trend, with a 32% decrease in production in the past year together with a decrease in the value of production of about 18%, which probably reflects declining grades for the mineral.

During 2007, mineral sands were produced in two discrete areas in Western Australia: the mid-west coastal plain to the north of Perth, where Iluka Resources Ltd has operating mines at Eneabba and Gingin, and the Tiwest Joint Venture has a substantial operation at Cooljarloo. In the southwest coastal plain, Iluka Resources Ltd has its major processing facilities at North Capel and currently sources heavy mineral concentrate from mines at Cloverdale and Waroona. Also in the southwest, Doral Mineral Industries Pty Ltd operates a small mine at Dardanup, while Bemax Resources Ltd has recently started up new mining operations at Gwindinup and Happy Valley. Olympia Resources Ltd is due to commence operations at Keysbrook around the end of 2008.

Iluka Resources has been associated with mineral sands mining in the south west of the State for more than 50 years. In August 2007, the company announced that it would be winding up operations in Western Australia in 2014 to focus on its operations in eastern Australia. This announcement has come 12 years ahead of the company's previous operational schedule (Department of Industry and Resources, 2007). Iluka's proposed cessation of operations in the State appears to be attributable to declining grades of heavy minerals in recent years, especially zircon from

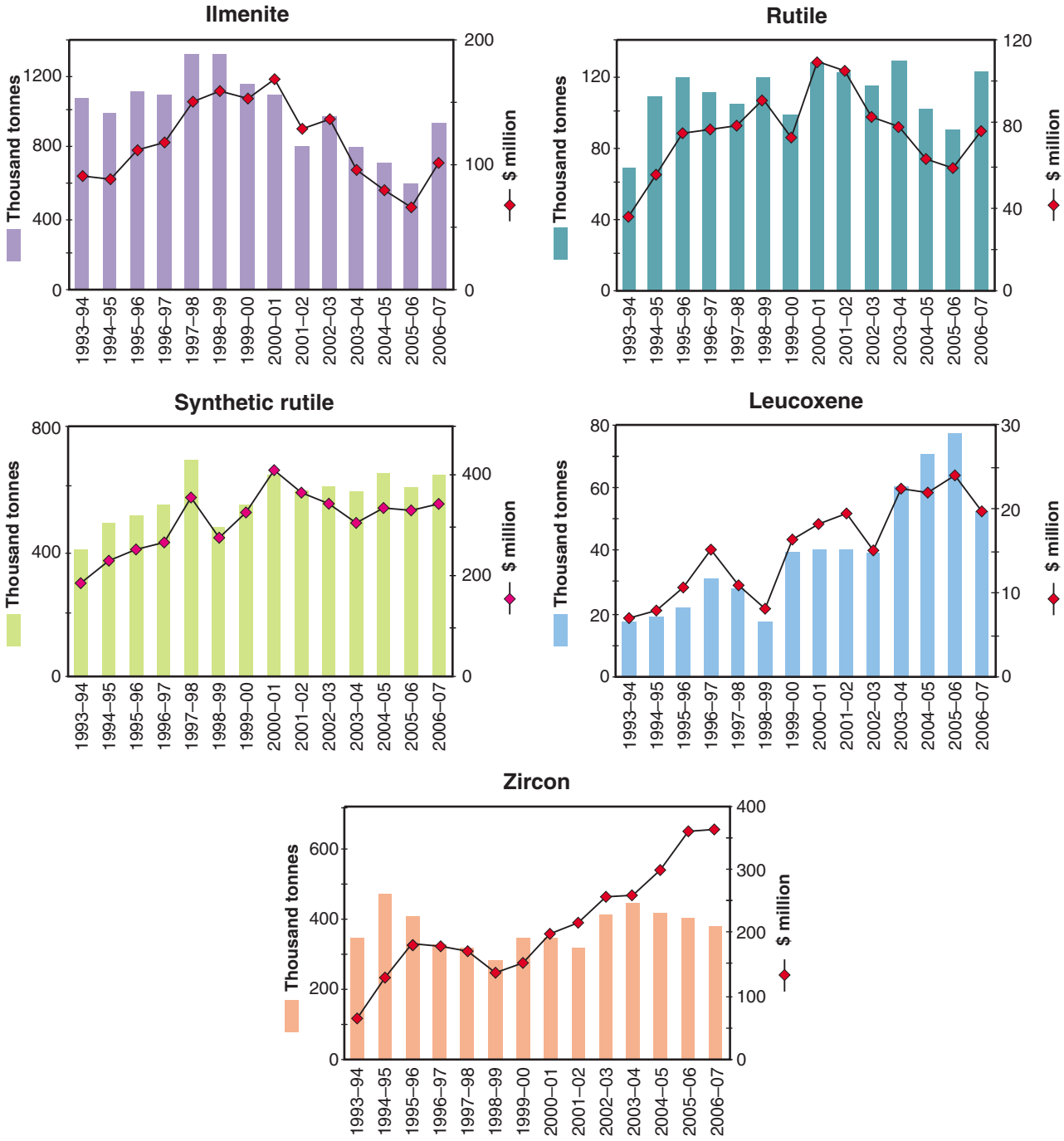

Figure 2. Trends in production (quantity and value) of titanium minerals and zircon in Western Australia, 1993–94 to 2006–07

the mid-west coastal plain around Eneabba, and also from the southwest coastal plain, combined with the apparent paucity of new, substantial deposits available for mining in many areas.

In the Southern Carnarvon Basin, immediately south of Shark Bay, Gunson Resources Ltd has received environmental approval for the Coburn mineral sands project to proceed and has finalized off-take agreements. The project is currently in final feasibility stage.

Processing and applications

Of the mineral sands produced in Western Australia, ilmenite ($FeTiO_3$) is most abundant. A substantial proportion of ilmenite is kiln-leached by the Becher process where iron is removed to form synthetic rutile (TiO_2). This form of value-adding may increase the value of the original ilmenite by well over 300%. Around the world, about 95% of processed titanium minerals is used in the manufacture of white, non-toxic, titanium dioxide pigment used mainly in paints, plastics, printing inks, and cosmetics. Other uses include the manufacture of paper, textiles, rubber, soap, and pharmaceuticals. The remaining 5% is mainly used in the manufacture of titanium metal, noted for its high-strength, non-corrosive and non-toxic properties.

In 2006–07, minerals sand exports from Western Australia were shipped principally to Asia (59%), with China the largest consumer at 22%. The remainder was exported to Europe (27%), North America (13%), and other (1%) (Department of Industry and Resources, 2007).

Currently, there are two titanium dioxide pigment plants operating in the State. The first of these, owned by the Tiwest Joint Venture as part of a fully integrated titanium dioxide project, is located at Kwinana, 30 km south of Perth. The second plant, located at Kemerton Industrial Park, 17 km northeast of Bunbury and operated by Millennium Inorganic Chemicals, is owned by the Lyondell Chemical Company. For a number of years the company has had environmental approval to expand the Kemerton plant's capacity from around 85 000 to 190 000 tpa. It appears this expansion project is on hold pending favourable market conditions (Prospect, 2007a).

South of Perth, in the Kwinana industrial area, are two plants where zircon is processed into fused zirconia (ZrO_2) and zirconium chemicals. The first of these, Doral Fused Minerals Pty Ltd, a subsidiary of Doral Mineral Industries Pty Ltd, produces about 4000 tpa of fused zirconia and 2000 tpa of silica fume (a co-product) from low-alumina zircon sand. Fused zirconia is used in the manufacture of fusion cast ceramics, partially stabilized zirconia, alumina zirconia, refractory products, and ceramic pigments.

In the same area, Doral Speciality Chemicals Pty Ltd acquired Millennium Inorganic Chemicals' zirconia plant in 2004. This operation has the capacity to produce 450 tpa of zirconia ceramic powder, 300 tpa of zirconium carbonate, 1000 tpa of zirconium sulfate, and 20 000 tpa of high-purity zircon flour and other micronized products including milled silica, garnet, and alumina. Zirconium chemicals are shipped to domestic and overseas mineral processors, particularly to TiO_2 pigment producers for enhancing pigment whiteness, and to high-technology industries manufacturing zirconia ceramics. The company also adds yttrium to stabilized zirconia powders for use in the manufacture of chemical fuel cells and oxygen sensors.

Zircon is also used in the manufacture of zircon refractories, foundry sands, and ceramics mainly due to its high melting point and low coefficient of thermal expansion. Other applications include the manufacture of zirconia gemstones, electronic-grade zirconia, zirconia fibre, and zirconium metal and high-technology alloys.

Location of significant mineral sand provinces

In Western Australia, the titanium mineral sands industry is currently located along the State's coastal plain extending over 850 km from Augusta in the far south to Shark Bay in the central west. This extensive area includes the southwestern and mid-western coastal plains of the Perth Basin, extending north into the Southern Carnarvon Basin at Shark Bay. Mineral sand concentrations in the region are distributed in a series of placer deposits contained in beach, marine–estuarine, dune, and lacustrine systems. These deposits are developed in places along a series of major parallel or semi-parallel strandlines in late Cenozoic sediments, up to 70 km inland from the modern shoreline. The strandlines represent changing sea levels and stillstand periods over this time, with the highest and oldest strands about 115 m above present sea level at Eneabba, with the youngest strands developed as concentrations along modern beaches.

In recent years, a new mineral sands province has been discovered around the perimeter of the Cenozoic Eucla Basin. Around 2004, word-class zircon-rich deposits such as Jacinth, Ambrosia and Tripitaka, containing up to 63% zircon, were discovered in western South Australia. More recently, exploration has been extended around the basin margin into southeast Western Australia, where rich dune and beach strandlines of mineral sand concentrations are being evaluated at Wanna Lakes, close to the South Australian border, and in the central south in the Balladonia area. Exploration in this new province is discussed under **Exploration and development**.

Perth Basin

The mid-west coastal plain

Cooljarloo, Dongara, and Jurien

Cooljarloo

The Cooljarloo heavy mineral sands mine and deposits located at Dongara and Jurien are owned by the Tiwest unincorporated joint venture comprising Exxaro Australia Sands Pty Ltd, and Tronox Western Australia Pty Ltd (50/50% holding).

The Cooljarloo mine, located 170 km north of Perth and 36 km southeast of Cervantes, forms part of the world's

largest integrated titanium dioxide project, incorporating dredging and dry-mining heavy mineral sands operations at Cooljarloo, the Chandala dry separation and synthetic rutile plants 60 km north of Perth, and the Kwinana titanium dioxide pigment plant 30 km south of Perth. The Cooljarloo deposit is hosted by a series of paleostrandlines deposited at elevations between 50 and 100 m above modern sea level, collectively known as the 'Munbinea Shoreline' located around the base of the Gingin Scarp (Baxter, 1976). High-grade mineralization appears to be concentrated around the mouth of a paleodrainage channel represented today by Mullering Brook.

Currently, the mine has a processing capacity of 20 Mtpa of ore, and produces approximately 0.7 Mtpa of heavy mineral concentrate comprising mainly ilmenite together with lesser quantities of rutile, leucoxene, zircon, and minor staurolite. Resources and reserves determined in late 2005 are given below (Register of Australian Mining, 2007/08a):

- Measured, indicated and inferred resources: 484 Mt at 2.5% mineral sands
- Proven and probable reserves : 174 Mt at 2.8% mineral sands

Mineral concentrate is road freighted to the Chandala processing plants where the dry mill separates the heavy minerals by electrical conductivity, magnetic susceptibility, particle size and specific gravity. Each year the plant produces about 0.42 Mt ilmenite, 70 000 t zircon, 35 000 t rutile, and 20 000 t leucoxene. The plant also produces smaller quantities of staurolite estimated at around 7000–10 000 tpa. Staurolite provenance and industrial applications are discussed in Fetherston and Searston (2004).

Also at Chandala, the synthetic rutile plant produces 0.23 Mtpa synthetic rutile, about half of which is exported with the remainder upgraded at the Kwinana pigment plant. This operation produces 0.11 Mtpa of pure white titanium dioxide pigment mainly for export to countries in the Asia–Pacific region. In March 2008, the company announced plans for the expansion of the Kwinana pigment plant as a result of strong demand for white pigment from the Asia–Pacific region. It is expected the upgraded plant, with a capacity of around 0.15 Mtpa, will come online in early 2010, subject to government approvals.

Dongara

The Dongara mineral sands deposit, 37 km southeast of the town of Dongara, was defined as a deposit of economic significance in 2002 by Magnetic Minerals Ltd. The deposit was subsequently purchased by the Tiwest Joint Venture for future development as supplementary feedstock for the mineral separation plant as the Cooljarloo resources are progressively depleted towards the end of 2009.

The Dongara deposit is located on paleostrandlines about 35 km along strike to the north of the major mineral sand deposit at Eneabba. These paleostrandlines form part of a probable northward extension of the Eneabba Shoreline situated at the base of the Gingin Scarp from about 80 to 130 m above present sea level (Baxter, 1976).

In late 2005, measured and indicated resources for the Dongara deposit were given as 76.7 Mt at 6.6% heavy minerals, and probable reserves at 20.2 Mt at 10.2% heavy minerals (50% ilmenite and 9% zircon; Kumba Resources, 2005).

Jurien

The Jurien deposit is situated 14 km south-southeast of the town of Jurien Bay. Also defined as a deposit of economic significance in 2002 by Magnetic Minerals Ltd, the Jurien deposit was acquired in 2005 by the Tiwest Joint Venture for future development as supplementary feedstock for the Cooljarloo plant.

Baxter (1976) describes the Jurien deposit as a series of five, closely associated, north-trending paleostrandlines up to 4 km in length with their bases ranging from 36 to 43 m above present sea level. The deposit lies about 2 km west of the base of the Gingin Scarp and is developed on the same Munbinea Shoreline as is the Cooljarloo deposit, 45 km to the southeast.

Indicated resource estimates for the Jurien deposit given in late 2005 were 25.6 Mt at 6.0% heavy minerals, and estimated probable ore reserves 15.7 Mt at 7.9% heavy minerals (54% ilmenite and 10% zircon; Kumba Resources, 2005).

Eneabba

The Eneabba mining operation, some 80 km south-southeast of Dongara and 7 km south of the Eneabba township, is one one of the State's oldest major mineral sands projects, having been in operation continuously since 1974. Currently owned and operated by Iluka Resources Ltd, Eneabba is also one of the world's largest zircon and rutile deposits. In December 2004, reserves and resources for Iluka properties in the mid-west coastal plain (at that at the time mostly for deposits at Eneabba) stood at proved and probable reserves of 218 Mt at 6.2% heavy minerals, and measured, indicated and inferred resources of 837.45 Mt at 5.2% heavy minerals (Iluka Resources, 2005).

The Eneabba operation is sited over nine, north-trending, mineralized paleostrandlines up to 12 km in length. These were deposited, possibly during the early Pleistocene, on the Eneabba shoreline at the base of the Gingin Scarp as a paralic beach, estuarine, and dune sequence during subsequent reductions in sea level from 128 to 82 m above present sea level. In this area, deposition occurred in a hook-shaped, north-facing embayment that acted as a trap for heavy minerals largely derived from the erosion of the underlying Yarragadee Formation. The origin and structure of the mineral sands deposits at Eneabba are discussed in more detail in Baxter (1976).

Currently, the Eneabba operation comprises ten mineral sand deposits that include Adamson (North and South), South Tails, Depot Hill (East and West), Allied Tails, IPL (South and North), Ocean Hill, and Brandy Flats. Of these, the South Tails and Depot Hills deposits, and more recently from early 2006 the previously mined Adamson South deposit, are current mining operations. In September 2006, Iluka Resources announced a

major extension to the Adamson South deposit with the confirmation of a substantial heavy mineral resource in the adjoining Adamson North deposit. Adamson North is estimated to contain measured, indicated, and inferred resources of 17.47 Mt at 4.0% heavy minerals comprising 40% ilmenite, 19% zircon and 6% rutile (Iluka Resources, 2006). A detailed description of the Adamson deposit is given in Shackleton (2005).

In recent years, mineral sand exploration has been carried out at Brandy Flats about 3 km north of the Eneabba townsite. In 2007, renewed exploration at the old Eneabba North minesite has indicated the presence of unmined strands containing up to 65% heavy minerals including 13% zircon. Also at this site, tailings from earlier mining operations containing up to 3% heavy minerals have been located. Further drilling is planned to fully assess this resource (Iluka Resources, 2008).

Ore from the Eneabba deposits is processed at two on-site, wet concentrators and the resulting heavy mineral concentrate transported to the company's Narngulu processing facility near Geraldton. Narngulu operations comprise dry heavy mineral separation, zircon finishing, and synthetic rutile processing. Stockpiled products are exported through the Port of Geraldton.

Gingin

Owned by Iluka Resources Ltd, the Gingin mineral sands mine and wet concentrator plant located 3 km west-northwest of Gingin townsite commenced operations in August 2005. The Gingin mine has been designed for a three-year operational life based on proven reserves of 8.3 Mt at 16% heavy minerals. Over this period, Gingin concentrate transported to the Narngulu processing plant is estimated to produce approximately 0.6 Mt ilmenite for feedstock to the company's synthetic rutile kilns to produce about 0.36 Mt synthetic rutile, as well as 0.31 Mt of chloride-grade ilmenite for export to the US, 75 000 t of rutile, and 65 000 t of zircon (Iluka Resources, 2004).

Situated on the Gingin shoreline, the deposit is contained in a clayey sand unit within a paralic succession at the base of the Gingin Scarp. The relatively deeply buried ore zone trends northward from Gingin Brook with one mineralized zone extending over 5 km (Baxter, 1976).

The company recently carried out test drilling at another mineral sands prospect at Boonanarring (mining lease M70/1194), about 12 km north-northwest of the Gingin minesite. This exploration activity was designed to investigate the possibility of locating an additional mineral sand resource capable of supplying supplementary feedstock to the Gingin wet concentrator plant. To date, no additional information has been released (Iluka Resources, 2007).

The southwest coastal plain

Capel operations and regional feedstock sources

The area around Capel, about 25 km south-southwest of Bunbury, was first mined for mineral sands in the late 1950s together with on-site concentration and heavy mineral separation. Since that time, mining activities have continued in the Capel region mainly in the Yoganup area. The Capel mineral sand mining operations are currently owned by Iluka Resources Ltd. At North Capel the company has major processing operations including two dry mineral processing plants and two synthetic rutile kilns. Processed mineral sand concentrates are exported through the Port of Bunbury.

By early 2007, most of the local Yoganup deposits including Yoganup Extended had been worked out except for remnant mining at Yoganup West. Accordingly, Iluka Resources extended the area from which mineral sand concentrates are currently sourced as feedstock for its Capel operations. In August 2007, the company indicated that in future it is likely that an increasing proportion of its ilmenite feedstock would be sourced from external sources. Currently, the Capel plants are supplied with mineral sand concentrates from two new mines at Cloverdale and Waroona (Iluka Resources, 2008).

Cloverdale

The Cloverdale mining project, located 9 km southeast of Capel, received approval early in 2007 and mining commenced later that year. Cloverdale has an estimated resource of about 2.2 Mt of heavy minerals and an expected economic life of 13 months (Prospect, 2007b). The mine is currently producing mainly ilmenite with reduced levels of zircon. Production from Cloverdale, combined with the output from the Waroona mine, now represents the primary ilmenite feedstock for Iluka Resources' two synthetic rutile kilns at Capel.

Waroona

Iluka Resources' Waroona mineral sands operation, 3 km northeast of the town, was approved for development in August 2006. The Waroona project contains a proven reserve of 8.3 Mt at 10.2% heavy minerals and has an estimated economic mine life of 42 months. Over this period, it is estimated the mine will produce about 0.19 Mt of ilmenite (sulfate-grade), 32 000 t zircon, and 25 000 t leucoxene (Prospect, 2007b).

In mid-2007, the mine and wet concentrator came into production but initial output was adversely affected by wet weather. This situation impacted on the supply of concentrate to the company's dry mineral processing operations at Capel causing an initial reduction in ilmenite and zircon production.

Wagerup

Also owned by Iluka Resources, the Wagerup mineral sands mine is located about 20 km north of Harvey. The deposit comprises mainly ilmenite with lesser quantities of leucoxene and zircon. Wagerup is mined principally for its ilmenite content (sulfate grade) that is mostly exported to offshore customers. The Wagerup mine is expected to remain in operation until around mid-2009.

Dardanup

Originally commissioned in late 2002 by Doral Mineral Sands Ltd, the Dardanup mineral sands mine, 17 km east of Bunbury, was estimated to have a mine life of about 15 years. In 2003, production had reached approximately

0.1 Mtpa ilmenite, and 10 000 tpa for both leucoxene and zircon. At that time, production was achieved by on-site processing ROM ore through a wet concentrator to produce a heavy mineral concentrate. This material was then trucked about 12 km to the dry plant at Picton for further dry processing.

In 2008, operations involve a 24-hour continuous mining and processing operation. At the Picton plant, the concentrate is dried and separated using both magnetic and electrostatic techniques to produce 0.11 Mtpa ilmenite, 5000 tpa leucoxene, 20 000 tpa HiTi70 (a high grade of titanium-rich minerals), and 15 000 tpa zircon. The majority of the products are exported through the Port of Bunbury to Asia and the US (Doral Mineral Sands, 2008).

Gwindinup and Happy Valley

The Gwindinup and Happy Valley mineral sand deposits, owned by Bemax Resources Ltd, are located on four contiguous mining leases between 4 and 11 km south of Boyanup. The Gwindinup mine is currently in development stage, having received environmental approval to proceed in 2007, and the environmental review and management plan for Happy Valley is due for completion in the first quarter of 2008. Production from Gwindinup is expected to come on stream following the completion of mining at Ludlow and continue for a period of at least six years.

Both sites at Gwindinup and Happy Valley each comprise two separate deposits sited on two distinct paleostrandlines at the foot of the Whicher Range escarpment. These deposits, containing about 10% zircon, have JORC-compliant reserves and resources listed below (Bemax Resources, 2006).

- Gwindinup North and South deposits
  Measured resources: 29.0 Mt at 7.2% heavy minerals
  Proved and probable reserves: 5.0 Mt at 13.7% heavy minerals (average grade)
- Happy Valley North and South deposits
  Measured resources: 9.0 Mt at 9.6% heavy minerals (average grade)
  Probable reserves: 6.0 Mt at 11.9% heavy minerals (average grade)

Ludlow and Tutunup

The Ludlow and Tutunup mineral sand deposits, located 34 km south-southwest of Bunbury and 20 km south of Capel respectively, are owned by Bemax Resources Ltd. Mining commenced at both sites in 2004. In 2005, the Tutunup deposit was worked out and operations shifted to Tutunup South. Mining continued at Tutunup South until mid-2007, when operations were completed. Combined production in 2006 from Ludlow and Tutunup South was 3.60 Mt at 10.34% heavy minerals. The Tutunup minesites are currently undergoing rehabilitation and the mineral concentrator has been relocated to the new Gwindinup operation (Bemax Resources, 2007a).

At Ludlow, annual production for 2007 yielded 0.27 Mt of heavy mineral concentrate from 2.53 Mt of ore before mining operations were completed in late November 2007 with final shipments of heavy mineral stocks to the company's mineral separation plant in Bunbury in the first quarter of 2008 (Bemax Resources, 2007b).

Keysbrook

The Keysbrook heavy mineral sands deposit, some 55 km south-southeast of Perth, is owned by Olympia Resources Ltd. The deposit has been subject to a feasibility study for a number of years and has been assessed with measured, indicated and inferred resources of 64 Mt at 2.6% heavy mineral sands for 1.67 Mt contained heavy minerals. Proven and probable reserves are estimated at 41 Mt at 2.7% heavy mineral sands comprising 1.12% ilmenite, 1.17% leucoxene, and 0.30% zircon, for 0.81 Mt contained heavy minerals (Olympia Resources, 2005a,b).

In November 2006, Olympia Resources entered into a life-of-mine toll treatment agreement with Cable Sands (WA) Pty Ltd (a wholly owned subsidiary of Bemax Resources Ltd) to treat future wet concentrate from Keysbrook at Cable Sands' processing plant close to Bunbury. Processed heavy mineral concentrates would then be shipped out of the Port of Bunbury to Olympia's customers in Europe and North America (Olympia Resources, 2006a).

Final environmental approval for the project to proceed was given by the Environmental Protection Authority in October 2007. The company is now seeking approvals from local government for mining to commence in the second half of 2008. The mine will produce about 0.1 Mt of heavy minerals valued at about $30 million per annum over an eight-year mine life (Olympia Resources, 2007a).

Southern Carnarvon Basin

Coburn

In March 2007, after almost four years work on the environmental approvals process, Gunson Resources Ltd received approval to proceed with the development of its Coburn project, a zircon-rich, mineral sands prospect in the Southern Carnarvon Basin, immediately south of Shark Bay and 130 km north of Kalbarri. The environmental approvals are based on proposals to progressively mine the north-trending Amy Zone mineralization over a mine life of about 20 years.

The linear Amy Zone, discovered in 2000, consists of an upper dunal horizon grading between 0.87% and 2% heavy minerals, and a lower, marine horizon with a high-grade core zone of over 2% heavy minerals. To date, the Amy Zone has been extensively drilled and evaluated over a distance of about 35 km from north to south (Figs 3 and 4).

Resource estimates for the deposit are based on results from 3100 drillholes completed in the southern end of the Amy Zone between 2000 and 2006. Total measured, indicated and inferred resources for the southern section of the deposit are 576 Mt at an average heavy mineral grade of 1.3% with a cut-off grade of 0.8%. In addition, there is an inferred resource based on more widely spaced

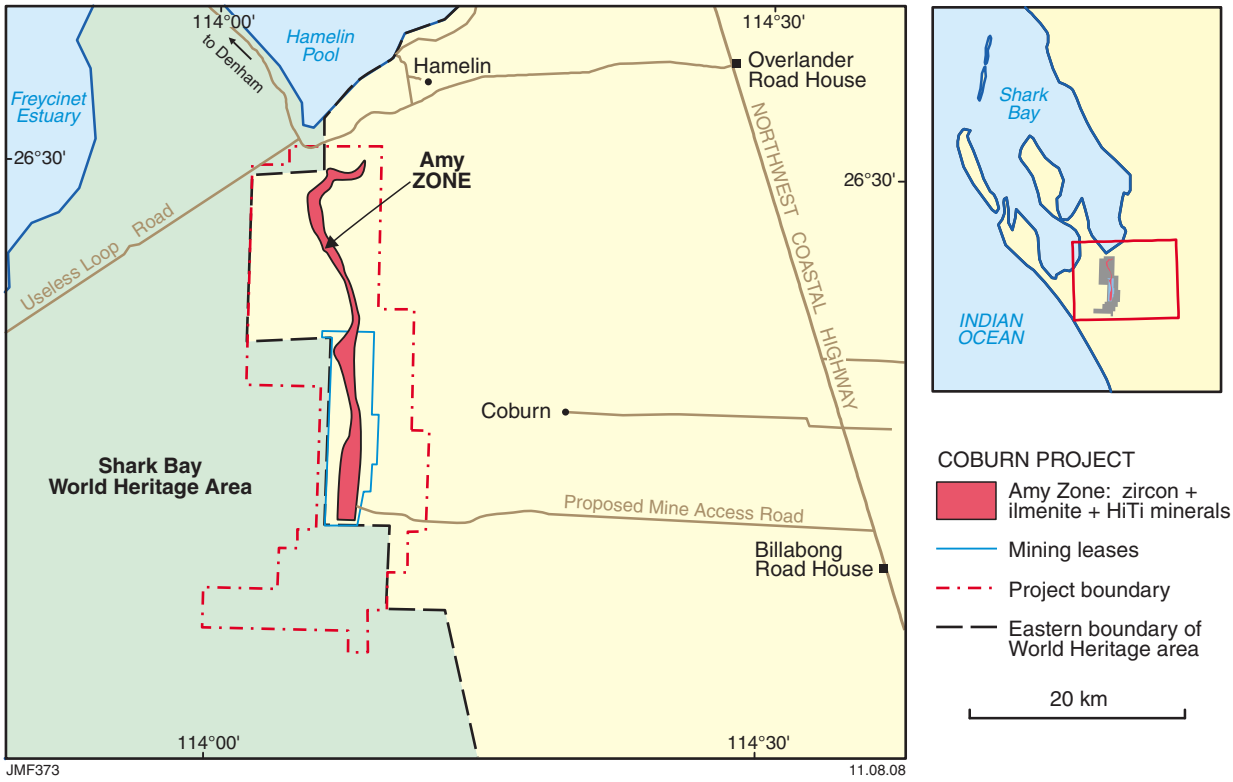

Figure 3. Map showing the linear, north-trending Amy Zone comprising the zircon-rich mineral sands orebody at the centre of Gunson Resources' Coburn project (modified after Harley, 2006)

drilling in the northern third of the deposit of 261 Mt averaging 1.4% heavy minerals. Pit optimization block models have been constructed from the measured and indicated resources given above. From these models, Gunson Resources has defined the trend of the proposed openpit mine with a strip ratio of waste to ore at 0.82:1 based on estimated proven and probable ore reserves totalling 124 Mt at an average grade of 1.3% heavy minerals (Gunson Resources, 2007a). Also, the company has estimated that 76% of the saleable heavy mineral concentrate to be recovered from the operation will comprise 40% ilmenite, 25% zircon, and 11% HiTi (high titanium-rich minerals) (Harley, 2006).

Figure 4. Air core drilling traverse over the Amy Zone of the Coburn project (after Harley, 2006)

In a move to fast track the Coburn mine to operating status producing around 38 000 tpa zircon over a 20-year mine life, Gunson Resources recently entered into two memoranda of understanding (MOU) with China Triumph International Engineering Company Ltd (CTIEC). These MOUs provide for CTIEC (through subsidiary and collaborating companies) to acquire a 40% participating interest in the project, and for CTIEC to be appointed as general contractor for the construction of the project. In addition, the MOUs provide for CTIEC to arrange for the construction of a mineral separation plant in China, and for an off-take agreement to purchase 20 000 tpa zircon. These agreements were due for completion by the end of 2007 so that construction of the Coburn mine, currently in final feasibility stage, and the Chinese mineral separation plant may commence pending final approvals (Gunson Resources, 2007b,c).

In April 2008, the company announced that, based on the results of the 2007 drilling program, there has been a substantial upgrade in heavy mineral resources and reserves for the Coburn deposit. Measured and indicated resources have increased to 718 Mt averaging 1.2% heavy minerals with a cut-off grade of 0.8%. Following pit optimization block modelling based on the upgraded measured and indicated resources, new proved and probable reserves totalling 306 Mt at an average grade of 1.2% heavy minerals were established (Gunson Resources, 2008).

Diamond

Over the past five years, diamond production in Western Australia has fallen by an overall 53% from 38.89 million carats (Mct) in 2002–03 to 18.22 Mct in 2007–07 (Fig. 5). In recent times, this decline in production appears to be largely due to continued variable, low-grade feed from the Argyle mine to the processing plant as the openpit nears the end of its economic life sometime in 2008.

Value of production for diamonds, last quoted in 2004–05, was $467.47 million for an annual production of 22.79 Mct. It should be noted that since that year, value of production figures for diamond are no longer available.

There are two diamond mines operating in Western Australia. The largest, the legendary AK1 (Argyle) pipe, located about 120 km south-southwest of Kununurra in the east Kimberley region, is wholly owned by Rio Tinto Ltd through its subsidiary Argyle Diamond Mines Ltd. The second, Ellendale mine, 140 km east-southeast of Derby in the west Kimberley, was formerly owned by Kimberley Diamond Company NL. In July 2007, Kimberley Diamond Company announced a friendly $300 million takeover by the United Kingdom-based Gem Diamonds Ltd.

Halls Creek Orogen

Argyle

The Argyle diamond mine has been in operation since 1985 where diamonds have been recovered from openpit mining and processing of lamproite ore from the AK1 diamond pipe (Fig. 6), and from nearby alluvial deposits at Smoke Creek and Limestone Creek. Since that time, the operation has produced over 678 Mct of diamonds to the value of A$14.3 billion. In 2005–06, the mine produced in excess of 29 Mct. Argyle diamond production by volume comprises about 5% gem grade and 70% near-gem grade that accounts for more than 95% of the value of Argyle Diamond's sales of uncut diamonds. Gem diamonds from Argyle range in colour from white to champagne to the famous pink variety for which the mine is renowned, and accounts for over 90% of world production of this rare diamond type. The remaining 25% of diamond production is classified as industrial grade used as abrasives in cutting, polishing, and machining processes (Department of Industry and Resources, 2007).

Currently, the primary diamond resource from the AK1 openpit is in decline and is expected to be exhausted sometime in 2008. In order to maintain continuing operations at the mine, the company announced in 2005 that it was to develop an underground mine to extract diamonds from the AK1 pipe by an extensive block cave mining operation. This $180 million project involves the excavation of 37 km of underground tunnels including four declines, two underground crusher chambers, and 2.8 km of vertical development work, part of which will house a vertical conveyor to raise diamondiferous ore to the surface. Underground mining is set to commence in 2010–2011 where the block cave mining operation will commence almost 500 m below ground level.

Under the current operational plan, it is estimated that underground mine life will run for eight years until 2018,

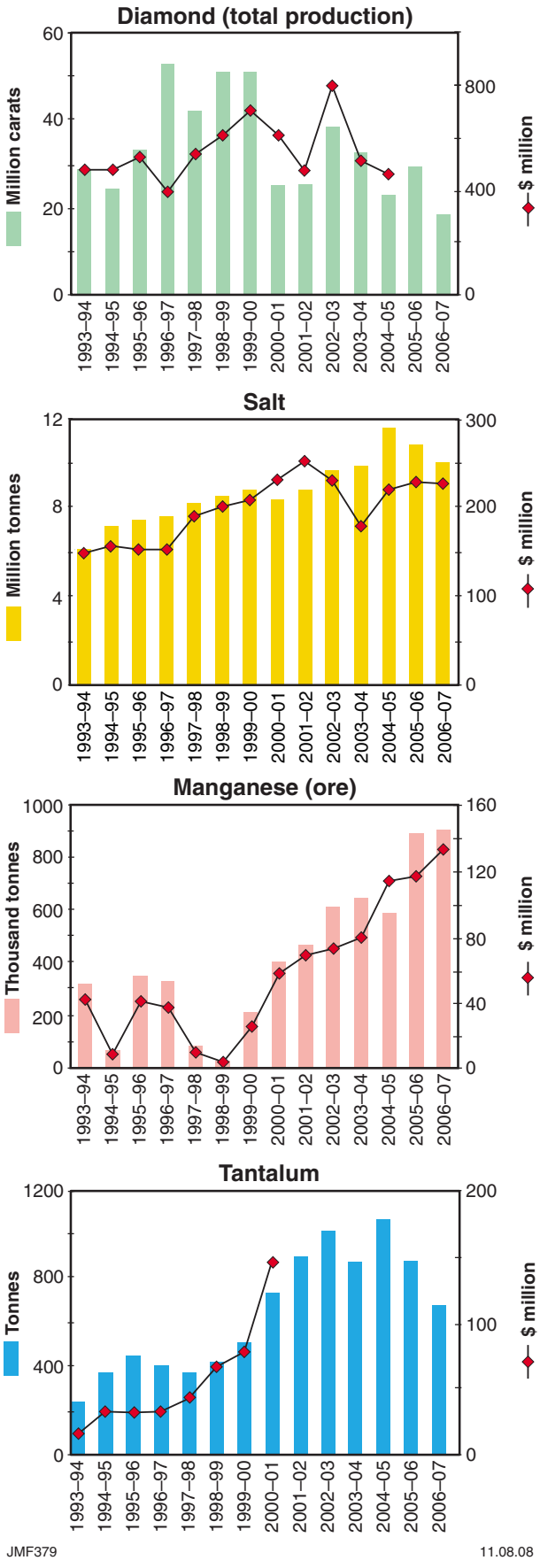

Figure 5. Trends in production (quantity and value) of diamond, salt, manganese ore, and tantalum in Western Australia, 1993–94 to 2006–07

JMF388 06.10.08

Figure 6. Argyle Diamond's extensive openpit over the AK1 diamond pipe in the east Kimberley region

during which about 62 Mt of diamondiferous ore will be extracted averaging around 20 Mct diamonds in each year of operation. It is also proposed that the life of the underground mine could be extended in a second phase of block caving for a further six years to 2024 (Prospect, 2007c).

Canning Basin (Leonard Shelf)

Ellendale

Mining commenced at Ellendale, Western Australia's second diamond mine, in June 2002 after Kimberley Diamond Company NL (KDC) purchased the Ellendale diamond field from Ashton Mining for $23 million in 2001. This acquisition gave KDC control over 46 lamproite pipes, 38 of which were known to be diamondiferous. From an initial production of almost 52 000 ct in 2002–03, the company has increased its output to 0.38 Mct in 2006–07 and achieved an average price of A$171 per carat. The mine produces mainly gem and near-gem diamonds together with only around 10% industrial grade stones (Department of Industry and Resources, 2007).

In July 2007, KDC directors recommended the acceptance of a friendly A$300 million cash takeover by Gem Diamonds Ltd from the United Kingdom. As part of the takeover deal, Gem Diamonds was to loan A$10 million to KDC to assist in progressing expansion plans at Ellendale. It was also agreed that Gem Diamonds would invest a further A$30 million to add value to current operations and to optimize performance of the Ellendale's three plants (Mining Journal, 2007a). The takeover was complete in December 2007, and both before and after that date, Gem Diamonds made significant improvements to two plants situated on the E9 diamond pipe and one on the E4 pipe resulting in improved process performance.

Ellendale is internationally well known as a source of fancy yellow diamonds that are much in demand. In 2007, the company announced that a record-sized, fancy yellow diamond weighing 18.5 ct had been recovered from the Ellendale operations. The company also revealed that stones from Ellendale Pipe 4 had an average weight of around 0.14 – 0.16 ct and varying up to 0.21 ct. Nine additional large stones, recovered in the previous six months, recorded weights in excess of 6 ct (Australia's Paydirt, 2007). Later that year, the first pink diamond of 1.58 ct was recovered from a new mining zone at the Ellendale 4 mine (Kimberley Diamond Company, 2007).

Currently, two dimondiferous pipes at Ellendale are being mined at Ellendale 9 and at Ellendale 4, located 20 km to the southeast. A third pipe, Ellendale 4 Satellite, in the vicinity of the Ellendale 4 pipe, is also in the resource category. Indicated and inferred resources for these three pipes are given below (Kimberley Diamond Company, 2006):

Pipe	*Ore*	*Grade*	*Contained diamonds*
	(Mt)	*(cpht)*	*(Mct)*
Ellendale 9	20.7	5.4	1.13
Ellendale 4	41.2	6.6	2.71
Ellendale 4 Satellite	16.0	7.1	1.13

Diamond production by KDC in 2006–07 was 0.38 Mct, a figure that more than doubled production of 0.15 Mct for the previous fiscal year. In February 2007, the company announced that measures being put in place to boost production would elevate it to the world's fifth-largest producer by June in that year. These measures included a A$26 M upgrade on the Ellendale 9 operation designed to double its output to 4.4 Mtpa. The overall effect of these improvements was expected to lift Ellendale's total output to 8.8 Mtpa for the recovery of 0.65 Mct for 2007.

In another related operation, Blina Diamonds, an alluvial diamond exploration and minor producer (51% owned by KDC), resumed mining in 2007 at the Ellendale 9 North project, and processing ore on a 24-hour basis. Blina Diamonds have an agreement with KDC to prospect for and mine alluvial diamonds within the KDC mining leases.

To date, Blina Diamonds has identified at least five diamondiferous paleochannels; the Western Channel at Ellendale 9 North from which 35 000 t of diamondiferous gravels were mined prior to 2007 yielding grades up to 25.29 cpht. The A Channel north of Ellendale 4 yielded bulk sample grades of 21.5 cpht, and another bulk sample from the Terrace 5 Channel south of the Ellendale 12 pipe returned a grade of 15.85 cpht with an average stone size of 1.08 ct. The largest diamond recovered from the Terrace 5 sample measured 6.03 ct. Recent bulk sampling by the company identified a 500 m downstream extension of diamondiferous gravels in the Western Channel covering 13 ha. The sampling operation yielded 1516 diamonds weighing 408 ct from an overall average grade of about 20 cpht, but ranging up to 52 cpht in selected areas (Mentiplay, 2007; Abeysinghe and Flint, 2008). Two other paleochannels, the Eastern Channel at Ellendale 9

and J-Channel southwest of Ellendale 4, are currently under investigation.

Salt

In 2007, Australia retained its position as the world's sixth largest salt producer (behind US, China, Germany, India, and Canada) as it has done for most of the last 20 years (Salt Institute, 2006). Australian annual production peaked in 2006 at around 12.4 Mt with about 93% of production coming from Western Australia. Since the 1993–94 fiscal year, the State's production steadily increased, reaching a peak of 11.6 Mt in 2004–05 before settling back to 10.1 Mt in 2006–07. Value of production over the last three fiscal years to 2006–07 averaged $226.4 million (Fig. 5).

Most salt production in Western Australia is from solar salt plants on the northwest coast. However, there are also significant quantities of salt in inland lakes, coastal lagoons, and ancient buried evaporites. Salt diapirs are known in the Officer and Canning Basins, but none of these are considered economically viable at present. Western Australian producers include Dampier Salt Ltd (Dampier, Port Hedland, and Lake MacLeod), Mitsui & Co., Ltd (Onslow, and Shark Bay), and WA Salt Supply Pty Ltd (Lake Deborah East, and Pink Lake) in the south of the State. Dampier Salt Ltd is currently the world's largest exporter of solar salt with 8.5 Mt sold from its three operations in 2005. Most salt is exported by bulk carriers (up to 93 500 t), from the northwest coast principally to South East Asia, especially Japan, China, South Korea and Taiwan, with other important markets located in the Middle East, Africa, and US.

Approximately 80–90% of exported salt is used by the chemical industry, mainly for caustic soda and chlorine manufacture leading to the production of a vast array of industrial chemicals for use in the textile, plastic, oil, paper, glass, detergent, tanning, and other industries. Salt is also used extensively in food processing and agricultural industries, as well as for softening of hard water and de-icing roads in cold climates.

Dampier, Port Hedland, and Lake MacLeod salt fields

These extensive solar salt fields on the northwest coast are owned by Dampier Salt Ltd, a consortium in which the majority shareholder (Rio Tinto) owns 64.9% together with minority owners Marubeni, and Sojitz Corporations (Dampier and Lake Macleod operations), and Marubeni Corporation, Nissho Iwai Australia Ltd, and Itochu Corporation (Port Hedland).

In 2006, combined salt production for this group was 8.3 Mt, representing an almost 2% reduction in annual production attributed to five cyclones in that year that caused flooding of salt ponds and damage to earthworks. It is expected that the residual impact from dilution caused by the record rains will be felt for about two years (Rio Tinto, 2006).

Dampier

With construction starting in 1969 and the first shipment of 19 000 t to Japan in 1972 , the Dampier salt project, 5 km south of the town of Dampier, has become the largest salt operation in Australia, producing around 3.6 Mtpa by the evaporation of seawater, and the second-largest individual salt producer in the world. The solar salt field covers an area of 14 000 ha, comprising nine concentrator ponds and 35 crystallizer ponds. The salt loader at Mistaken Island has the capacity to load ships ranging in size from 6000 t up to 94 000 t (Fig. 7).

Port Hedland

Purchased in 2001 from Cargill Australia, the Port Hedland operation about 30 km east of the town is the second-largest solar salt producer in Australia, with the capacity to produce 3.2 Mtpa. Seawater is pumped into a series of concentration and crystallizer ponds that cover an area of almost 9000 ha. Each year between 20 and 40 cm of high-quality salt is harvested from the crystallizer pans and washed and stockpiled ready for export via the 2000 tph Port Hedland loader mainly to markets throughout Asia.

Lake MacLeod

At the Lake MacLeod salt operation about 80 km north of Carnarvon, natural brine is recovered from shallow wells (depths of 4–6 m), and is circulated by gravity through an evaporating pan system to extract salt. This operation, purchased by Dampier Salt in 1978, has a production capacity of about 1.9 Mtpa. Stockpiled salt is transported about 25 km to the ship loading facility at Cape Cuvier for export. In 2006, shareholders approved a proposal to expand the capacity of the Lake MacLeod operation by 26% (Rio Tinto, 2006).

Shark Bay and Onslow salt fields

Mitsui & Co. Ltd is currently the major stakeholder in the solar salt projects at both Shark Bay and Onslow. Having been a 30% shareholder in the Shark Bay Salt joint venture

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Figure 7. Mistaken Island salt-loading facility for ships at Dampier

for over 30 years, Mitsui acquired 100% ownership in February 2005. In July of the following year, the company invested ¥7.2 billion to acquire Akzo Nobel NV's 90% holding in the Onslow Salt Pty Ltd. These acquisitions make Mitsui the third-largest salt supplier to the South East Asian market with a total annual capacity of 3.8 Mt (Mitsui, 2007).

Shark Bay

The Shark Bay solar salt field is located at Useless Loop on the western side of Shark Bay, 140 km south of Carnarvon. First developed in 1965 to supply growing export markets in Asia, Shark Bay was Australia's first modern salt field. The operation is approximately 6 km long and is enclosed by levees through which seawater is fed into a system of evaporation and crystallizer ponds. In recent years, the operation has been expanded by the completion of a primary evaporation pond covering 2600 ha designed to bring the total area up to 7000 ha with production capacity of 1.3 Mtpa (Fig. 8). The company operates its own private port facilities for 32 000 t vessels at Useless Loop to export salt to the Asian market.

Apart from salt production destined for the South East Asian chemical industry, the company is able to produce extremely pure, 'crystal clear' salt in this environment of low rainfall and exceptionly pure seawater. This high-quality salt is currently in demand by Japanese and other food processors in Taiwan, Indonesia, and the Philippines.

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Figure 8. Satellite image showing the solar salt ponds at Useless Inlet, Shark Bay (centre). White, stockpiled solar salt is clearly visible at the salt loader site adjacent to Useless Loop (centre right; after NASA Earth Observatory, 2007)

Onslow

Located about 12 km east of the town of Onslow on the northwest coast, the Onslow solar salt field commenced operation in early 1997 with the first salt harvest in April 2001, closely followed by the first shipment of 45 000 t to South Korea. Today, Mitsui has ramped annual salt production capacity up to 2.5 Mt from evaporator ponds covering 8600 ha. This operation exports salt in vessels up to 50 000 t from its Onslow port facilities mainly to Japanese and other South East Asian chlor-alkali chemical manufacturers.

Lake Deborah East and Pink Lake

WA Salt Supply Pty Ltd produces salt from Lake Deborah East, located near Koolyanobbing, 65 km north of Southern Cross and 450 km east of Perth. At Lake Deborah East, over 200 000 tpa salt is harvested and stockpiled following evaporation of water collected in the lake during winter rains. The crystallized salt is washed on-site and then railed in containers to the company's Hamilton Hill refinery in Perth.

The company's other operation is located at Pink Lake, 5 km northwest of Esperance. The Pink Lake tenements are capable of producing about 15 000–20 000 tpa of high-quality industrial salt. Some raw material is sold on-site and the remainder transported to the Hamilton Hill refinery for processing mainly as water-softening salt for export.

Most of the company's high-quality, refined salt is supplied to the domestic salt market while around 20% of production is exported to countries such as Singapore, Fiji, Mauritius, Reunion, Brunei, and the United Kingdom. A wide range of salt types is produced including butcher's salt, cheese salt, coarse salt, hide salt, petroleum drilling salt, sheep-skin salt, sodium-reduced salt, superfine salt, swimming-pool salt, table salt, textile dye bath salt, and water-softening salt. Other Western Australian customers include three chlor-alkali plants, and the petroleum drilling industry in the State's northwest (WA Salt Supply, 2007).

Manganese

Hamersley Basin

Woodie Woodie

Western Australia's only operating manganese mine at Woodie Woodie is operated by Pilbara Manganese Pty Ltd. In January 2008, this operation (formerly Consolidated Minerals Pty Ltd) became a wholly owned subsidiary of Palmary Enterprises Ltd. Woodie Woodie is located in the East Pilbara manganese province, 325 km southeast of Port Hedland in the east Pilbara region. Mining originally commenced at Woodie Woodie in 1954 and continued until 1982, when operations were shut down for seven years.

Mining re-commenced in 1989 and was taken over by Consolidated Minerals in May 1999. Since that time there has been a substantial overall increase in both tonnage and value of manganese ore from extremely low levels in 1998–99 to record highs in excess of 0.90 Mt with an estimated value of $135 M in 2006–07 (Fig. 5).

During 2006–07 the company maintained operating costs at historic levels while experiencing an increase of 4% in the average price of lump ore to US$2.34 per dtmu (dry metric tonne unit). In 2007, the company announced updated resources and reserves for the Woodie Woodie operation with measured, indicated and inferred resources of 15.47 Mt at 41.5% manganese, and proved and probable reserves of 8.71 Mt at 41.5% manganese.

At Woodie Woodie, economic manganese mineralization comprising pyrolusite, cryptomelane and braunite appears to be derived mainly from manganese-rich fault and chert breccia pipe structures intersecting late Archean Carawine Dolomite and the overlying Paleoproterozoic Pinjian Chert Breccia. Recent studies indicate that the manganese may have been transported by major hydrothermal systems and deposited in low-temperature, distal areas in large cavities and fissures in the Carawine Dolomite and Pinjian Chert Breccia. These void spaces may have been formed during a period of Proterozoic karstic weathering, causing the dissolution of dolomite and calcite (Jones, 2007).

The Woodie Woodie operation consists of a series of opencut mines and exploration pits, extending for almost 20 km along a north-trending zone. Manganese ore is sourced from multiple openpit mining operations, principally major deposits contained in the Greensnake and Rhodes pits as well as other operations including Chutney and Bells opencuts. Ore from the pits is blended to maintain a consistent grade and is then processed through a heavy media separation plant to produce both lump and fine grades. Processed manganese ore is then shipped by 90 t road trains to Port Hedland for export to countries in South East Asia such as China, Taiwan, Korea, India and Bangladesh, as well as to the Middle East, Norway, and Eastern Europe (Consolidated Minerals, 2007).

Around 90% of manganese is incorporated in steel-making processes while the remaining 10% finds mainly non-metallic applications in the manganese chemical industry, particularly in the manufacture of manganese dioxide, and more recently electrolytic manganese dioxide (EMD) that is incorporated in most contemporary zinc–carbon, alkaline, lithium–manganese disposable batteries as well as lithium-ion rechargeable batteries for added power and greater dependability. China currently produces the bulk of world supply of EMD, with other major manufacturers in the US, Japan, South Africa, Greece, and at Newcastle in eastern Australia (King, 2006).

In recent years, Pilbara Manganese has maintained an active exploration program consisting of mapping, EM and IP surveys, and drilling over about 13 pits and prospects in the Woodie Woodie area. In 2007, the company announced that exploration had located an additional resource of 1.68 Mt from the Rhodes, Topvar and Austin deposits, with most of the resource (1.4 Mt) located in the extensions to the Rhodes orebody. Drilling revealed that this orebody is open to the north and east, and investigations are continuing.

Other significant exploration results have been returned from drilling at the Sardine–Ranchu–Minnow prospects, now considered to form part of a discrete orebody. A number of significant intersections were also returned from the Chutney East, and Tench–Ghost prospects, and additional target generation is underway at the nearby Tarra Tarra – Depot Creek–Skull Springs prospects following the 2006 EM survey and geological mapping program (Consolidated Minerals, 2007).

Tantalum

Tantalite is the principal ore of the rare metal, tantalum. In the tantalum industry, enriched tantalite concentrate is consumed mainly in the manufacture of tantalum metal powder used by the electronics industry for the production of tantalum capacitors and, to a lesser degree, computer memory chips and processors. Numerous uses for these components exist in the computer, communications, automotive, and instrumentation industries. Other tantalum metal applications include advanced technology alloys, especially turbine blades in aircraft engines, non-corrosive metal in the medical and chemical industries, and tantalum carbide products for use in metal cutting and drilling (Fetherston, 2004).

In 2004, there was considerable upheaval in the Western Australian tantalum mining industry with the world's largest tantalum producer, Sons of Gwalia Ltd (SOG) going into administration on 8 September because of an untenable financial situation related to its gold production. At that time the company controlled about 75% of the world's defined tantalum reserves from deposits at Greenbushes and Wodgina and it supplied about 50% of world demand. At 30 June 2003, SOG's total proved and probable reserves stood at 204.8 Mt at 0.024% Ta_2O_5, and total measured, indicated and inferred resources were estimated at 292.4 Mt at 0.016% Ta_2O_5 (Sons of Gwalia, 2003).

The administrators, Ferrier Hodgson, worked to keep the advanced metals division (tantalum, tin, and lithium) in operation. Firstly, a long-term take or pay contract was signed with German producer, HC Starck, the world's largest tantalum consumer, following the expiry of its current contract in 2005. The new contract, for the years 2006 to 2008 inclusive, is for the supply of 800 000 lbs per annum (362 tpa) of tantalum concentrate with the buyer having the option to purchase an additional 200 000 lbs per annum (91 tpa). At current demand, this contract effectively represents 25% of mined global tantalum production (Sons of Gwalia, 2004).

At the same time, management and administrators approved an $8.0 million upgrade to the processing plant in the west Pilbara Wodgina mine. This 12-month upgrade was to improve process recoveries due to changes in ore characteristics as the mine progressed from oxide to primary ore sources. Soon afterwards, the administrators advised Haddington Resources Ltd as part of their resolution of SOG's debt situation, that they were only in

a position to receive tantalum concentrate from Bald Hill until the end of September 2005 (see below under **Bald Hill**).

By February 2006, the administrators decided to close the underground tantalum mine at Greenbushes that had been re-opened only in late 2004, as well as the opencut mine that had been operating on reduced tonnages during this period. It was announced the operational restructure was to maximize production at the lower cost operation at Wodgina, leaving the Greenbushes tantalum operation in care and maintenance. Also in that month, after protracted negotiations, a second agreement was signed with SOG's other off-take partner, Cabot Corporation from the US, for a significantly reduced supply of concentrate (MiningNews.net, 2006).

Sons of Gwalia's period of administration was finally resolved in June 2007 when Resource Capital Fund, a private equity company from Denver in the US, won control of the company with a bid of $205 million in the face of strong competition from rival US company Bracewell & Giuliani. Following the successful takeover bid, the company was re-named Talison Minerals Pty Ltd in August 2007. Talison is now the world's largest producer of tantalum concentrate, producing between 25% and 33% of global supply from the Wodgina deposit alone (Mining Journal, 2007b).

Despite problems experienced by the local industry during this period, tantalum mining attained peak production of 1063 t during the 2004–05 fiscal year. This result was not to last, as in the last two years to 2006–07 production declined to 674 t, roughly equivalent to production levels of seven years ago (Fig. 5).

Yilgarn Craton – South West Terrane

Greenbushes

The Greenbushes mine, owned by Talison Minerals Pty Ltd and located about 70 km south-southeast of Bunbury, is developed on a pegmatite dyke swarm emplaced over a strike length of 7 km. The largest pegmatite body is 3.3 km long and up to 250 m wide. The tin–tantalum–spodumene pegmatites are made up of four layered units without a classic concentric zonation pattern. The atypical zonation pattern seen in this deposit includes a border or contact zone, a K-feldspar zone, an Na- (or albite) zone containing the main tin–tantalum mineralization, and an Li- (or spodumene) zone, the main source of lithium mineralization (Partington et al., 1995). At 30 June 2003, total proved and probable tantalum reserves for Greenbushes mine stood at 142.8 Mt at 0.018% Ta_2O_5, and total measured, indicated and inferred resources were estimated at 192.2 Mt at 0.016% Ta_2O_5 (Sons of Gwalia, 2003).

When in operation, Greenbushes tantalite ore was mined in association with cassiterite (tin ore). About 3.5 Mtpa of the ore, containing 450 g/t tantalum and 950 g/t tin, was processed in an on-site tantalum primary processing plant to produce a low-grade tantalite concentrate of about 4–6% Ta_2O_5. As well as cassiterite, the material also contained minor ilmenite, monazite, zircon, and arsenopyrite impurities. The concentrate was then sent for secondary processing where it was upgraded to high-grade tantalite concentrate averaging 20–30% Ta_2O_5. The remaining tin–tantalite concentrate was processed in an electric-arc furnace where the tin metal was cast into ingots, and the slag refined in a second furnace capable of producing tantalum glass containing 15–25% Ta_2O_5 (Fetherston, 2004).

Yilgarn Craton – Eastern Goldfields Terrane

Bald Hill

The Bald Hill mine, owned by Haddington Resources Ltd, lies about 55 km east-southeast of Widgiemooltha in the Yilgarn Craton. Between 2004 and 2005, tantalum mining operations were carried out in a number of comparatively shallow openpits. Over this period, most ore was derived from the high-grade South Pit while other pits such as Hills End and Hill View were progressively mined out. Quarterly ore production averaged almost 80 000 t. At the end of June 2005, measured, indicated, and inferred resources stood at 0.424 Mt at 0.038% Ta_2O_5. By September 2005, the South, and Boreline pits remained in production until mining operations were suspended soon afterwards.

Suspension of mining activities was ultimately brought about by the failure of the company's agreement with Sons of Gwalia Ltd (SOG), that provided for SOG to purchase all tantalum concentrate produced at Bald Hill. Following the appointment in August 2004 of administrators Ferrier Hodgson to oversee the the resolution of SOG's debt situation, the administrators advised that they were only in a position to receive Bald Hill concentrate until the end of September 2005. Following this announcement, Haddington Resources found that they were unable to secure a viable off-take price for the Bald Hill concentrate on the open market, owing to the current downturn in the demand for tantalum and depressed market prices. The entire operation was placed in care and maintenance in December 2005 and existing concentrate inventories were sold off in the first half of 2006 (Haddington Resources, 2006a,b).

Pilbara Craton

Wodgina

Talison Minerals' Wodgina mine, about 100 km south of Port Hedland in the Pilbara Craton, produces tantalite from a series of stacked rare-metal pegmatite sheets (Sweetapple et al., 2001). Host rocks for the Mount Cassiterite pegmatite group in this area consist of a sequence of metasedimentary rocks comprising fine-grained psammites with pelitic biotite interbeds. These rocks are extremely weathered to at least 80 m below surface, whereas the pegmatites have been affected by deep weathering to at least 50 m depth.

In the area of the interlinked openpits of Mount Cassiterite and Mount Tinstone, there are four stacked pegmatite

sheets ranging from 5 to 80 m thick, mostly gently dipping between 20° and 25° to the southeast. The uppermost of these is the thick, deeply weathered Mount Tinstone sheet, followed by the thin Hanging Wall sheets beneath which is the thick Main sheet at Mount Cassiterite. The lowermost unit, known as the Lower sheet, is a very large tantalum resource between 50 and 200 m thick with the footwall extending to 400 m below surface (Fig. 9). The three uppermost sheets at Mount Cassiterite and Mount Tinstone are currently mined for high-grade tantalum ore. The Lower sheet contains lower Ta_2O_5 grades averaging 0.014% and is expected to be retained as a future tantalum resource (Fetherston, 2004).

Main ore minerals for the Mount Cassiterite pegmatite group are wodginite, cassiterite and tapiolite, with subordinate manganocolumbite, manganotantalite with microlite, and traces of calciotantite. The grainsize for tantalum and tin minerals rarely exceeds 0.5 mm, with the average being in the range 0.1 – 0.25 mm. At 30 June 2003, total proved and probable tantalum reserves for the Wodgina mine stood at 62.0 Mt at 0.037% Ta_2O_5, and total indicated and inferred resources were estimated at 100.2 Mt at 0.017% Ta_2O_5 (Sons of Gwalia, 2003).

Each year about 3.2 Mt of ore from the Wodgina operation is crushed and processed on-site to produce a primary low-grade tantalite concentrate. This material is then bagged and transported by road about 1700 km south to Greenbushes for upgrading to high-grade concentrate in the company's secondary processing plant.

Bauxite and alumina

In 2006–07, Western Australia produced almost 12.0 Mt of alumina, valued at $4.82 billion, from bauxite mined in the Darling Ranges to the east and southeast of Perth (Fig. 10). The two companies in Western Australia involved in bauxite mining for the alumina industry are Alcoa World Alumina Australia, and Worsley Alumina Pty Ltd. In 2006, these Darling Range operations produced 32% of the world's and 64% of Australia's total alumina supply. Currently,Western Australia has a range of diverse markets for alumina exports with China taking 21%, South Africa and Bahrain 17% each, United Arab Emirates 15%, Mozambique 8%, Canada 7% , US 6%, and other countries 9% (Department of Industry and Resources, 2007).

Alcoa mines bauxite from the Huntly and Willowdale mines, situated about 15 km east-southeast and 35 km south-southeast of Pinjarra respectively. Huntly is currently the world's largest bauxite mine but both mines are currently the lowest grade operations worldwide. Ore from the Huntly mine is transported by conveyor to the Pinjarra alumina refinery. Crushed Huntly ore is also railed from a stockpile at Pinjarra to the Kwinana alumina refinery. Willowdale ore is transported to the Wagerup alumina refinery via a conveyor. In 2006, the long-awaited upgrade of the Pinjarra refinery was completed to a capacity of 4.2 Mtpa.

Worsley Alumina is a joint venture between BHP Billiton Ltd (86%), Japan Alumina Association (Australia) Pty Ltd (10%) and Sojitz Alumina Pty Ltd (4%). Construction of the Boddington mine, about 120 km southeast of Perth,

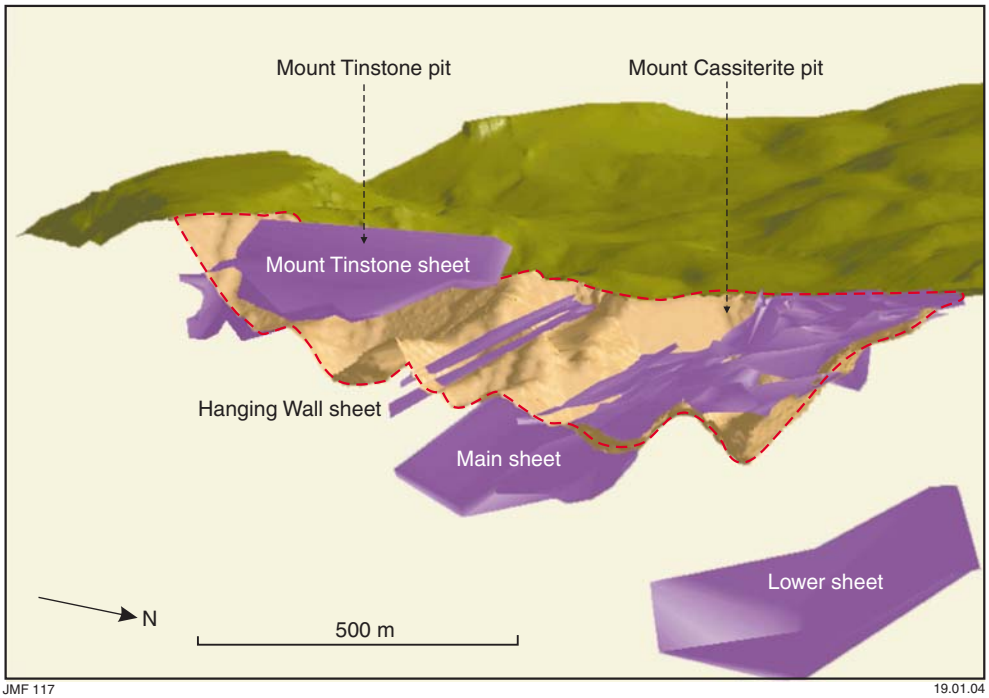

Figure 9. Block diagram showing the distribution of tantalum-rich pegmatite sheets at the Mount Cassiterite and Mount Tinstone openpits (Fetherston, 2004)

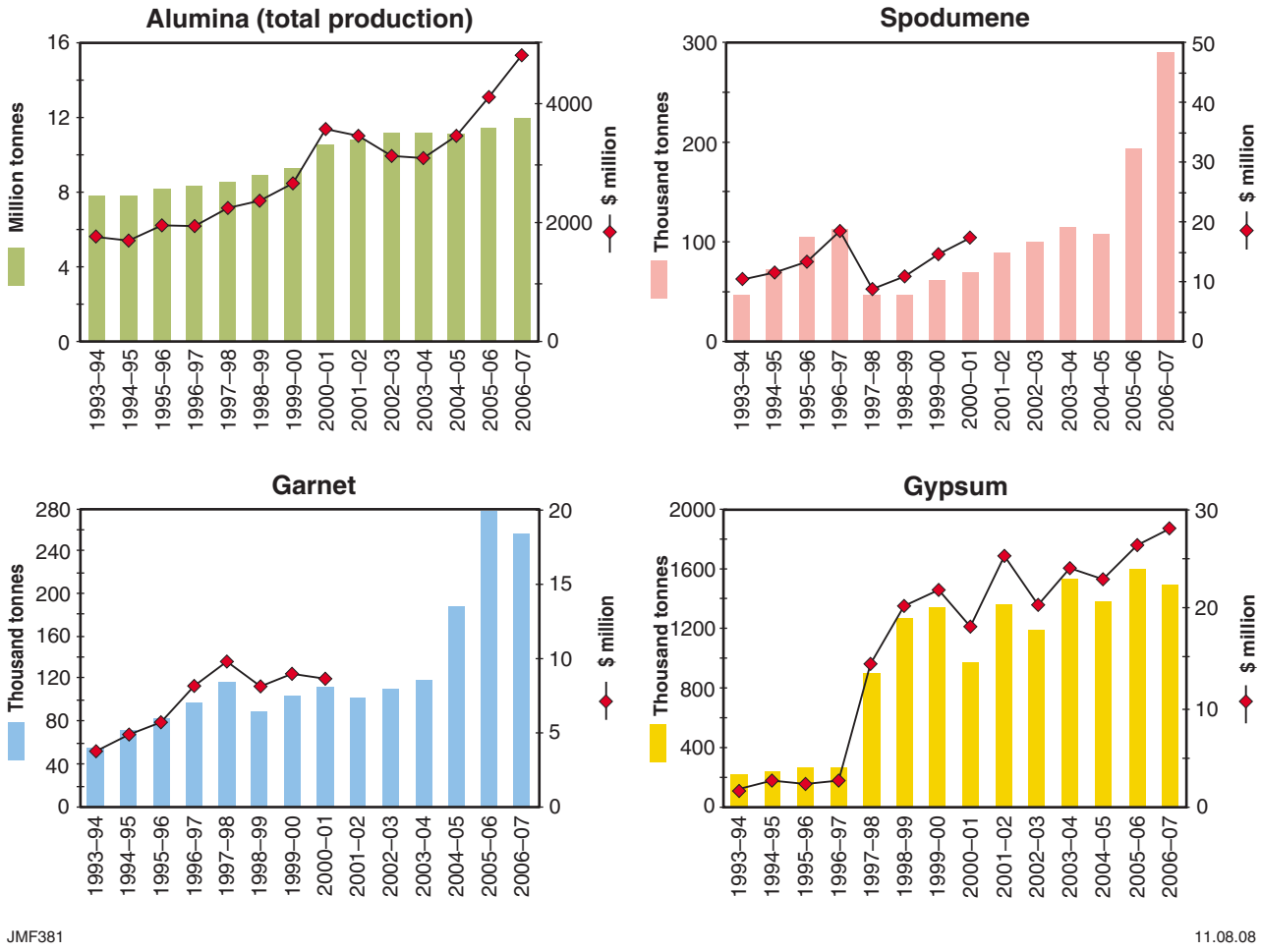

Figure 10. Trends in production (quantity and value) of alumina, spodumene, garnet, and gypsum in Western Australia, 1993–94 to 2006–07

commenced in 1980, with first ore extracted in 1984. Operations were later expanded to the nearby Saddleback area, 50 km north-northeast of Collie. Bauxite ore is transported 51 km by overland conveyor to the Worsley refinery with an alumina capacity of 3.2 Mtpa. Refined alumina is then transported a further 50 km by rail to the Port of Bunbury for export.

Most of the alumina produced is sold and exported from the State as feedstock for aluminium smelting, but a smaller quantity is allocated by Alcoa for non-metallurgical applications. Based on best estimates for 2007, approximately 270 000 t of alumina valued at over $85 million were specially treated for the manufacture of hydrated and calcined aluminas for use in various industrial processes. These operations are carried out by Alcoa at the alumina refinery at Kwinana, 30 km south of Perth.

Calcined alumina

Alcoa produces about 100 000 tpa of calcined alumina, destined for the manufacture of fused alumina and also for export markets specializing in sintered alumina. At Alcoa's plant, three grades of calcined alumina are manufactured: the KA-01 grade (with a 70 m^2/g surface area and <0.45% Na_2O), and two, smaller surface area, low-soda grades: KA-25 (60 m^2/g surface area and <0.2% Na_2O), and KA-13 (15 m^2/g surface area and <0.2% Na_2O). The KA-01 grade has uses in the manufacture of abrasives, ceramics, refractories, and glass. In the low-soda grades, KA-25 is a feedstock for white, refractory grade, fused alumina, and KA-13 is a feedstock for sintered alumina.

Hydrated alumina

Alcoa's plant has the capacity to produce 170 000 tpa (alumina basis) of hydrated alumina (also known as alumina hydrate). The plant manufactures two grades of hydrated alumina, with the KC-30 grade (containing >99% hydrated Al_2O_3 and <0.3% Na_2O) used as a filler in building boards and as a fire retardant in carpet backing. The more purified KB-30 grade (containing >99.5% hydrated Al_2O_3 and <0.25% Na_2O) is used in the manufacture of alum (aluminium sulfate), sodium aluminate, poly-aluminium chloride, and artificial zeolites.

Fused alumina

Doral Fused Minerals Pty Ltd, a subsidiary of Doral Mineral Industries Pty Ltd, operating out of Kwinana, uses KA-25 grade low-soda, high-purity, calcined alumina, supplied by Alcoa, as feedstock for the manufacture of white, refractory-grade, fused alumina. This is produced in two 3.3 MVA electric-arc furnaces, with a total capacity of 22 000 tpa fused alumina. The resulting high-purity, fused, granular material is extremely hard (9°on Mohs scale) with a melting point of around 2050°C. The fused alumina is sized to customer specifications, with most exported to South East Asia, South Africa, Europe, and North America, and a smaller quantity going to markets in eastern Australia. This material finds applications in an extensive range of refractories and in the abrasives industry as blasting and abrasive grits.

Spodumene (lithium)

Yilgarn Craton – South West Terrane

Greenbushes

In 2004, the world's largest spodumene producer, Sons of Gwalia Ltd (SOG) went into administration on 8 September owing to an untenable financial situation related to its gold production. The company's period of administration was resolved in June 2007 when Resource Capital Fund, a private equity company from the US, won control of SOG. Following the successful takeover bid, the company was renamed Talison Minerals Pty Ltd . Although tantalite mining at Greenbushes ceased in 2005, lithium mining continued unabated through the periods of administration and transition to the new owners.

The Greenbushes deposit in the Yilgarn Craton, 70 km south-southeast of Bunbury, is the world's largest, hard-rock, lithium resource contained in the mineral spodumene, a lithium–aluminium silicate. The main source of lithium mineralization is developed in discrete bodies within the Li-zone (spodumene zone) of the fractionated Greenbushes tin–tantalum–spodumene pegmatite (Partington et al., 1995). Deep drilling programs at Greenbushes in the early 1980s confirmed the existence of a large, high-grade spodumene orebody containing >4% Li_2O.

Spodumene is extracted from the Lithium openpit, adjacent to the tantalum mining operation in the Cornwall openpit. Last quoted reserves and resources for spodumene in June 2003 were proved and probable reserves of 7.73 Mt at 4.1% Li_2O, with a lithium metal content of 0.31 Mt together with measured and indicated resources of 4.9 Mt at 3.5% Li_2O with a lithium metal content of 0.17 Mt (Sons of Gwalia, 2003). Spodumene production from Greenbushes has experienced an overall increase since 1997–98 with by far the biggest increase of over 50% from 0.19 Mt in 2005–06 to 0.29 Mt in 2006–07 fiscal year (Fig. 10).

The spodumene processing plant produces a number of high-grade spodumene concentrates. The high-grade circuit treats about 30 tph crushed ore at containing 4.4% Li_2O. The coarser fraction, containing about 5% Li_2O, is dried and sold as glass-grade spodumene. Finer fractions are processed in the primary plant to produce high-grade concentrates containing about 7.5% Li_2O.

Applications for spodumene in the glass industry are in the production of low thermal-expansion glass and glass ceramics, monochromatic and colour television glass components, container glass for the bulk packaging industry, high-quality tableware, perfume containers, and fibreglass. Ceramic applications include low thermal-expansion cookware, fully vitrified ceramic tiles, sanitaryware, and frits and glazes. Other applications are in the refractory, cement, metallurgy, and foundry moulding industries.

Currently, the world supply of lithium minerals is dominated by lithium–rich solar salt sourced from lake brine deposits in the Andes mountains of Chile and Argentina. These countries produce about 46% of the total supply of lithium metal equivalent (LME). Western Australia's hard rock spodumene production from Greenbushes is over 17% LME of world production, followed by China, producing both lithium brine and spodumene at about 12% LME (Tahil, 2006). In recent years, there has been a shortfall of lithium minerals and brines on world markets of 5000–10 000 t lithium carbonate equivalent (LCE). Talison Minerals estimates that apart from its additional production in 2006–07, the company could have sold an additional 5000 t LCE to existing and new customers. The company expects a more balanced world marketing situation around 2008, with expansion of brine production in both China and Chile, as well as increased production by the Chinese chemical industry, to a situation where production begins to match demand (Miller, 2007).

Basic raw materials

During 2006–07, almost 5.9 Mt of basic raw materials (also known as construction materials), produced in Western Australia and valued at $54.4 million, was reported to DoIR. However, a large proportion of basic raw materials produced during 2006–07 remain unreported. This is because numerous quarrying operations, operating on privately owned land, mine a variety of basic raw material commodities under extractive quarry licences issued by local government bodies. In this situation, these materials are not defined as being minerals under the Mining Act, 1978; hence, production statistics are not reported. Accordingly, total basic raw material production for the State is likely to be many times the reported tonnage.

Basic raw materials comprise broken stone sized from boulders to cobbles, crushed rock for aggregate, river gravel, low-value limestone and clay, and concrete- and filling-grade sand. These materials are sourced throughout the State by industry and local government. All materials are low-value commodities that are generally sourced as close as possible to the local market or construction site, to keep transportation costs to a minimum. Most basic raw materials are used in the building industry or as materials for road construction. Other uses include dam-site raw materials, material for construction of breakwaters and retaining walls, and for railway ballast.

Garnet

Southern Carnarvon Basin

Port Gregory

Almost all garnet production in Western Australia is sourced about 85 km north-northwest of Geraldton, from the Port Gregory operations of GMA Garnet Pty Ltd. Minor garnet production may also be sourced as a byproduct from other heavy mineral sands operations. Total garnet production for the State during 2006–07 was 0.259 Mt (Fig. 10).

The Port Gregory garnet deposits are present as high-grade placers in dune systems parallel and adjacent to Hutt Lagoon. The high proportion of almandine garnet in the sand is derived from the garnet-rich gneissic rocks of the Neoproterozoic Northampton Complex, inland from Kalbarri (Plate 1). Earlier this decade, the deposit had proven reserves of more than 8 Mt of garnet. GMA Garnet also has the right to mine other previously secured resource areas.

In 1998, GMA invested $4.5 million in a 200 000 tpa wet separation plant at Port Gregory. This upgrade effectively made the GMA operation the world's largest single garnet producer. At this location, garnet sand extracted from paleostrandlines, is processed in the separation plant equipped with spirals and hydrosizers to produce a wet almandine concentrate. This material is subsequently transported to GMA's Narngulu dry treatment plant near Geraldton for drying and further processing. Bulk garnet product is stockpiled in storage sheds at the Port of Geraldton prior to export.

GMA garnet is produced in a variety of size ranges for various applications from 100 to 600 μm diameter (0.1 – 0.6 mm). Chief amongst these is the industry standard configuration (300–150 μm) principally for water-jet abrasive blast cleaning applications for cleaning hulls of drydocked ships, as well as cleaning applications in the petrochemical industry, chemical and industrial plants, steel bridges and the like. Other grades find application in high-speed water-jet cutting, and high- and super fine precision edge cutting. Other applications for garnet powder include concrete and floor finishing products, anti-slip coatings, water purification, undersea cables, and for blasting denim material (GMA Garnet, 2007).

Gypsum

In Western Australia there are about 180 gypsum deposits, with a total resource of potentially economic gypsum of about 1.5 Gt. During 2006–07, gypsum production in Western Australia was 1.5 Mt, valued at $28.40 million (Fig. 10). This shows gypsum production in the State has remained relatively constant over the last four fiscal years since 2003–04, averaging around 1.5 Mtpa while value of production has slowly increased over the last three years by about 23%.

The bulk of the State's production is exported, primarily to Japan. Within the State, the main gypsum-consuming industries include cement, plaster, agriculture, and mining. There may also be opportunities for value-added production such as plasterboard, to supply international and domestic markets.

Barred basin and birrida deposits

The largest gypsum resources in Western Australia are in barred basin and birrida deposits in coastal areas, where seawater has been partly or totally cut off from the ocean.

Lake MacLeod

The Lake MacLeod deposit, 80 km north of Carnarvon, is the largest of this type in the State, where bedded gypsum, about 2 m thick, formed on the surface and within saline playa sediments by the barring of a former marine embayment. Operated by Dampier Salt Ltd, the Lake MacLeod deposit is the State's major gypsum producer, with an annual production of up to 1.5 Mt. The dredged raw gypsum is leached with bore and potable water to reduce chloride levels to produce a gypsum grade suitable for use in wallboard and plaster manufacture. Destined for export, the purified gypsum is transported to the ship loading facility at nearby Cape Cuvier. The volume of the gypsum layer at Lake MacLeod has been estimated to exceed 2000 million cubic metres containing about 3.5 billion tonnes of gypsum, and the mineable resource is in excess of 300 Mt.

Other deposits

Large deposits of barred basin and birrida-type gypsum are also located in the Shark Bay area, but development prospects are poor because of their location within the Shark Bay World Heritage area. Farther south, gypsum is currently mined from a birrida deposit at the Jurien Bay North, about 12 km north-northwest of the town of Jurien Bay. At this deposit, CSR Readymix Ltd mine substantial quantities of plasterboard-grade gypsum.

Playa lake deposits

Most of Western Australia's inland gypsum deposits are located in playa lakes in the southwest region. Of these deposits, 13 have gypsum reserves in excess of 1 Mt. At Lake Moore and Lake Cowan, seed gypsum reserves are estimated at 100 Mt and 12.5 Mt respectively (Jones, 1994).

Principal producers from this region include Bywaters at Lake Goorly (industrial and agricultural grade), Cockburn Cement at Lake Hillman (cement grade), Gypsum Industries of Australia (a subsidiary of Westdeen Holdings Pty Ltd) at Cowcowing Lakes South (agricultural grade), HB Brady and Co. from Lake Brown (industrial grade), Whitfield Minerals Pty Ltd from Lake Cowan (gypsum for production of shotcrete, known as 'Aquacrete', for mining industry applications), and Wandell from Scaddan (agricultural grade). In addition, there are about 16 smaller agricultural-grade gypsum producers mining from playa lakes that extend through the agricultural region from north of Esperance on the south coast, almost to Dongara, south of Geraldton.

Limestone and limesand

In 2006–07, reported limestone and limesand production for Western Australia was about 3.79 Mt, valued at $23.24 million (Fig. 11). In addition, it is likely that a substantial quantity of low-grade limestone produced in the State remains unreported to the DoIR. This is because a number of limestone and limesand quarries operate under extractive quarry licences on privately-owned land and production statistics from these operations are not reported as such operations are outside the realm of the Mining Act (1978). Major consumers of limestone and limesand in the State are the cement and mining (alumina, gold, nickel and mineral sands) industries of around 30% each, with the remainder taken up by the construction and the agricultural industries.

Despite Western Australia having large resources of high-grade limestone of the order of a few billion tonnes and average limestone and limesand production over the last five years of 4.09 Mtpa, cement clinker with an average annual value of $18.14 million, has been imported into the State. These imports, from Japan, Malaysia, Philippines and Singapore, were apparently intended for the production of Portland cement. This tends to indicate that the State's current production levels of high-grade limestone and limesand are insufficient to satisfy current demands of the local market.

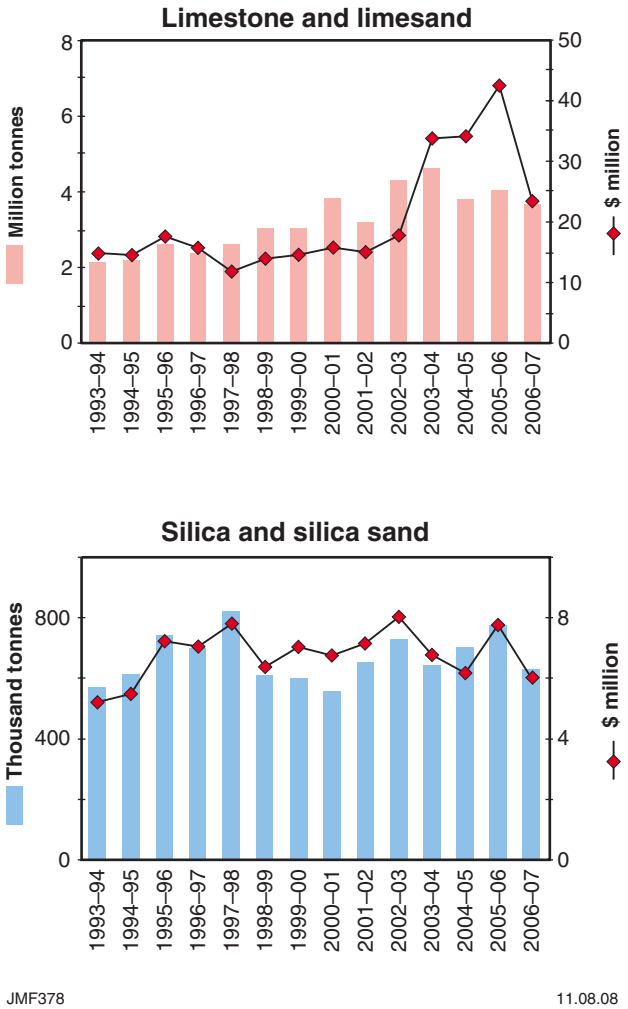

Figure 11. Trends in production (quantity and value) of limestone and limesand, and silica and silica sand in Western Australia, 1993–94 to 2006–07

Commercial limestone and limesand deposits are located mainly in the coastal region extending from Geraldton to Bunbury, in proximity to population centres representing areas of high demand. The main sources of limestone and limesand industry are the Pleistocene Tamala Limestone and the Holocene Safety Bay Sand (limesand), which extend southwards along the west coast from Kalbarri. Equivalent units are also found in places along the south coast from Augusta to Albany. Other large deposits are located at Rawlinna in the limestone of the Miocene Eucla Basin, and as surface calcrete at Windarra near Laverton in the Eastern Goldfields.

Currently, there are 18 limestone producers in the State. The largest of these is the Windarra deposit, 35 km northwest of Laverton, operated by Murrin Murrin Holdings Pty Ltd, where calcrete is mined as a source of $CaCO_3$ for metallurgical applications in the processing of lateritic nickel. In recent years, estimates of production from this operation appear to be in the order of 0.7 – 0.8 Mtpa. Other large producers include Cockburn Cement Ltd (a division of Adelaide Brighton Ltd) from its Eucla Basin deposit at Rawlinna, and PMR Quarries Pty Ltd producing limestone for the construction industry from its Postans quarry in the Kwinana area. In the area north of Perth, extending from Waneroo north to Moore River, there are ten quarrying operations producing high-grade calcarenite limestone as building block material. In 2006–07 this industry produced an estimated 0.41 Mt for the dimension stone industry. Other smaller limestone producers operate from deposits located near Carnarvon, Exmouth, Kununurra, and Point D'Entrecasteaux.

Limesand consists of broken shell fragments incorporated mainly in coastal beach and dune fields rich in $CaCO_3$ (up to 86%). The State's limesand industry currently has 11 operations, located in places from Perth north to Shark Bay. By far the largest mining operation is in Cockburn Sound, around 6 km southwest of Fremantle, where Cockburn Cement Ltd dredge a substantial quantity of limesand (shellsand) from their leases for the manufacture of cement at their Kwinana plant.

Other operations are mostly located in limesand dune fields on the west coast between Lancelin and Dongara. Largest amongst these mines are Cockburn Cement's Denison deposit near Dongara (cement manufacture), and at Lancelin, Aglime of Australia (a subsidiary of Westdeen Holdings Pty Ltd) operate a deposit for agricultural lime manufacture. Other limesand operations in this area are located at Cervantes, Coolimba, Green Head, and Sandy Point. Also, farther north, small quantities of limesand (coquina) are spasmodically mined from a lease on the shore of L'Haridon Bight in Shark Bay, about 40 km southeast of Denham.

Locations for all operating limestone and limesand deposits are given in Appendix 1 and further information is available in Abeysinghe (1998).

Silica and silica sand

Total recorded production of silica and silica sand in Western Australia during 2006–07 was 0.631 Mt valued at $6.02 million, which represents a decrease of 19% in production on the previous year's result (Fig. 11). It should be noted that there is also a considerable amount of unrecorded tonnage of silica sand mined from private land by Kemerton Silica Sand. This operation has the capacity to produce up to 0.5 Mtpa.

In the State, silica rock for silicon metal production is produced by Simcoa Operations from its mine in the Moora area. Silica sand is produced by Rocla Quarry Products Pty Ltd from a quarry in the Gnangarra area north of Perth, Kemerton Silica Sand Pty Ltd from a site in the Kemerton area north of Bunbury, AustSand Pty Ltd northeast of Albany, and BHP Billiton Nickel West Pty Ltd at Mount Burges north of Coolgardie.

Silica (chert)

Pinjarra Orogen

Moora

Simcoa Operations, owned by the Japanese Shin-Etsu Chemical Company, operates the Kemerton silicon metal project. High-quality lump silica, required for silicon metal smelting, is sourced at Kiaka Brook about 12 km north of Moora from the Mesoproterozoic Noondine Chert in the Pinjarra Orogen. At this locality is an extensive chert deposit, originally estimated to contain a proven high-grade reserve of 2 Mt at 99.3% SiO_2 together with substantial additional resources. Last reported annual production (in 2005) was over 105 000 t and since that time production is understood to have increased markedly.

At the Moora minesite, chert is mined from opencuts, crushed into fist-sized lumps, and transported by rail to the silicon smelter at Kemerton Industrial Park, about 20 km northeast of Bunbury. At the smelter, the rock is mixed with very low-ash jarrah charcoal and chemically reduced in two 27 MVA submerged-arc furnaces to produce silicon metal, which is tapped off and cast as large ingots before sizing to customer specifications. The Kemerton plant has the capacity to produce 32 000 tpa of high-grade silicon metal.

Principal uses for silicon metal are in the manufacture of high-strength aluminium alloys (50% of production) for the automotive and aerospace industries, while the remainder finds applications in the production of silicones and other silicon chemicals for applications in the semi-conductor industry, and in the manufacture of optical glass, optical fibre, and silicon solar panels. Currently, 85% of production is exported to the US, Japan, the Middle East and other countries, with the balance used for domestic consumption by aluminium smelters in eastern Australia. A byproduct of the silicon smelting process is silica fume consisting of microscopic hollow spheres, collected from the gases emanating from silicon furnaces. About 10 000 tpa of silica fume is collected and sold principally for use as an additive in high-strength or corrosion-resistant concrete and in industrial refractories.

Silica sand

Major silica sand-producing areas in the State include the Gnangara area in the northern Perth metropolitan area, Kemerton 30 km northeast of Bunbury, Mindijup 40 km northeast of Albany, and Mount Burges 20 km northwest of Coolgardie. Export-grade material is sold mainly into South East Asian destinations, especially Japan and South Korea. In 2006–07, total production of silica sand is estimated to be in excess of 0.75 Mtpa. Industrial applications for silica sand include the manufacture of glass (including container glass, sheet glass, and glass panels and tubes for television and computer applications), sodium silicate and other silicon-based chemicals, ceramics and ceramic glazes, silicon carbide abrasives, foundry moulds, filtration media, adhesive and grout manufacture, and scour sand for industrial cleaning.

Perth Basin and Albany–Fraser Orogen

In the Perth Basin, deposits of high-grade silica sand are present within the Bassendean Sand, a clean, well-rounded and well-sorted Pleistocene eolian sand. This sand forms a broad belt about 20 km wide aligned parallel to the present-day coastline, located 5–10 km inland and extending from north of Perth to south of Bunbury, along the Swan Coastal Plain. Equivalent units are present in many places along the south coast, particularly in the Albany area, where it overlies the Proterozoic Albany–Fraser Orogen.

The high-grade silica sand formed in high dunes of the Bassendean Sand by the removal of iron, alumina, and soluble salts by the downward movement of acidified rainwater. This process leaves behind an upper leached zone, which varies in thickness from a few centimetres to more than 10 m. Deposits identified to date range in size from less than 200 000 t to around 200 Mt. Washed silica sand averages 99.7% SiO_2, with trace amounts of iron, titania, alumina, and other oxides. Chromium trioxide is absent from all coastal deposits. The well-sorted silica sands from the Swan Coastal Plain fall mostly into the 200–600 µm particle size range; sands in the Albany area on the south coast are typically finer, at 100–350 µm (Abeysinghe, 2003).

Perth region

In the Perth region, silica sand is mined by Rocla Quarry Products from their Lexia quarry in the Gnangara area, about 20 km north-northeast of the city. This operation, with proven on-site reserves in excess of 50 Mt (for all sand grades: concrete, filling, and silica sand), has an annual capacity in excess of 1.5 Mt.

Silica sand with an overall purity of 99.87% SiO_2 is washed on-site and sized to customer specifications, mainly between 200 and 600 µm. Finished products for export are hauled to Kwinana for bulk loading onto ships of up to 40 000 t capacity. Most of the material is exported to Singapore, Malaysia and Thailand, with the remaining product supplied in bulk bags to South Australia, Victoria, New South Wales, Queensland, and regional Western Australia (Rocla Quarry Products, 2004).

Kemerton

The largest silica sand deposit in Western Australia is located at Kemerton in the Bunbury region and was originally estimated to contain about 200 Mt of high-grade material. Kemerton Silica Sand Pty Ltd is a 50/50% joint venture between Japanese companies Itochu Corporation and Tochu Co. Ltd. The processing plant, with a maximum capacity of 450 000 tpa, was originally commissioned in April 1966.

This project is the State's only wet-mining operation for silica sand using a suction cutter dredge. The top 3.5 m of sand is mostly removed as overburden but on occasions may be used as feedstock for low-alumina product. The silica sand orebody below contains clayey material with significant amounts of alumina. Market specifications require a special high-quality silica sand containing a prescribed level of alumina of about 2.4% and with very tight controls on grain size and level of impurities. Once removed from the pond, the silica sand slurry is piped to the plant where washing, attritioning, desliming, screening, classifying, and removal of heavy minerals are carried out. The sand is then stockpiled to drain to achieve a final moisture content of less than 5%.

The finished product, referred to as high-quality feldspathic silica sand, is transported to the Port of Bunbury where 55 000 t vessels transport the material to speciality glass manufacturers in Japan and other countries in South East Asia (Kemerton Silica Sand, 2007).

Mindijup

At Mindijup, AustSand Mining Ltd, a joint venture between Tomen Australia Ltd (50%) and Tochu Corporation (50%), commenced production in 1995 from a deposit originally estimated to contain more than 20 Mt of high-grade silica sand. In late 1997, the plant was upgraded to increase production and the circuits were modified to allow production of a range of silica grades for use in glass making, foundry casting, and the construction industry. Last reported production of processed silica sand for 2005 was almost 107 000 t but more recently annual production appears to have declined as indicated by exports of silica sand through the Port of Albany to Japan of about 56 000 t in 2007 (Albany Port Authority, 2007).

Yilgarn Craton – Eastern Goldfields Terrane

Mount Burges

The Mount Burges silica sand deposit, some 20 km northwest of Coolgardie, is operated by BHP Billiton Nickel West Pty Ltd as a source of silica flux used in the company's nickel smelter near Kalgoorlie. The deposit is located in an area of extensive sandplains and dunes of variable thickness overlying duricrust and Archean granitic basement. The original reserve estimate for this deposit was 4.65 Mt at 85% SiO_2, 7.5% Al_2O_3, 2.14% Fe_2O_3, and 0.4% CaO, together with additional resources of 0.83 Mt at a similar grade (Abeysinghe, 2003). Last recorded production in 2005 was almost 160 000 t valued at about $0.61 million. In recent years, estimates indicate silica sand production from the Mount Burges area appears to have been maintained at roughly similar levels.

Talc

Western Australia is the largest producer of talc in Australia, with production coming from two sources, the Three Springs mine, 275 km north of Perth, and Mount Seabrook, 460 km northeast of Geraldton. Production figures are no longer available for talc produced in Western Australia but it is estimated that the State has experienced an average decrease in annual production of around 3.7% over the past nine years since 1997–98, when maximum production of over 191 000 t was achieved.

Pinjarra Orogen

Three Springs

The Three Springs talc deposit, owned Luzenac Australia Pty Ltd, a wholly owned subsidiary of Rio Tinto, has the capacity to produce 0.2 Mtpa. Last reported production for (2004–05) was 0.134 Mt, together with a reported value of production of $11.40 million. Three Springs talc is exported primarily into South East Asia, for use in paper, paint, and plastic manufacture.

Talc mineralization at Three Springs is hosted by the Moora Group dolomite of Proterozoic age, just above an unconformable contact with Archean basement. Chlorite-rich, clastic sedimentary rocks may be present between the talc deposit and the basal unconformity. The talc deposit is a subhorizontal, strata-bound lens up to 40 m thick formed by hydrothermal replacement of the host dolomite. Minor hangingwall lenses are intercalated with the host dolomite above the major body. The high-grade talc at the Three Springs mine is a massive, cryptocrystalline, waxy, grey-green to white steatite with brightness varying from 80 to 90%. Common impurities in the fresh talc are chlorite, scattered quartz veins, and pyrite. The cryptocrystalline nature of the talc gives it a number of advantages, such as ease in grinding, good opacity, low abrasiveness, and consistently high brightness. The talc is not fibrous and does not contain asbestiform minerals (Abeysinghe, 1996).

In 2003, Rio Tinto reported that the Three Springs deposit had proven and probable reserves of 6.0 Mt in the area of the mine and adjoining leases, as well as indicated resources of 3.2 Mt.

Capricorn Orogen

Mount Seabrook

The Mount Seabrook deposit consists of a Proterozoic schist–quartzite unit grading upward into a dolomite–chert–quartzite–talc unit, with talc developed as steeply dipping lenses within dolomite. The dolomite–quartzite–talc unit and the schist are intruded by granitic rocks on

the eastern side of the mine area. In 1966, the deposit was reported to contain measured and indicated resources totalling 1.55 Mt of high-grade talc, with further potential as the talc zone is open-ended along strike (Abeysinghe, 1996).

Since 2001, the deposit has been operated as a 50:50 joint venture between Unimin Talc Pty Ltd, and Industria Mineraria Italiana Fabi (Australia) Pty Ltd (IMI Fabi). Last reported production figures, from 2004–05, were 9536 t together with a reported value of production of $1.17 million.

Over the years, mining at Mount Seabrook appears to have occurred on a campaign basis, according to demand. During mining campaigns, a quality control system has been used to remove quartz and dolomite impurities from the talc in the ROM stockpiles. In this process, the +40 mm lumps are first hand sorted on a conveyor belt. The finer –40 to +10 mm material is then passed through an optical sorting machine to remove the smaller sized quartz and dolomite fragments, leaving the high-grade material for final processing. The talc ore is then crushed, washed, graded, and stockpiled at the mine site prior to road transport to Geraldton.

Export-grade material is then shipped to customers mainly in Europe. Approximately 40% is destined for sale as cosmetic-grade talc, while a substantial proportion of the remaining ore is suitable for industrial talc applications. Unimin has also transported ore to eastern Australia for processing and sale both locally and in South East Asia.

Dimension stone

Western Australia has a small but vibrant dimension stone industry in which it is estimated the State produces more natural-cut stone, together with a large volume of reconstituted limestone blocks, than any other state. Total production is difficult to quantify because many natural stones are quarried from private land and production figures from these operations are not reported to DoIR. Production reported for 2006–07 amounts to only 1976 t (Table 1), but does not include an estimated 406 000 t of cut and reconstituted limestone blocks recorded under limestone production, and a further 15 000 t of granite, sandstone and quartzite production estimated from operations on private land. These estimates bring total dimension stone production to approximately 420 000 t for 2006–07.

Currently in Western Australia, there is scope to develop high-grade dimension stone deposits from many visually attractive granites and dolerites (black granite), marbles, sandstones, and other rocks. In recent years, local companies have provided material for a number of overseas niche markets as well as successfully competing with imported products in the supply of dimension stone for use as facing material on office buildings and paving applications in central city sites, particularly in eastern Australia.

At present, a number of high-quality dimension stone quarries around the State are in care and maintenance. It is possible that this situation may soon change as recently there has been considerable interest in bringing a number of these operations back into production in the short term, as well as for the development of several sites containing new varieties of dimension stone.

The dimension stone industry, particularly in southwest Western Australia, is discussed in more detail in Fetherston (2007).

Black granite

King Leopold Orogen

Wombarella Creek

In the west Kimberley region, at Wombarella Creek, about 150 km east-northeast of Derby, there are numerous occurrences of ‘black granite’ (a commercial name for dolerite or gabbro). This material, known as ‘Kimberley Black’ is very fine grained, is generally without flaws, and takes an extremely high polish. During the 1990s, some sites were quarried for large, high-grade black granite boulders that were backhauled to Perth for processing into large blocks for export, mainly to Japan, for use in the funerary industry. These quarries are currently in care and maintenance.

Granite

Albany–Fraser Orogen

Willyung Hill

A small quarry in a massive Proterozoic granite has been established by Albany Monumental Masons on Willyung Hill, 10 km north-northwest of Albany, adjacent to the large CSR Readymix aggregate quarry but at a higher elevation on the hill. At this site, comparatively small quantities of coarse-grained, megacrystic, grey granite are quarried in block form suitable for the manufacture of stone monuments at the company’s processing plant in Albany.

Esperance

About 14 km east-northeast of Esperance, a visually attractive pinkish-brown, medium-grained, massive granite is quarried by AustralAsian Granite Pty Ltd at Mount Edward. Known as ‘Desert Brown’, this Proterozoic granite has found many applications as facing slabs on commercial buildings, especially the ANZ Bank World Headquarters in Melbourne (Fig. 12).

Fraser Range

At Fraser Range, about 80–100 km east of Norseman, there are many sites containing Proterozoic granite, black granite, gneiss and other metamorphic rocks. A number of these appear to have some potential for development as dimension stone operations. There are also two established quarries in the area, the first of these, located at Ten Mile Rocks, is known as ‘Garnet Ice’, a spectacular, white–pale grey granitic gneiss, containing swirling bands of black biotite and studded with red almandine garnets

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Figure 12. The ANZ Bank World Headquarters in Melbourne, is faced with slabs of visually attractive, pinkish-brown, 'Desert Brown' granite from Esperance

(1–4 mm diameter). This quarry is currently in care and maintenance.

Twenty kilometres southeast of Ten Mile Rocks is the largest operating quarry in the region. This site is the source of a stone known as 'Verde Austral', a metamorphosed granite with charnockitic affinities. This massive, medium–coarse-grained rock is extremely hard and polishes to a deep olive green colour. It has proved to be an excellent dimension stone in such applications as pavers and kerbstones in streetscape design, and as polished wall panels in contemporary buildings, and has been used extensively in central Sydney for these purposes.

King Leopold Orogen

Wombarella Creek

Wombarella Creek, about 150 km east–northeast of Derby in the west Kimberley region, is also the site of a visually attractive, pearlescent, grey granite known as 'Kimberley Pearl'. This massive, coarse-grained, Proterozoic granite was quarried during the early 1990s and was cut and polished as stone panels for facings on large city buildings. A coarser variant of Kimberley Pearl, known as 'Kimberley Storm', was also quarried about the same time from a nearby quarry. Although both quarries are currently in care and maintenance, resources of both stones appear to be extensive and quarry site access comparatively easy. Recently, there has been some interest in the possibility of reopening these operations in the near future.

Yilgarn Craton – Murchison Terrane

Boogardie

The Boogardie orbicular granite, located about 35 km west of Mount Magnet, is possibly the State's most unusual granitic dimension stone. This rare form of Archean granite contains closely spaced, light- to dark-grey, orbicules measuring about 10 cm along the longest axis (Fig. 13). The orbicules comprise both radiating and concentric shells of mainly hornblende and plagioclase surrounding coarsely crystalline cores of variable composition, and are contained in a coarse matrix of granitic composition (Bevan, 2004).

Previously quarried mostly for spectacular, polished stone panels, bench and tabletops, and hand-carved artisanal works, this stone is currently not produced, with the quarry in care and maintenance. Notwithstanding, the unusual orbicular texture of this stone has attracted attention from overseas in recent times and it is possible the quarry may soon be back in production.

Yilgarn Craton – South West Terrane

The southwestern area of the Yilgarn Craton contains numerous granites and granitic gneisses that have at some time been quarried as a dimension stone and many others remain to be explored for this purpose. Over the years, production of granite from this area has been somewhat erratic, being largely geared to the demands of the construction industry for cut stone slabs for use as cladding on new office buildings, paving stone streetscapes, and monument construction.

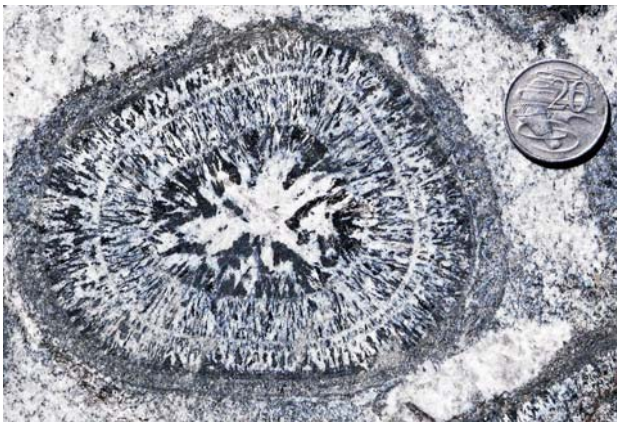

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Figure 13. An orbicule in Boogardie orbicular granite. These structures, around 10 cm in diameter (longest axis), comprise radiating and concentric shells of mainly hornblende (black) and plagioclase (white) surrounding coarsely crystalline cores

Some of the most notable, visually attractive granites supplied to the construction industry since the 1990s include the 'Albany Green', located about 10 km west-southwest of Jerramungup. This is a grey-green, medium- to coarse-grained granite containing large K-feldspar phenocrysts. Mined by Melocco Stone Pty Ltd, this stone was used in the construction as part of an apartment complex in Sydney.

In the Watheroo–Namban area, between 30 and 40 km north-northeast of Moora, there are three quarries, all currently in care and maintenance, all with Archean graintoids containing variable proportions of large, pink K-feldspar megacrysts and abundant coarse-grained green plagioclase. In the Watheroo area, the small 'Verde Lope' quarry was acquired by Granites of Australia in recent years, whereas stone was last extracted from the extensive 'Valmere Green' quarry in 1994–95. Ten kilometres south, the Namban quarry was also operated in the early 1990s. At that time, the visually attractive 'Mulroy Green' granite from this site was in demand for polished stone panels. Cut slabs may be seen in the floor of the external porch at the main entrance to Parliament House in Perth. All quarries in the Watheroo–Namban area are generally in good condition and should be easily be re-accessed in the event of a new quarrying program.

About 20 km south of Jerramungup, the 'Laguna Green' granite was mined by Wales Quarries until 2004, when it was put into care and maintenance. This Archean, coarse-grained and attractively coloured gumleaf-green granite containing K-feldspar megacrysts was selected by Australian architects in 2003 for the new Australian War Memorial at Hyde Park Corner in London. Approximately 190 t of Laguna Green granite was exported to the United Kingdom for the construction of the memorial. The completed monument was subsequently awarded two architectural prizes for Australian stone by the Australian Stone Advisory Association in 2006.

Also awarded an architectural prize for Australian stone in 2006, for the best commercial interior, was 'Austral Juperana' stone, from a quarry located 20 km south of the town of Bruce Rock, 220 km east of Perth. Austral Juperana is an Archean, metamorphosed granite with a granofelsic texture displaying little or no foliation. This hard, medium-grained, spectacular stone typically has a pinkish beige to yellow gold crystalline matrix with occasional greenish-yellow overtones. Veining ranges from red-brown to dark grey in colour and forms visually attractive swirling patterns distributed throughout the rock. These colours and textures appear to have found favour with the architectural industry in recent times.

Operated by AustralAsian Granite Pty Ltd, the operation produces Austral Juperana in 10 t blocks by close-spaced drilling and diamond wire sawing. Blocks are subsequently graded and placed in a stockpile for on-site client selection. In a nearby quarry, the company produces a reddish variety of Austral Juperana known as 'Austral Waterfall'. This stone has light to dark grey veins unevenly distributed throughout a reddish matrix.

Limestone

Perth Basin

In the Carabooda–Nowergup and Moore River areas, about 40 and 75 km north of Perth respectively, limestone blocks are cut from the Tamala Limestone mainly for use as building blocks, retaining walls, and pavers. The main area of operation is Carabooda–Nowergup, where there are currently eight quarrying operations centred around Wesco and Hopkins Roads and Wattle Avenue. At these sites, and at Moore River, operations involve the initial rough sawing of quarry blocks that are either sold in their natural state, or further processed by diamond sawing to produce a vast array of bricks, blocks, wall cladding, pavers, and shaped stone profiles. Companies operating in these areas include Limestone Resources Australia, Meteor Stone, Italia Limestone, Limestone Building Blocks, Limestone Natural, and Crown Limestone Supply.

In places, in some of the Carabooda–Nowergup quarries, the limestone is too soft for block cutting, as is the case farther north at Yanchep, and south of Perth at Hope Valley in the Kwinana area. In this situation, limestone is removed by ripping and is crushed, mixed with cement and other additives, and pressesed into large reconstituted limestone blocks commonly used for internal and retaining walls and as pavers. Companies specializing only in reconstituted limestone blocks include Archistone (Yanchep), and Stoneridge Quarries WA (Hope Valley).

Marble

Edmund Basin

In the Proterozoic Edmund Basin, between 120 and 220 km southeast of Onslow and centred on the Ashburton and Yannerie River systems, dolomitic marbles are found in many places. These marbles occur in many different colours (from white through to black) and in many textures including a number of brecciated varieties. The high quality of many of these marbles is demonstrated in their various attractive colours, and relative hardness (harder than calcitic marble) that allows the stone to be precision cut and to take a very high polish. In times of increased demand these physical attributes may lead explorers to re-examine many of these deposits.

Currently, there are two marble mining operations operating in the Edmund Basin: on Maroonah Station and in the Nanutarra area. Between 2001 and 2006, production of marble in this region gradually increased from about 200 tpa to a maximum of over 1800 tpa in 2005.

Maroonah

On Maroonah Station, 220 km southeast of Onslow, a mid-green dolomitic marble from the early Proterozoic Irregully Formation has been quarried on a campaign basis at a site near Sheela Bore. This marble, originally marketed as 'Desert Green' has been quarried since 2001. Around 2006, new owners Pilbara Stone Pty Ltd re-named the marble 'Pilbara Green'. Pilbara Green is a visually attractive green to pale green serpentine marble containg white and dark green veins and appears to have been sold

mainly to processors in eastern Australia for cutting and polishing for distribution to local markets.

Nanutarra

In the Nanutarra area, about 120 km southeast of Onslow, Stone Dimensions of Australia Pty Ltd operates two dolomitic marble quarries also located in the Irregully Formation. The lower quarry produces a spectacular, brecciated, burgundy-red marble named 'Rosso Venezia'. The overlying marbles, in the upper quarry, comprise white to cream and pale brown varieties named 'Austral Pearl', 'Austral Dream' and 'Austral Brown' respectively.

Sandstone and quartzite

Canning Basin

Mount Jowlaenga

In the Mount Jowlaenga area, about 65 km west-southwest of Derby, Meteor Stone mines on a campaign basis from a number of quarries in the Early Cretaceous Melligo Sandstone. The fine- to very fine grained sandstone varies both in colour and degree of re-silicification between quarry sites. In the northern area, 'Kimberley Sandstone' is produced from two quarries where the sandstone varies from pale beige at one site, to multicoloured forms displaying prominent liesegang banding varying from yellow to pink, red, and mauve over a beige-coloured sandy matrix. Farther south, other sandstones quarried tend to be much harder resulting from re-silicification, varying from 'Argyle White' to an extremely hard, beige variety known as 'Kimberley Quartzite'.

Quarry blocks are backhauled to Perth for processing into products such as wall-cladding panels as seen in the beige sandstone cladding the Motorola Building at the University of Western Australia, and as multicoloured panels and pavers in the award-winning Federation Square in Melbourne.

Hamersley Basin

Pinderi Hills

'Karratha Stone', an indurated, red-brown, quartz sandstone, is sourced from the Archean Hardey Formation in the Pinderi Hills area about 40 km south-southeast of Karratha. At the quarry, Karratha Stone is recovered by ripping as natural flagstones. Colours vary from cream to brown, pale-green and pink. Flagstones are graded on-site according to colour and texture and transported on pallets to construction sites where they are mostly used in their natural state in paving and wall construction. This material has been effectively used in feature walls in Kings Park in Perth.

Perth Basin

Donnybrook

'Donnybrook Sandstone' has been sourced for over 100 years from a number of quarries in the Early Cretaceous Donnybrook Sandstone located about 40 km south-southeast of Bunbury. The feldspathic sandstone varies at different sites and stratigraphic levels from predominantly fine to moderately coarse grained, and from white to beige, to mottled yellow, deep pink and golden brown. Many forms also display visually attractive concentric, pale- to golden-brown liesegang ring banding. It is the fine-grained texture and natural hardness of many of the Donnybrook sandstones that give the stone its reputation as a dimension stone well suited for the production of high-precision cut blocks, as well as intricate, high-quality carving. Fine examples of Donnybrook sandstone buildings completed between 1900 and 1964 may be seen around Perth city, especially the General Post Office, and the new Parliament House.

Current stone companies at Donnybrook include, Gosford Quarries Pty Ltd (Acrogem quarry), Donnybrook Sandstone Company (Donnybrook Stone quarry), and Meteor Stone (Beelerup quarries). These companies specialize in the preparation of high-quality sandstone blocks and slabs mainly intended for the building industry.

Yilgarn Craton – South West Terrane

Toodyay

About 10 km southwest of the town of Toodyay and about 65 km northeast of Perth, is an Archean quartzite known as 'Toodyay Stone'. The resistant quartzite occurs in a northwest-trending zone, 1 to 2 km wide, and forms prominent ridges extending over many kilometres. Interpreted as an orthoquartzite (the metamorphosed equivalent of a sedimentary quartz sandstone or chert), the stone occurs as massive to flaggy bands consisting of interlocking quartz grains, with minor muscovite, fuchsite (chrome muscovite mica), feldspar, and accessory minerals. The pale green fuchsite is most abundant in flaggy bands, where it forms pale green coatings along cleavage planes (Fetherston, 2007).

Toodyay stone has been mined intermittently for many years from numerous quarries. The current operating company, Toodyay Stone, quarries up to 5000 tpa of quartzite from three operations producing stone in a variety of colours from silvery pale green (Salt Valley Road quarry), to red to mid-brown (Lovers Lane quarry), and mid- to dark brown (Black and Tan quarry). The stone is generally very hard and splits to form smooth, natural flagtones mainly used as pavers and in walls as part of buildings or freestanding structures. Currently, the pale- to mid-brown varieties appear to be a popular choice with architects and landscape designers.

Tiger iron

Pilbara Craton

Ord Ranges

In the Ord Ranges, about 60 km east of Port Hedland, a banded jaspilite rock known as 'Tiger Iron' is mined on an intermittent basis. Tiger Iron contains thin alternating bands of red jasper, black hematite, and smaller amounts of golden-yellow tiger eye (a silicified form of crocidolite

often used as a semi-precious stone). These alternating bands may vary from straight to highly contorted, tight folds. As a dimension stone, it has been used as speciality interior floor and wall tiles, and in decorative stone ornaments.

Clay minerals

Attapulgite

Yilgarn Craton – Murchison Terrane

Lake Nerramyne

Attapulgite is a cream to grey hydrated magnesium silicate clay mineral. The origin of the name attapulgite is from the type locality Attapulgus in Georgia, US. Today, attapulgite is used as the commercial term for the same mineral known as palygorskite originally described from Palygorsk, near the Ural Mountains in the Russian Federation. Australia's only producing attapulgite mine, owned and operated by Hudson Resources, is located at Lake Nerramyne, located approximately 140 km northeast of Geraldton.

The Lake Nerramyne deposit forms part of a Cenozoic lacustrine sequence located in a series of playa lakes occupying a paleodrainage system that originally flowed into the Murchison River. In the deposit, attapulgite is overlain by 1.0 – 4.0 m of sandy soil, calcrete, and silcrete overburden. The orebody ranges in thickness from 1.0 to 4.5 m of high-grade attapulgite, which in turn overlies white to brown kaolin and weathered granitic material. Figures quoted by Abeysinghe (2002) show that the deposit has proven reserves of 10 Mt and inferred resources of 100 Mt. Currently, only a small part of the prospective area for attapulgite has been explored Attapulgite ore is strip-mined by bulldozers and back-hoes, and then spread out to dry in the sun before being transported to Hudson Resources' processing plant at Narngulu, near Geraldton. The last annual production reported for attapulgite (in 2005) was almost 9800 t valued at $1.02 million.

At the Narngulu plant, the company produces milled, sized, and bagged products to customer specifications. Because of the very large surface area of attapulgite combined with high absorption capacity, and its ability to decolourize and deodorize liquids, the product is largely destined for the pet litter market. Other applications for attapulgite include a variety of speciality products: as a bleaching agent for edible oils, especially for palm oil produced in Malaysia, as a filtration agent in the manufacture of jet and bio-diesel fuels, as a water retention agent in the agriculture and horticulture industries, as an industrial filler, and in the pharmaceutical industry (Hudson Resources, 2008a).

Bentonite (saponite)

Pinjarra Orogen

Watheroo

Bentonite is the commercial term applied to the smectite group of clay minerals, in particular the sodium and calcium montmorillonites. Other smectite clays include beidellite (aluminium-rich), nontronite (iron-rich), hectorite (lithium- and magnesium-rich), and saponite (magnesium-rich).

In Western Australia, there are deposits of magnesium-rich bentonite (saponite) in a series of claypans in an area approximately 20 km north-northeast of the town of Watheroo (40 km north of Moora). Saponite, like sodium bentonite, is a swelling clay, but with a low cation exchange capacity. These clays appear to have formed by the reaction of magnesium-rich waters with colloidal silica and minor alumina in a lacustrine environment. Chemical analyses reveal the presence of both Mg bentonites as well as Ca–Mg bentonites with the saponite content varying from 50 to 94% (Abeysinghe, 2002). Other minerals present in variable amounts include calcite, dolomite, quartz, halite, and gypsum.

In this area, Watheroo Minerals Pty Ltd owns mining leases over two claypans (Lakes A and E). The company commenced operations at these sites in 1999. At that time, the deposits were estimated to contain a combined, inferred resource of around 0.31 Mt with the potential for a much larger resource. Laboratory test work indicated that the material could be used as pet litter, a stockfeed additive, a geotechnical sealant, and a soil conditioner to improve nutrient retention and wettability of soils, and could possibly be upgraded to meet drilling mud specifications.

The company currently produces comparatively small amounts of bentonite that appear to vary from around 1000 to 3500 tpa. The material is marketed as two different grades. Bentonite A is a semi-granulated clay that is a mixture of saponite with very finely disseminated calcite and dolomite, whereas Bentonite E is a high-grade beige-coloured saponite. The material is used primarily as a sealant in dams and ponds. Other applications include a soil conditioner, stock feed supplement, and as an absorbent for heavy metals and organic compounds.

Further information relating to the geology, properties and potential applications of the Watheroo bentonite is given in Fetherston et al. (1999).

Construction clay (common clay)

Perth Basin and Yilgarn Craton – South West Terrane

Construction clay includes a wide variety of clay and weathered fine-grained rocks, such as shale, that are used to make products such as structural and fire brick, drain tile, vitrified pipe, and roofing tile. It is also one of the raw materials used in the manufacture of cement. Most of the construction clay produced in Western Australia is used in the manufacture of bricks, pipes, and tiles, with a smaller quantity being consumed in the local cement manufacturing industry (Abeysinghe, 2002).

Early this decade, production of construction clay in Western Australia, reported to DoIR, was about 19 000 t valued at about $191 000. However, the total tonnage produced today is many times this amount since there are numerous construction industry clay pits operating under extractive quarry licences on privately owned land and production statistics from these operations are not reported.

Most production is from numerous pits located around the outer Perth Metropolitan Area that produce a variety of construction clays for local brick and tile manufacturing plants. Earlier estimates put this at approximately 20% alluvial plastic clay, 29% semi-plastic clay, and the remaining 51% as non-plastic clay. In this region, construction clays are extracted from Cenozoic and Mesozoic units of the Perth Basin in the Guildford–Swan Valley, Bullsbrook and Muchea areas. Along the Darling Fault zone from Byford to Mundijong, clay shale is extracted from the Proterozoic Armadale Shale, and in the Darling Ranges and farther east, residual clays have been extracted from lateritic regolith profiles over Archean granites and granitic gneisses in the Yilgarn Craton in areas such as Jimperding Hill, and Bakers Hill.

Also in this area, alluvial clays are present in paleochannel deposits such as Goomalling and Mount Kokeby. As well as material for the construction industry, these alluvial deposits were previously mined as a source of kaolin for ceramic and industrial filler applications (Abeysinghe and Fetherston, 1999).

In the Perth Metropolitan Area, there are three principal manufacturers (Midland Brick, Metro Brick, and Austral Bricks) producing structural clay products that may include bricks, pipes, pavers, and roofing tiles to supply mostly the local market. At Geraldton, 420 km north of Perth, Geraldton Brickworks manufactures bricks using locally available clays (Abeysinghe, 2002).

Semiprecious stones

The State has a wide variety of semiprecious and ornamental stones. Mining is usually carried out by individuals or small groups of prospectors, often on a campaign basis where various deposits may be selectively mined to provide sufficient saleable material for a number of years. Accordingly, semi-precious stone production tends to fluctuate from year to year. In 2006–07, production amounted to 325 489 kg valued at over $0.25 million. Only semiprecious stones currently produced or with a history of recent production are reported here, with locational details listed in Appendix 1.

Southern Carnarvon Basin

Mookaite

In 2006–07, by far the largest quantity of semi-precious stone extracted was a spectacular, multicoloured form of chalcedony, locally known as ‘mookaite’. The stone, found on Mooka Station about 135 km east of Carnarvon, was formed by the re-silicification of the Cretaceous Windalia Radiolarite in the Southern Carnarvon Basin. Mookaite is predominantly yellow and red and contains numerous irregular patches and vein-like structures that often display many other colours (white, mauve, pale brown etc.). Some examples appear to have a brecciated texture. The material is very hard and takes a high polish, making it suitable for carved and polished artwork (Fig. 14).

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Figure 14. A coffee table top inlaid with a mosaic of multicoloured, polished ‘mookaite’. Mookaite is a form of chalcedony derived from the re-silicification of the Cretaceous Windalia Radiolarite (table top shown is approximately 50 cm from left to right)

Hamersley Basin

Agate and jasper

In 2006–07, crazy lace agate from the Paleoproterozoic Hamersley Basin was also mined in considerable quantity. This semiprecious stone is located about 75 km north northwest of Newman, where it occurs in association with siliceous caprock and calcrete as part of a regolith profile overlying the Archean Wittenoom Formation. Crazy lace agate is a visually attractive, multicoloured stone ranging from white to orange, mauve, grey and black, with somewhat irregular concentric banding.

Also in the Hamersley basin are a number of operations mining variable quantities of highly coloured and textured banded jaspers. These jaspers are sourced from jaspilite-rich zones in banded iron-formations from locations such as Snowy Mount, Divide Creek, and Roy Hill. These jaspers are marketed under names such as ‘snake skin’ and ‘picture jasper’.

Yilgarn Craton – Eastern Goldfields Terrane

Chrysoprase and magnesite

In recent years, chrysoprase and associated magnesite were mined from Boyce Creek near Yerilla, Binti Binti and Marshall Creek, all located north of Kalgoorlie in the Eastern Goldfields. Chrysoprase is a microcrystalline variety of chalcedony that varies from light to dark green with the green colour being due to the presence of varying amounts of nickel. It commonly forms irregular, thin, subhorizontal sheets, or exists as nodules in the lower part of nickel-rich regolith that is often capped with magnesite. In 2006–07, mining operations at Boyce Creek produced a considerable quantity of comparatively valuable, green chrysoprase along with larger quantities of massive, extremely hard magnesite. Magnesite from this area commonly exhibits a pale greenish hue, and

when polished takes a very high sheen. In the same year, smaller quantities of magnesite were also produced from Binti Binti.

Gascoyne Complex

In 2006–07, small quantities of rose quartz, amethyst, and dravite (a light to dark brown form of tourmaline) were mined in the Paleoproterozoic Gascoyne Complex, located east-northeast of Carnarvon.

Pilbara Craton

In recent years, variable quantities of tiger eye (a golden-brown, chatoyant semi-precious stone) from the Ord Ranges, and Pear Creek Jade (a form of chrome-stained chert) were obtained from the Port Hedland region in the Pilbara Craton.

Yilgarn Craton – Murchison Terrane

West of Paynes Find in the Archean Murchison Terrane, small quantities of a massive, microcrystalline dravite–schorl (a black form of tourmaline), known in the lapidary trade as 'warrierite,' were extracted from a site on Lake Mongers near Warriedar Station.

Other semiprecious stones

In the past, many other semi-precious stones have been mined in the State, including variscite, amethyst, Pilbara jade, precious opal, beryl, as well as many siliceous stones. These and other stones are described in Hickman (1990), and Geological Survey of Western Australia (1994).

Phosphate rock

Christmas Island, an Australian territory, administered from Western Australia, is located in the Indian Ocean approximately 1600 km northwest of Onslow. The island has an extensive resource of commercial-grade, indurated phosphate known as Christmas Island rock phosphate (CIRP). This resource is owned by Phosphate Resources Ltd.

CIRP has been one of the region's few commercially available high-reactivity rock phosphates. This attribute makes it an excellent binding agent and it has been used by superphosphate factories in South East Asia and the Australia–Pacific region. The high reactivity of CIRP makes phosphate ions available to plants in acid soils, without the need for acidulation in fertilizer factories.

Since 1990, the company has mined and exported phosphate from the island to Australia, New Zealand, Malaysia, Thailand, and Indonesia. The last recorded phosphate production for Christmas Island by the British Geological Survey was 0.757 Mt in 2005 (British Geological Survey, 2007).

In 2006, the company, which is the island's largest employer, applied for an additional 200 ha of forested land for mining leases to extend current mine life (estimated between 5 and 7 years) to 10–12 years. The initial application was refused by the Federal Minister for the Environment and Water Resources. An appeal of the decision is currently before the Federal Court and is expected to be heard in 2008 (Lawson, 2007).

Other minerals with recent production

Over the last 5–7 years, a number of industrial mineral operations have been shut down owing to economic considerations (market access, company takeovers etc.) resulting in a variety of minerals no longer being produced in Western Australia, at least in the short term. These include potash feldspar, pigments (red iron oxide, and micaceous iron oxide), and two of the three existing spongolite operations.

Feldspar

Significant deposits of high-quality potash feldspar are contained within zoned pegmatite bodies in the Pilbara Craton at Pippingarra, 35 km south of Port Hedland, and at Mukinbudin in the Murchison Terrane of the Yilgarn Craton, 250 km east of Perth. Early in the current decade, both deposits were acquired by Unimin Australia Ltd. At Pippingarra, mining ceased in 2002 to join the Mukinbudin mine on care and maintenance. In 2002–03, feldspar production from Pippingarra was over 43 000 t. It is probable that both deposits still contain substantial feldspar resources.

In operation, feldspar from Pippingarra was shipped from Port Hedland mainly to Unimin's plant in Malaysia, where the material was processed for sale to customers in South East Asia. In this region there has been a continuing demand for high-quality feldspar with an elevated potash content intended for use in the glass and ceramics industries, especially for the manufacture of television tubes and screens, neon glass, and ceramic tiles.

Pigment — iron oxide

It appears that most of Australia's natural iron oxide pigment currently comes from Western Australia, where it is mined by Unimin Australia Ltd on a campaign basis in the form of red iron oxide. Previous pigment miners included Imdex Ltd (1996–2001), who mined, processed and distributed micaceous iron oxide, an anti-corrosive pigment known as MIO (an uncommon crystalline form of hematite) on the world market.

Red iron oxide

The Little Wilgie Mia pigment deposit, located in the Murchison Terrane of the Yilgarn Craton in the Weld Range about 330 km east-northeast of Geraldton, was operated by Unimin Australia Limited until 2007, when it

was subject to a takeover by Atlas Iron Ltd, explorers for iron ore. In 2007, Unimin mined and stockpiled red iron oxide pigment on-site to maintain supplies for a number of years to their processing plant in Perth.

At Little Wilgie Mia, high-grade iron oxides have been formed by the supergene enrichment of Archean jaspilitic banded iron-formation (BIF) of the 'Wilgie Mia beds' during a period of deep weathering in the early Cenozoic. Red iron oxide has been mined by drill and blast opencut methods and the crushed ore transported by road to the company's red oxide grinding plant in Perth. Premium-grade red oxide, typically ≥90% Fe_2O_3, ≤0.3% MgO, and 0.4% CaO, is sold as a pigment for use in paints, ceramics, and cement products. The last recorded production (in 2005) was 2173 t valued at $0.44 million. It is understood that the mine is currently in care and maintenance.

Micaceous iron oxide (MIO)

The MIO deposit, which was mined between 1996 and 2001 and owned at that time by Imdex Ltd, is located on the slopes of Mount Gould, about 400 km northeast of Geraldton. In this area, steeply dipping lenses of high-grade MIO, are interbedded with specular hematite, and iron-rich metasedimentary rocks in a thick sequence of Archean chloritic schist in the Narryer Terrane of the Yilgarn Craton. At that time, the company was mining the G6 MIO lens, estimated to contain indicated and inferred resources of 236 000 t with additional potential along strike and at depth. Mount Gould also contains a number of other MIO occurrences that have not been adequately explored for estimates to be made of the total MIO resource available.

After primary crushing on site, the silver-grey ore was trucked to the company's Perth facility for specialized milling to customer specifications. Tests on the Mount Gould ore indicated it was >90% Fe_2O_3, with a natural platelet length of about 70 µm and thickness of up to 10 µm, with very low sulfur values of about 0.01%, making it at least equal to world standard material from Austria. Micaceous iron oxide is used as a pigment in anti-corrosive paints for coating steel structures, such as large bridges, industrial plants, and offshore oil rigs. Between 1996 and 2001, the company exported over 16 500 t of MIO valued at $3.85 million (under the name IMDOX) to Europe, US, Japan, and other Asian countries.

In 2007, the Mount Gould mining lease was also taken over by explorers in the iron ore industry, but the MIO mine is probably still in care and maintenance.

Spongolite

Spongolite is a lightweight, porous sedimentary rock, composed principally of siliceous, rod-shaped spicules from fossil sponges. It is similar to diatomite (a light-coloured, soft, friable and siliceous sedimentary rock composed of microscopic skeletal diatoms). Spongolite has a number of useful properties: it is chemically inert, non-toxic, very lightweight, has excellent water absorbent, fire resistant, and insulating properties, and is able to maintain its structural integrity when wet.

Along the south coast between Albany and Cape Arid (east of Esperance), there are extensive outcrops of the Upper Eocene Pallinup Formation (part of the Bremer Basin) that contain a thick sequence of spongolite enclosed in a clayey matrix (Gammon et al., 2000). Spongolite has been used as an efficient absorbent media in the pet litter and agricultural industries, and as lightweight building blocks in the construction of houses and other buildings in the area from Mount Barker, 45 km north of Albany, to Ravensthorpe, about 70 km west of Esperance.

There are three spongolite quarries in the Mount Barker area. The first of these at Woogenilup, 17 km northwest of the town, produced large tonnages of spongolite for the pet litter industry until a few years ago. The last comparatively small production from Woogenilup was in 2007, by Australian Diatomaceous Earth Environmental Pty Ltd, before the mining lease lapsed early in 2008. A second operation, known as Red Gum Spongolite, 20 km northeast of Mount Barker, is currently mining small quantities of spongolite for incorporation as a water absorbent in soil fertilizers. The third local spongolite quarry is located 12 km east of Mount Barker. At this site, spongolite was mined until a few years ago as a lightweight dimension stone known as 'Mount Barker stone'. This quarry is currently in care and maintenance but appears to contain substantial spongolite resources.

Minerals currently under development

Rare earth elements

In recent times, demand for rare earth elements (REE) has been growing strongly between 8 and 10% per annum, with world production estimated at 95 000 tpa. However, this figure does not allow for growth of new REE applications such as hybrid cars, thus leaving a estimated shortfall in production of about 3000 tpa (Winter, 2006). China is by far the largest REE producer with about 90% of world production with much smaller production coming from US, India, the Russian Federation, and other minor producers. Current excess demand may largely be picked up by Lynas Corporation when production from the Mount Weld deposit comes on stream in the second half of 2008.

Traditional uses for REEs include polishing and colouring glass, sintering aids in ceramics, catalysts in petroleum cracking and in catalytic converters in car engine exhausts, and in a variety of alloys in the metallurgical industry. More recent REE applications in high-technology industries include compact fluorescent lightbulbs, phosphors in computer and plasma screens, rechargeable nickel–metal hydride batteries used in hybrid cars, and as neodymium supermagnets in electric motors designed for use in hybrid cars, wind turbine generators, and electronic components such as DVD drives.

Yilgarn Craton – Eastern Goldfields Terrane

Mount Weld

The Mount Weld carbonatite pipe, 35 km southeast of Laverton, is host to what may be the world's richest REE deposit and currently is the only commercially viable deposit outside China. Discovered in 1988, the deposit was extensively drilled by Ashton Mining Ltd and areas of discrete mineralization were found to be concentrated in a thick regolith zone overlying the carbonatite pipe. A number REE deposits were identified with the largest being the extensive Central Lanthanide deposit. Other discrete zones of polymetallic mineralization consisting of niobium–tantalum, and zirconium were also identified, together with an extensive phosphate-rich resource in the the lower regolith (Fig. 15).

The current project commenced in October 2001, when Lynas Corporation Ltd announced its 100% acquisition of the Mount Weld REE–Ta–Nb project from Anaconda Industries Ltd. This was followed in June 2002 with an extended period of feasibility studies to undertake marketing and technical studies. Feasibility studies were completed in 2005, in which it was proposed to mine 2.8 Mt of proved and probable reserves at 15.5% rare earth oxides (REO) in the first 14 years of mine life. The study proposed that the REO ore was first to be openpit mined, crushed and stockpiled at Mount Weld, and transported by road and rail to Esperance port. From Esperance the ore was to be exported to Shandong Province in China for beneficiation using Chinese REE technology and ultimate production of rare earth and iron oxide concentrates (Lynas Corporation, 2005).

In December 2006, it was announced by Lynas Corporation that it was shifting its REE processing facilities to Malaysia. This move was apparently brought about by recent tightening of regulations controlling the issue of export licences for REEs by the Chinese Government and the imposition of a 10% export tariff, coupled with increases in REE production costs within China (Industrial Minerals, 2006). Following protracted negotiations with the Malaysian Government and State authorities, a letter of intent for the purchase of land for the construction of the REO processing plant was signed in September 2007. The site is at Gebeng in Pahang State, about 2.5 km from the Port of Kuantan on Malaysia's east coast. Final approvals for the project to proceed were granted early in 2008.

The proposed $220 million plant will be designed to carry out final separation and product finishing operations, and will accommodate progressive increases in REE production from 5000 tpa in phase 1 and ultimately reaching 21 000 tpa. First production from the plant is scheduled for the second half of 2008. During this period, Lynas Corporation has concluded three off-take sales contracts in excess of US$310 million with REE customers. These contracts represent the entire 5000 t annual REE production from the initial stage of the processing plant. (Prospect, 2006; Lynas Corporation, 2007). Following the granting of environmental approvals

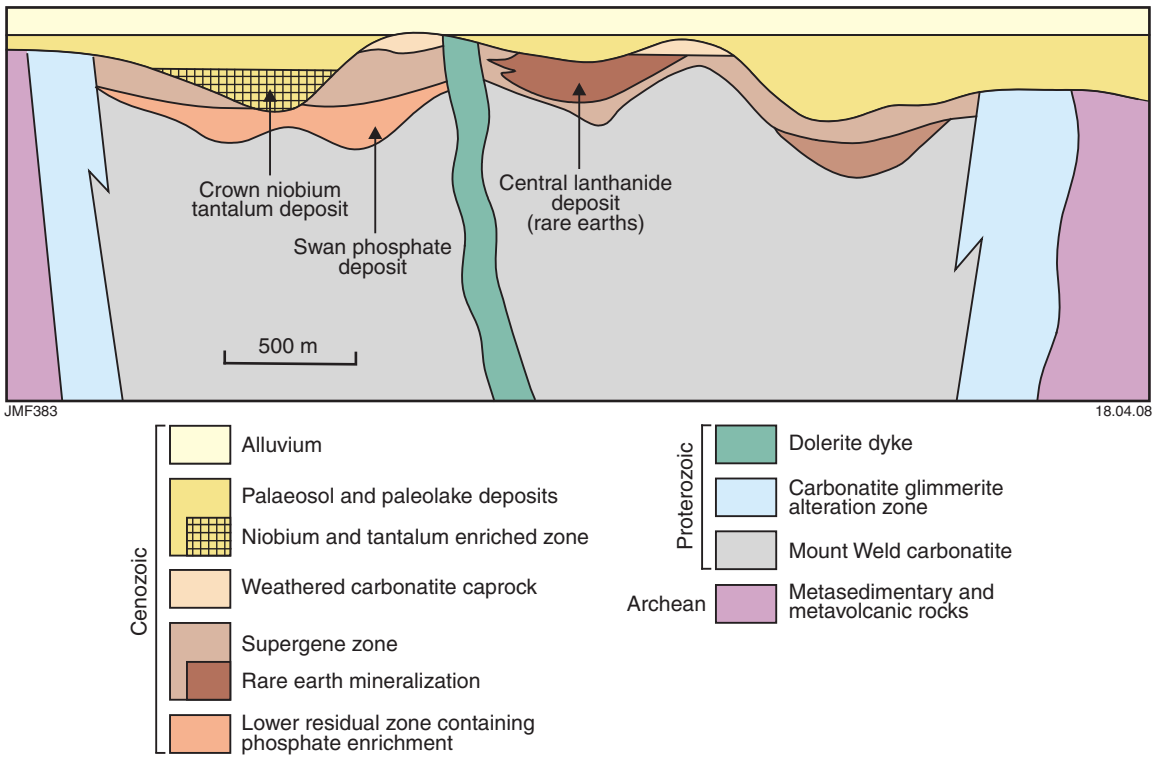

Figure 15. Schematic cross section of the Mount Weld carbonatite pipe showing mineralized zones of rare earth elements, niobium–tantalum, and phosphate incorporated within the overlying regolith (courtesy Lynas Corporation Ltd)

to build a concentration plant at Mount Weld in late 2007, a mining contractor moved onto the site in December and by the end of March 2008, over 2.0 Mm^3 of overburden had been removed from the openpit and 0.32 Mm^3 of ore had been mined, graded, and stockpiled (Industrial Minerals, 2008a).

In early 2008, Lynas Corporation announced an updated resource increase of 17% over previous figures established in 2002. This increase is due to a revised geological interpretation that included results from infill drilling from the 2007 exploration program. The company also announced that, because of substantially increased REE prices since 2002, it was appropriate to reduce the resource cutoff grade from 4.0% to 2.5% REO. Accordingly, the Central Lanthanide deposit at Mount Weld is now estimated to contain resources totalling 12.2 Mt at 9.7% REO at a cutoff grade of 2.5% yielding 1.18 Mt REO (Industrial Minerals, 2008b). Previous analytical test results showed the Central Lanthanide deposit to contain an indicative mix of predominantly light REOs from CeO_2 (46.7%), La_2O_3 (25.5%), Nd_2O_3 (18.5%), Pr_6O_{11} (5.32%), Sm_2O_3 (2.27%), to Eu_2O_3 (0.443%), together with minor proportions of heavy REOs: Dy_2O_3 (0.124%), and Tb_4O_7 (0.068%; Lawrence, 2006).

The 2007 exploration program also identified an additional heavy REE resource immediately to the southeast of the Central Lanthanide deposit. This new deposit, known as the Southern Zone, apparently contains a rare earth suite biased more towards the heavier REEs. The Southern Zone is estimated to contain resources of 2.8 Mt at an average grade of 4.0% REO to yield 0.11 Mt of rare earth oxides (Industrial Minerals, 2008b).

Vanadium

Yilgarn Craton – Murchison Terrane

Windimurra

The Windimurra vanadium deposit is located 70 km southeast of Mount Magnet. Vanadium mineralization is contained within the Windimurra Complex, a cumulate-layered, Archean mafic–ultramafic intrusive body. The deposit consists of a near-surface, deeply weathered, vanadiferous titanomagnetite horizon extending to a depth of 40 m over a strike length of more than 25 km. Mineralization occurs in a magnetite-rich horizon known as the Sheppard's Discordant Zone. The weathered orebody is in the form of a shallow dipping series of up to 50 discrete magnetite bands ranging from 0.02 to 2.0 m thick within a matrix of magnetite gabbro/leucogabbro and rare pods of anorthosite. Early in 2006, only 5 km of strike length had been drill tested. Current resources for the deposit total 147.75 Mt at 0.46% V_2O_5, which includes a proven reserve of 50.4 Mt at 0.49% V_2O_5 (Avery, 2006; Prospect, 2007a).

Over the period 2000–04, the deposit was initially operated by the Precious Metals Australia Ltd (PMA)/ Xstrata plc joint venture as Australia's only producing vanadium mine. By late 2000, Xstrata had assumed complete control of the project with production peaking at over 5600 t of V_2O_5 concentrate in 2002. In late 2004, production was abruptly terminated as the company had apparently determined the deposit was no longer economic at prevailing vanadium prices of about US$1.70–1.80 per pound (A$6.66–7.03/kg). In its five years of operation, the mine produced almost 13 700 t of V_2O_5 concentrate (Fig. 16). After a legal dispute with Xstrata that was finally settled in 2005, PMA regained ownership of the project. In late 2006, PMA entered into an agreement to grant Noble Resources Ltd a 10% interest in the venture in exchange for cash and securities totalling $21.7 million, plus the right for Noble Resources to purchases the entire output of the mine (Fetherston and Searston, 2004; Register of Australian Mining, 2007/08b).

The company recently completed a feasibility study to reopen the mine with 15% increased capacity to 5500 tpa. At that time it was found that estimated costs have risen from $120 million to $296 million. The new openpit design incorporates a 185 m-wide opencut that will advance in both directions along strike to a depth of 40 m. The weathered orebody, that is largely mineable by rip and push techniques, is estimated to have an initial mine life of 25 years. At the same time, the new processing plant has been redesigned for the production of 85% ferrovanadium with only 15% as V_2O_5 concentrate (Avery, 2006; Mining Journal, 2007c). In October 2007, PMA announced a company name change to Windimurra Vanadium Ltd, and in January 2008 the company announced that it had secured a $200 million funding package to complete the redevelopment of the project in line with the proposed recommissioning date in the second half of 2008 (Jacoby, 2008).

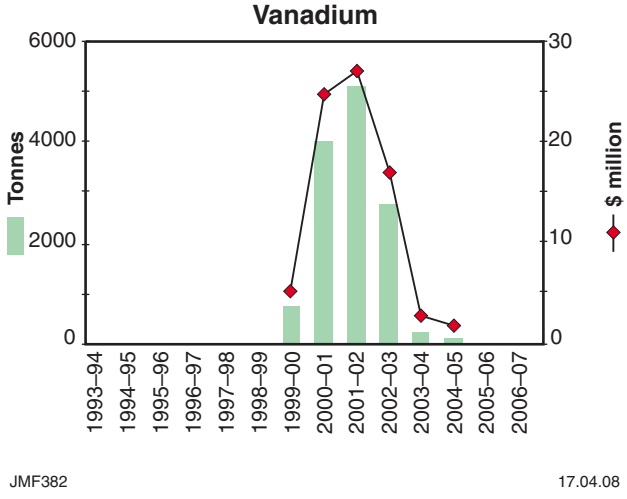

Figure 16. Trends in production (quantity and value) of vanadium in Western Australia, 1999–00 to 2004–05

Exploration and proposed developments

Diamond

Canning Basin (Leonard Shelf)

Ellendale area

In recent years, the Leonard Shelf in the northern Canning Basin, centred on the Ellendale area between 80 and 160 km east of Derby, has been covered by numerous exploration licences held by diamond exploration companies. Although this area is known to contain a large number of prospective lamproite pipes and significant geophysical targets for diamond exploration, to date no new significant finds have been reported.

Blina Diamonds, the company currently mining alluvial diamonds around Ellendale 4 and 9 diamond mines, also owns a number of exploration licences and mining leases surrounding the northwestern extent of KDC's Ellendale mining area. Preliminary exploration has shown that the area contains a large number of geophysical targets for diamondiferous ground, including aeromagnetic and ground EM, as well as 54 known lamproite pipes that have mostly been inadequately explored to date (Blina Diamonds, 2006).

In 2005, United Kimberley Diamonds NL (now United Minerals Corporation NL), following up on previous alluvial sampling at Cam Creek in its Ellendale South project that previously yielded 35 microdiamonds per 100 kg, carried out unsuccessful exploration on the 21 ha Cam Creek lamproite pipe (UKD 1; MiningNews.net, 2005). In the following year, the company discovered a small lamproite pipe (UKD 2) also in the Ellendale South area. Follow up petrological work indicated that the pipe had a silica-rich, leucitic composition and was not prospective for diamonds (United Kimberley Diamonds, 2006a).

Exploration in 2005 by Caldera Resources Pty Ltd, 25 km southeast of Ellendale 4 mine, located numerous microdiamonds in tuffaceous deposits as well as chromite diamond indicator minerals (Australia's Paydirt, 2006a).

In December 2007, Graynic Metals Ltd completed a joint venture with King Leopard Diamonds Ltd over areas at Napier Downs to the northwest of Ellendale, and at Noonkanbah and Walgidgee Hills located about 80 km to the south. Of particular interest is the extensive Walgidgee Lamproite pipe, with a diameter of about 2.5 km and covering about 490 ha. This intrusion was previously explored in the 1990s and yielded 891 microdiamonds and 62 macrodiamonds. In 1998, Diamond Rose NL recovered 11 macrodiamonds; 6 colourless white, 4 brown and 1 yellow (Graynic Metals, 2007).

Other exploration companies with interests in the region since 2005 includes Paramount Mining Corporation Ltd with high-resolution aeromagnetic lamproite targets in the Ellendale area, and to the northwest in the Napier Downs area. Another prospective explorer is Astro Diamond Mines NL, which holds an exploration licence 8 km along strike to the southeast of the Ellendale 4 mine. The company was to have flown magnetic surveys over the area in late 2007 (Astro Diamond Mines, 2007), but no new exploration results have been reported to date.

Halls Creek Orogen

Argyle mining area

Since 2005, companies have held numerous tenements for renewed exploration around the Argyle diamond mine. Argyle Bow River Diamonds Ltd (now a Conquest Mining Ltd, and Continental Goldfields Ltd joint venture) acquired the right to re-explore areas of terrace and other gravels around the old Bow River and Smoke Creek alluvial diamond mining operations. Other local areas to be investigated by the company were at Mount Pitt, Bow River West, and MacPhee Creek. United Kimberley Diamonds NL (now United Minerals Corporation Ltd) sampled gravels at their Doon Doon and Christmas Creek prospects, and Astro Diamond Mines NL investigated lamproite dykes west of the Argyle mine and similar dykes at Hadrians Wall a few kilometres farther west. To date no results from these exploration programs have been reported (Argyle Bow River Diamonds, 2005; Astro Diamond Mines, 2005).

Wood River

In March 2008, Paramount Mining Corporation Ltd reported that it recovered a small, clear white diamond (>0.5 mm in diameter) from its Wood River project, approximately 180 km west of the Argyle mine site. The diamond was recovered from a creek sample adjacent to an anomalous area of strongly warped sandstone, about 300 m in diameter. It is proposed the deformation of this area may be related to the possible emplacement of a kimberlite. In previous years, two other diamonds had been recovered from the local area. Analytical work for indicator minerals and diamonds is continuing (Paramount Mining, 2008).

Kimberley Basin

Phillips Range

In 2005, United Kimberley Diamonds NL (now United Minerals Corporation Ltd) completed bulk sampling at the Aries diamond pipe cluster in the central Kimberley area, 150 km north-northeast of Fitzroy Crossing. Bulk sampling yielded diamonds 22.5 ct recovered from 2169 t (Australia's Paydirt, 2006b).

Moonlight Valley

In 2006, United Kimberley Diamonds moved the focus of its operations to Moonlight Valley, an area with a setting analogous to that of the Aries pipe about 5 km to the north. In June, a ground-based gravity survey was carried out to target large individual kimberlite pipes or pipe clusters

that may be diamondiferous. The gravity survey identified 13 anomalies for potential kimberlite pipes that were subsequently drilled in the third quarter of 2006 to search for elements with a kimberlitic affinity, such as niobium and chromium. Results of this sampling program are yet to be released (United Kimberley Diamonds, 2006b).

Hamersley Basin

Blacktop

In late 2006, Tawana Resources NL in joint venture with De Beers, carried out a bulk sampling program at the Blacktop 1 kimberlite dyke, about 90 km south-southwest of Karratha. Approximately 6000 t of material from the dyke were processed in a dense-media separation plant and the heavy mineral concentrates processed by X-ray diamond recovery methods. From this material, 2320 diamonds were recovered with a total weight of 163.89 ct with the largest stone weighing 1.41 ct. Most stones were white, dodecahedral diamonds and were all recovered from the +1.0 to -19.0 mm size fraction of the processed material. The grade of kimberlite from Blacktop 1 Kimberlite Blows bulk sampling was variable from 6.39 to 8.63 cpht (Tawana Resources, 2007a).

Follow-up sampling over a wider area yielded indicator minerals results suggesting the presence of two new east-northeasterly trending kimberlite dykes at Blacktop East, about 8 km northeast of Blacktop 1 (Tawana Resources, 2007b). The joint venture has subsequently withdrawn from all of its exploration tenements except for E47/1125 covering the Blacktop East kimberlite fissures.

Caduceus prospect and other exploration sites

In late 2006, Flinders Diamonds Ltd drilled a single 147 m hole at its Caduceus prospect within its Hamersley diamond project 70 km north-northwest of Tom Price. Excessive brecciation and silicification of the Brockman Iron Formation resulted in poor penetration and low core recovery resulting in suspension of drilling. Despite the poor drilling results, it was established that no kimberlite was intersected (Flinders Diamonds, 2006).

In mid-2007, the company conducted a heavy mineral sampling for diamond indicator minerals over its Hamersley project tenements as well as other tenements farther east at Bold Cliff, and Mulga Downs. Of the 49 samples collected most were returned with negative results except for one sample from Bold Cliff that contained a single pyrope garnet (Flinders Diamonds, 2007).

Edmund Basin

Ullawarra

The Ullawarra area in the Edmund Basin, about 170 km west-southwest of Paraburdoo, has been prospected by Paramount Mining Corporation Ltd for a number of years. The area of interest, known as the Barlee Range kimberlite province, is situated on the western margin of the Mesoproterozoic Edmund Basin. In this area, kimberlites have intruded Proterozoic sedimentary rocks and intercalated dolerite sills.

In 2005, the company carried out a regional heavy mineral sampling program over 30 identified target areas. Of these areas, 11 yielded heavy mineral results worthy of follow-up work, and three in the Barlee Range area (UL 25, UL 27 and UL 28) are likely to host kimberlitic rocks. Definitive indicator minerals discovered include G10 pyrope garnet and chrome diopside. Other areas of interest include kimberlite dykes at Ullawarra 1 near Ullawarra Homestead and farther to the northwest at Barlee K1 in the Mount Palgrave area. At the completion of the sampling program the company was planning to define targets for a future drilling program (Paramount Mining, 2006).

Paterson Orogen

Runton project

Since 2005, Caldera Resources Pty Ltd has carried out a trenching and drilling program at its Runton kimberlite prospect in the Cronin Hills, about 375 km east of Newman. The Runton project has targeted three extensive, ultramafic dykes that have intruded sedimentary rocks of the Proterozoic Paterson Orogen. The largest intrusive body, the Southern Dyke, is 10 km long, with the two others comprising a 300 m-wide, 8 km-long body named the Northern Dyke. A central, intrusive body known as the Central Anomaly contains extensive carbonate mineralization in overlying tuffaceous rocks. Tuffaceous zones within the Northern and Southern Dykes were found to contain numerous diamond indicator minerals: chrome spinels and clinopyroxenes that indicate a probable kimberlite/lamproite source (Australia's Paydirt, 2006a).

In November 2006, a follow-up drilling and shallow trenching program was carried out in the steeply dipping Southern Dyke, involving seven RC holes for a total of 374 m and two trenches. Further diamond indicator minerals were recovered including G9 and G10 pyrope garnet, chrome spinel, picroilmenite, and clinopyroxene indicating that the dyke is a large, potentially kimberlitic, diamondiferous body with an area of at least 50 ha. In early 2007, further laboratory work on the drill and trench samples from the Southern Dyke yielded two diamonds measuring 0.5 × 0.175 mm, and 0.4 × 0.35 mm. The first of these was a clear stone, while the latter was a fancy peach/tan-coloured variety (Caldera Resources 2007a,b).

Diatomite

Perth Basin

Numerous diatomite deposits are present in Quaternary lake and swamp sediments along the Swan Coastal Plain from north of Geraldton to south of Bunbury. In past years, substantial deposits that have attracted some interest include a number of interdunal lakes in the Badgingarra–Dandaragan area, as well as southeast of Dongara, and Yeal Swamp north of Perth. Hudson Resources is the current owner of eight of the diatomite deposits between Perth and Dongara and for a number of years has conducted a research and development program on new diatomite applications and markets.

These diatomite deposits were mostly prospected in the late 1990s by Hudson Resources. At that time the company carried out a feasibility study and identified the Badgingarra deposit, 75 km west-northwest of Moora, as being the most prospective deposit. A program of trial mining took place in March 1998 and 15 000 t of filter-grade diatomite was stockpiled. The Badgingarra deposit was estimated to contain proved and probable reserves of 0.32 Mt. The company also identified another deposit at Drak, 10 km to the southeast, with an inferred resource of 0.2 Mt.

Diatomite deposits in other areas include the Dongara deposit, 25 km south of the town with inferred resources of 0.5 Mt. In the Moora–Dandaragan area, Tara 1 and 2 deposits have inferred resources of 45 000 and 25 000 t respectively, the Yere Yere deposit has inferred resources of 60 000 t, with another deposit located close by at Mathawandry. Another extensive deposit is located at Yeal Swamp in the Gingin area, about 60 km north of Perth (Hudson Resources, 2008b).

Refined and processed diatomite is commonly used as an efficient filter to separate suspended solids from fluids and is extensively used for the filtration of liquid foodstuffs especially beer, wine, and fruit juice, as well as industrial solvents, oils, pharmaceuticals, and swimming pool water. Diatomite is also used in lightweight refractory bricks because of its low thermal conductivity and high insulation properties, as a filler in paint, plastics and silicone rubber on account of its high brightness, high surface area and absorptive capacity, as an absorptive medium in pet litter and, because of its relative hardness, as a fine polishing medium.

Dimension stone

Jasper

Hamersley Basin

Mount Brockman

In June 2005, a group of prospectors unearthed a large pod of banded tiger eye jasper on a mining lease in the Hamersley Ranges, approximately 55 km northwest of Tom Price. Measuring about 3.0 m in length by 0.5 m in height, this spectacular pod contains subparallel bands and blebs of multicoloured jasper ranging from green to yellow, orange, red, blue and purple, interspersed with parallel bands and irregular blebs of golden yellow tiger eye (Fig. 17). The pod was subsequently sawn and polished into full-size 3.0 m slabs that are currently marketed as decorative wall panels.

Yilgarn Craton – Murchison Terrane

Fields Find

Another banded jasper forming part of an Archean suite of felsic sedimentary rocks and with potential as a dimension stone has recently been discovered by Australian Gem Resources at Fields Find about 50 km northwest of Paynes Find. This visually attractive, stone, known as 'Desert Sunset', consists of parallel red, yellow and black

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Figure 17. A multicoloured, polished slab of visually attractive tiger eye jasper from an exploration site near Mount Brockman in the Pilbara region (slab is approximately 1.25 m in length)

jaspilite bands that outcrop over a strike length of 2.0 km. In operation, the company intends to extract well-cut blocks between 5 and 20 t by diamond sawing prior to transport to the Port of Fremantle for export. During processing, it is expected this hard stone should take a very high polish.

Marble

Edmund Basin

Maroonah

In 2007, Pilbara Stone Pty Ltd carried out drilling in the Mesoproterozoic Irregully Formation on its Belloti and Pindanni prospecting licences, 12 km northwest of its 'Pilbara Green' marble quarry on Maroonah Station. To date, results from drillcores indicate the presence of quality marble that is generally of a paler green than the Pilbara Green at the nearby quarry. The company is continuing with its exploration program.

Parry Range

Pilbara Stone Pty Ltd also carried out an extensive geological exploration and drilling campaign in 2006–07 for marble in the Irregully Formation at three sites on their exploration licence E08/1408 in the Parry Range between 20–33 km east and southeast of Nanutarra Roadhouse (Appendix 1). At Bluff Well in the north of the tenement area, there is a sequence consisting of pale brown marble overlying off-white marble with buff-coloured highlights. Drilling results from this area tended to indicate that high-quality surface samples were generally not consistent with cores returned from drillholes.

In the south of the exploration licence, drilling revealed the presence of more consistent grades of high-quality marble. At Wadrah Bore, 12 diamond drillholes recovered high-quality pink and white marble, while at Motin Bore, 3.5 km farther east, six drillholes encountered cream to pink marble together with good quality mahogany red

marble of limited thickness. The exploration program is continuing in 2008.

Fluorite

Halls Creek Orogen

Speewah

The Speewah fluorite deposit, about 90 km south of Wyndham, was discovered in 1905. Since that time, the deposit has been subjected to numerous exploration projects, the most notable being that of Elmina NL from 1987 to 1995 that led to an indicated and inferred resource of 4.4 Mt at 23.6% CaF_2 at a cut-off grade of 10% CaF_2. A full description of Elmina NL's previous exploration of the Speewah deposit is given in Abeysinghe and Fetherston (1997).

In 2006, exploration of the Speewah deposit was renewed by Mineral Securities Ltd, who completed a 20-hole reverse circulation drilling program. This program targeted the B-Vein South, an extension to the previously explored fluorite-rich B-Vein, as well a new target at the West Vein, 5 km to the southwest. The exploration program also resulted in the discovery of the E-Vein, another potentially large zone of fluorite mineralization adjacent to B-Vein South and with a strike length of 2.0 km.

Notable drillhole results from B-Vein South included 25 m at 18.67% CaF_2 (5% cutoff), including 19 m at 22.52% CaF_2 (10% cutoff). Drillhole results from West Vein included 10 m at 39.38% CaF_2 (5% cutoff). Mineral Securities intends to return in the 2008 field season to carry out drilling and appraisal of the E-Vein system (Mineral Securities, 2006).

Kaolin

Yilgarn Craton – South West and Murchison Terranes

Although production of kaolin in the State has been very low in recent years, the prospectivity potential for high-grade deposits of kaolin is very encouraging. The principal area for exploration is in the southwestern and western areas of the Yilgarn Craton, which is composed largely of granitic and metamorphic rocks derived from granites and covers vast areas of the southern interior of the State (Plate 1). The granitic rocks of this region are mostly covered by Cenozoic deep-weathering profiles, commonly comprising thick kaolinitic saprolite, some of which constitute high-grade residual (primary) kaolin deposits.

In the mid-1990s, CRA Exploration carried out extensive exploration in the southwestern Yilgarn Craton for high-whiteness kaolin deposits suitable for the international paper coating and general filler markets, with specifications comprising 60% kaolin and less than 2% iron and titanium oxides with the remainder being quartz and trace amounts of feldspar and mica. A number of suitable deposits were located, with the main focus on a site in the Ockley–Wickepin area (Sparks deposit) about 50 km east-northeast of Narrogin. This deposit contains an indicated resource of 29 Mt of high-grade paper-coating and filler-grade kaolin.

Early in the current decade, Minerals Corporation Ltd investigated the Bradley deposit at Kerrigan, about 350 km east of Perth and 25 km southeast of Karlgarin. This deposit has an inferred resource of 80 Mt of 45% kaolin at <10 μm particle size. The kaolin is present at a depth of 6 m, extending to a maximum depth of 30 m to a weathered granite basement.

More recently, Minerals Corporation has turned its attention to its Swan River kaolin project at the Meckering deposit, about 125 km east-northeast of Perth, and at Jacobs Well and Jacobs Well South prospects, both approximately 125 km east of Perth. In March 2007, the company announced indicated and inferred resources for the Meckering deposit of 65.0 Mt averaging 41.9% kaolin with an average brightness value of 83.4% (Minerals Corporation, 2007a). The company also operated a pilot plant at Kwinana until June 2007, where physical properties of the raw material were successfully tested in the trial production of paper- and ceramic-grade kaolin. Because of the pure nature of the clay, tests for pharmaceutical-grade kaolin were also proposed. In June 2007, the company announced that it had completed the restructuring of its china clay projects into a single entity to be known as Australian China Clays Ltd to be registered on the London Stock Exchange (Minerals Corporation, 2007b).

Other large, residual, high-grade kaolin deposits awaiting development in the South West Terrane include the Jubuk deposit, 200 km east of Perth, with measured and inferred resources of 48.9 Mt of high brightness, low abrasion clays; Gabbin, 210 km northeast of Perth, with inferred resources in excess of 8.4 Mt; and Tambellup, 110 km west-northwest of Albany, with an indicated resource of 7.1 Mt. Two previously mined secondary kaolin deposits, developed in paleochannels and lacustrine environments, are located at Goomalling, 132 km northeast of Perth, and Mount Kokeby, 105 km east-southeast of Perth. In the west of the Yilgarn Craton in the Murchison Terrane, two other kaolin deposits are present: the Mullewa deposit, 100 km east-northeast of Geraldton, with measured and indicated resources of 2.04 Mt, and the Mount Gibson kaolin deposit near Lake Moore, with inferred resources of 56 Mt (Abeysinghe and Fetherston, 1999).

Manganese

Bryah Basin

Horseshoe South

In 2008, Process Minerals International (PMI, a subsidiary of Mineral Resources Ltd), concluded an agreement with Peak Hill Manganese Pty Ltd, owners of the old Horseshoe South manganese mine and associated mine dumps. The Horseshoe South Mining area is situated about 130 km north of Meekatharra in manganiferous sedimentary rocks of the Paleoproterozoic Horseshoe Formation within the Bryah Basin.

In this operation, it appears that PMI intends to access remaining manganese-rich mine dumps that remain in-situ after BHP's mining activities at Horseshoe between 40 and 60 years ago. It is estimated that the remaining dumps may contain a manganese resource of up to 0.5 Mt. It is understood that PMI intends to process manganese ore from the dumps on-site at the rate of about 0.24 Mtpa, and that the upgraded ore will be transported to Port Hedland for export.

Pilbara Craton, East Pilbara manganese province

Ant Hill and Sunday Hill

In late 2007, HiTech EnergyLtd were involved in the advanced design of a new alkaline-grade EMD* plant at Halol in Gujarat State in India. This plant is being designed to utilize low-grade manganese fines material averaging 28% manganese remaining at mine sites following removal of the higher grade lump and chip manganese for silicomanganese alloy production for use in steel-making processes. A future development at the plant could include the addition of an additional circuit producing electrolytic manganese metal flake (EMM) to increase the company's high-tech product range. Recently, HiTech Energy applied for a number of patents covering intellectual property relating to specialist methods of sulfur dioxide leaching and solvent extraction for EMD and EMM production.

HiTech Energy currently holds tenements in the manganese-rich Ant Hill and Sunday Hill areas about 85 km southwest of the Woodie Woodie mine. The company is examining the feasibility of stockpiling medium- to low-grade manganese fines after removal of coarser grades from these sites. These fines could be used as feedstock to the Indian EMD plant, and possibly for a future processing plant located in Australia assuming appropriate cost savings could be achieved (Scott, A, 2007, written comm.).

The company is looking to increase previously established inferred resources for Ant Hill of 0.42 Mt at 29.5% manganese, and 4.70 Mt at 18.5% manganese at Sunday Hill. Considering the inferred resource for Ant Hill covers only 10% of the area prospective for manganese it is expected that this resource may be substantially increased in future investigations. Surface magnetic and gravity surveys that identified a number of possible manganese targets at Sunday Hill have recently been completed. A follow-up drilling operation has been approved for 2008 (HiTech Energy, 2007).

South Woodie Woodie

The South Woodie Woodie exploration area is centred around Enacheddong manganese prospect in the east Pilbara region about 50 km south of the Woodie Woodie manganese mine. Exploration in this area was until recently carried out by Churchill Mining PLC, but in late 2007 the project was acquired by Spitfire Resources Ltd, a newly registered company on the ASX.

In 2006, Churchill Mining carried out an airborne magnetic and radiometric survey of the South Woodie Woodie area. This survey identified the location of the Paleoproterozoic Pinjian Chert Breccia overlying the late Archean Carawine Dolomite, host to the major manganese deposits in the region, extending over about one-third of the project area. A versatile time-domain electromagnetic (VTEM) geophysical survey was conducted over the northern half of the area of Carawine Dolomite underlain by the Pinjian Chert Breccia in which 38 targets for potential manganese mineralization were identified. Of these, 14 were selected as high-priority targets for a follow-up induced polarization (IP) survey that resulted in the identification of eight discrete targets for a drillhole program. Spitfire Resources has announced that it intends to drill the eight IP-defined targets in 2008 (Spitfire Resources, 2007).

It was also noted that previous investigations on the geophysical characteristics of manganese deposits at the Woodie Woodie mine had indicated that not all manganese prospects in the area are electrically conductive. Accordingly, it was recognized that other geophysical methods such as gravity surveys should also be deployed to define targets for drill testing.

Northwest Officer Basin

Table Hill project

In 2005, AusQuest Ltd flew an airborne electromagnetic (GEOTEM) survey over the Savory Creek area of the northwest Officer Basin. The survey identified 11 electromagnetic targets of interest that were followed up in mid-2007 with ground EM surveys over ten of these tagets. In the September quarter of 2007, an exploratory hole (THDD01) was drilled into a prospective target in the Boondawarri Creek area, approximately 180 km east-southeast of Newman. A downhole electromagnetic probe confirmed that manganese mineralization was the cause of the GEOTEM anomaly. Examination of the recovered core confirmed the presence of a 3.9 m-thick layer of massive manganese mineralization at a depth of 287 m. Subsequent analyses gave averaged results of 47.5% manganese together with low iron (<1%) and phosphorus (0.04%).

Further work on conductivity–depth sections produced from the GEOTEM data indicated that the interpreted manganese mineralization forms a sheet-like body, dipping shallowly to the south at depths ranging from about 120 m in the north to over 300 m in the south and extending over an area of at least 6 × 3 km (AusQuest, 2007).

At least three more areas of prospective, sheet-like, electromagnetic conductors have been targeted for future drilling projects. Drilling is expected to take place in the second quarter of 2007 to test anomalies where the manganese bodies may occur at depths shallower than those previously examined.

* EMD: see page 16.

Padbury Basin

Mount Padbury

In early 2008, Montezuma Mining Company Ltd carried out rock chip sampling in the area immediately south of the old Mount Padbury manganese mine in the Peak Hill mining district, about 120 km north-northwest of Meekatharra. The Mount Padbury mine closed in 1982 after producing a total of 7300 t of metallurgical grade manganese with an average content of 48% manganese (Fetherston, 1990).

During January and February 2008, the company identified six manganese-rich target zones extending along a mineralized corridor over 2.5 km in length. Two surveys in the area recovered a total of 23 rock chip samples from areas of surface enrichment. The maximum assay value for manganese from one sample was 55.8% together with 3.8% iron , and a low phosphorus value of 0.009%. Average values obtained from the 23 samples were manganese 38.46%, iron 11.05%, and phosphorus 0.35%. To date, the sampling program has covered only 20% of the exploration area and further surveys are due to be carried out to identify zones areas of manganese enrichment (Montezuma Mining, 2008a,b).

Yilgarn Craton – Eastern Goldfields Terrane

Mount Thirsty

In October 2007, Barra Resources Ltd announced an increase in in-situ resources based on air core drilling results and block modelling of their polymetallic cobalt–nickel–manganese lateritic deposit at Mount Thirsty, 20 km north-northwest of Norsemen. As a result, indicated and inferred resource estimates have been upgraded to 20.97 Mt at 0.14% cobalt, 0.62% nickel, and 1.01% manganese containing 0.029 Mt cobalt, 0.13 Mt nickel, and 0.21 Mt manganese. The Mount Thirsty resource appears to be confined to a single, north-trending orebody at shallow depth over 1100 m in length, almost 600 m in width, and averaging 12 m in thickness. The company considers there is potential to further extend the resource to the south and also to the west where the mineralization remains open (Barra Resources, 2007).

Phosphate

Southern Carnarvon Basin

Cardabia

In March 2008, newly listed Syndicated Metals Ltd began evaluation of its Exmouth Project, a phosphate prospect located in the Cardabia area around 125 km south of Exmouth. In this area, the company has acquired extensive exploration licences centred along Cardabia Greek, to the south of the Giralia Range. Exploration will be based on previous work by CRA Exploration Pty Ltd in 1988–91 in which CRA located phosphate nodule-rich horizons at several intervals within Upper Cretaceous units of the Southern Carnarvon Basin.

Exploration by CRA in this area demonstrated the presence of phosphate nodule horizons located at contacts between the Gearle Siltstone and the Toolonga Calcilutite, and between the Toolonga Calcilutite and the Korajon Calcarenite. Phosphatic nodules from these zones, contained within a matrix of non-phosphatic, calcareous clay, gave an average assay value of 30.3% P_2O_5. Five of the 13 CRA aircore drillholes in the area, yielded P_2O_5 values between 25 and 27% from the +5 mm size fraction. At that time, CRA considered the deposit to be uneconomic based on mineralized horizon thicknesses and density of nodules within these horizons.

As a result of the recent four-fold increase in world prices for phosphate, Syndicated Metals intends to reappraise this phosphate prospect. The company has also indicated that it intends to search for paleodepressions in the Upper Cretaceous sedimentary rocks, where greater concentrations of phosphatic nodules may be encountered (Syndicated Metals, 2008).

Yilgarn Craton – Eastern Goldfields Terrane

Mount Weld

At the Mount Weld carbonatite deposit, about 35 km southeast of Laverton, the lower regolith horizon comprises a residual zone containing concentrations of less soluble minerals, particularly apatite, magnetite, and vermiculite formed by dissolution and weathering of the primary carbonatite. In this zone, apatite concentrations have formed areas of phosphate-rich mineralization (Fig. 15). The phosphate-rich zone, comprising the Swan and Emu deposits, contains an inferred resource of more than 250 Mt with an average P_2O_5 content of 18.1% (Duncan, 1990; Lynas Corporation Ltd, 2002).

Around the beginning of the decade, Anaconda Nickel Ltd and Wesfarmers CSBP Ltd planned to develop the Mount Weld phosphate deposits. In 2000, an aircore drilling program was completed, returning high-grade phosphate results. Work also continued on the delineation of the Emu phosphate resource, and the removal of iron during processing. A scoping study was completed with positive results relating to the commercial viability of a Goldfields chemical complex (Anaconda Nickel Ltd, 2000, 2001).

In April 2002, Anaconda sold the Mount Weld tantalum, niobium, and REE mineralization to Lynas Corporation Ltd; however, the dedicated phosphate mineral lease was retained by Wesfarmers CSBP Ltd. Since that time this project appears to have been placed on hold.

Potash minerals

Officer and Canning Basins

Lake Disappointment and Lake Auld

In a preliminary sampling program in 2006, Reward Minerals Ltd collected lakebed solids and brines from Lake Disappointment in the Officer Basin, 300 km east of Newman, and from Lake Auld in the Canning Basin, about

430 km east-northeast of Newman. These samples were intended to test for potash concentrations present in the lakes (Reward Minerals, 2006). Results for soluble sulfate of potash (K_2SO_4) were:

	Lakebed solids[*]	*Lakebed brines*[†]
• Lake Disappointment	0.33–0.61%	1.00–3.50%
• Lake Auld	0.74–0.82%	3.10–3.37%

[*] grams K_2SO_4/100 g dry lakebed solids

[†] grams K_2SO_4/100 g of lake brine

In 2007, encouraged by these results, the company acquired eight extensive exploration licences covering the surface of Lake Disappointment, and another exploration licence covering the surface of the northern half of Lake Auld.

In February 2007, the company carried out a hydrogeological assessment program at Lake Disappointment to evaluate the lake's potash potential. This exploration program consisted of a series of 30 holes drilled on a nominal 5 × 5 km grid. To achieve this objective, a specially constructed 'geoprobe' drilling rig was transported over the muddy lake surface to each drill site by helicopter (Fig. 18a,b). The drilling recovered cores of lakebed sediments at intervals and sealed in plastic tubes to retain their structure and brine content for further analysis. In addition to the drilling exercise, a program of trenching and test pumping was also carried out at three sites to evaluate the brine flow regime present in lakebed sediments.

The drilling program revealed that the unconsolidated sediments in the floor of Lake Disappointment range from at least 3.0 m to a maximum of 10.0 m in thickness with an average of 4.1 m. In addition, heavy brine flow was encountered in every drillhole. Brine flow parameters from field data are currently under investigation. Figures to date indicate that brine samples drawn from drillholes averaged 12.56 g K_2SO_4/l, with maximum values as high as 20.01 g K_2SO_4/l.

Sufficient data were obtained from the drilling program at Lake Disappointment to allow for the calculation of an indicated resource estimate of contained K_2SO_4 in the lake floor sediments based on estimated sediment depth, and surface area of the lake based on assumptions relating to lake margins (Reward Minerals, 2007):

- Lower indicated resource estimate:
  7705 Mt at 3.17 kg/t for 24.43 Mt K_2SO_4
- Upper indicated resource estimate:
  8635 Mt at 3.17 kg/t for 27.37 Mt K_2SO_4
  (in this estimate, the average K_2SO_4 content per tonne (3.17 kg/t) has been derived from the average analysis of the whole drillcore)

To date, no new exploration work has been reported from Lake Auld.

Other potash prospects

Other relatively minor potash prospects are located in the Dandaragan–Gingin area, at Lake Chandler, 50 km north of Merredin, and Yaringa, southeast of Shark Bay. All these prospects were evaluated pre-2003 and are outlined in Fetherston and Searston (2004).

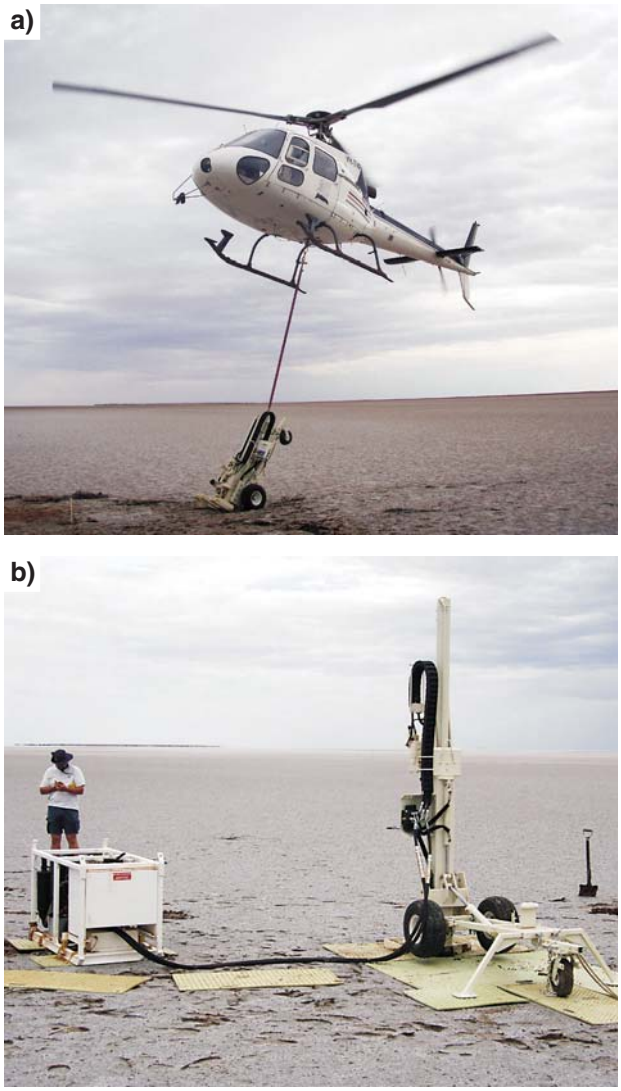

Figure 18. Potash exploration on the brine-saturated mud flats of Lake Disappointment: a) helicopter transport of a specially constructed 'geoprobe' drilling rig to a drillsite; b) the assembled drill rig in operation recovering cores from lakebed sediments (courtesy Reward Minerals Ltd)

Rare earth elements

In recent years, re-evaluations of prospectivity and metallurgy have been conducted over REE deposits at Cummins Range, and Brockman in the east Kimberley region. Other REE deposits include the Yangibana and Frasers deposits in the Edmund region in the central west of the State, and the John Galt deposit and associated Corkwood Yard alluvials in the east Kimberley.

Gascoyne Complex

Yangibana and Frasers

Between 1986 and 1988, a series of 12 widely separated REE prospects were evaluated by reconnaissance drilling in the Yangibana area, 280 km east-northeast of Carnarvon.

Within the exploration area, mineralization was found to be contained in thin, tightly folded ironstones and consisting of REE in association with anomalous base metal values. At that time, project owners, Hurlston Pty Ltd, reported resources for all Frasers and Yangibana prospects totalling 3.53 Mt at an average grade of 1.64% REO (Pooley, 1988, 1989). It should be noted that these resource estimates pre-date the JORC code for reporting of resources. No new exploration appears to have occurred since that time.

During 2001, Frasers REE deposit was acquired by Aztec Resources Ltd (Aztec Resources, 2001). Currently, Frasers REE deposit is owned by Mount Gibson Iron Ltd following the takeover of Aztec Resources in January 2007, whereas the majority of the Yangibana REE prospects are owned by Vistarise Ltd.

Halls Creek Orogen

Cummins Range

The Cummins Range carbonatite, 130 km south-southwest of Halls Creek, was discovered by CRA in 1978 by testing an aeromagnetic anomaly. Based on widely spaced, shallow drilling, CRA announced an estimated resource of 3–4 Mt grading 2–4% REO. This polymetallic deposit was also shown to contain significant uranium, phosphate, tantalum–niobium, scandium, zircon, yttrium, vermiculite and iron mineralization.

At that time, it was indicated that the highest REO grades are located in the upper weathered zone where leaching, dissolution, and silicification of carbonatitic rocks have led to the enrichment of REE-bearing resistate minerals in the oxidized zone of weathering. Assays from the weathered zone returned grades of up to 0.27% Ce, 0.16% La, 0.11% Ne, 35 ppm Eu, and 18.3% P_2O_5, although grades were shown to decrease rapidly toward the base of the oxidized zone. In 1989, the deposits were concluded to be subeconomic (Weir, 1989).

Since 2001, the Cummins Range area has been investigated by Navigator Resources Ltd. In mid-2007, the company drilled 464 m in a 21-hole reconnaissance aircore drilling program across the carbonatite deposit (Fig. 19). This survey yielded significant REO values that included 48 m at 3.2% from 36 m, 4 m at 8.2% from 36 m, 4 m at 5.3% from 44 m, and 32 m at 2% from 44 m together with high grades for niobium of up to 3.0% Nb_2O_3 over 4 m. Rare earth oxide results to date indicate that the deposit is quite similar to that at Mount Weld with the indicative mix of predominantly light REOs from CeO_2 (47.5%), La_2O_3 (27.6%), Nd_2O_3 (16.2%), Pr_6O_{11} (5.0%), Sm_2O_3 (1.7%), to Gd_2O_3 (1.0%) (Navigator Resources, 2007).

In March 2008, the company announced that resource modelling based on its 2007 drilling program had identified a high-grade zone with resources estimated at 1.1 Mt at 3.5% REE. The high-grade zone appears to be open-ended and is incorporated within a thicker halo of lower-grade mineralization totalling 3.6 Mt at 1.3% REE. The drilling program also identified two partially overlapping zones of phosphate (13.1 Mt at 10.0% P_2O_5), and uranium (1.3 Mt at 0.04% U_3O_8) (Navigator Resources, 2008).

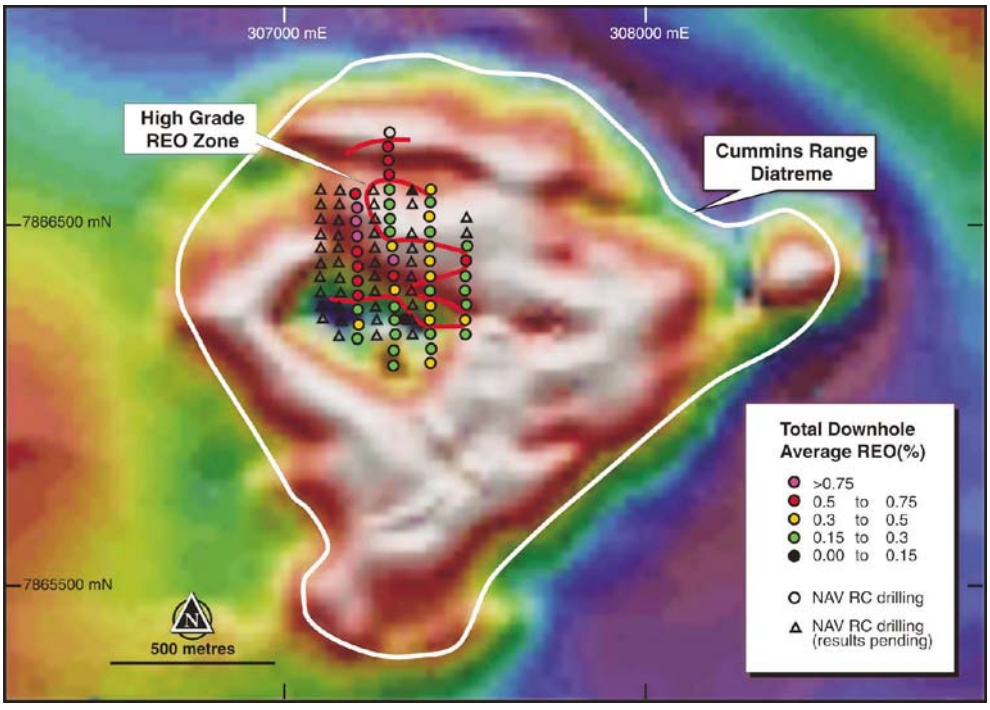

Figure 19. High-grade rare earth oxide (REO) zone at Cummins Range indicated by drillholes from the 2007 exploration program. The Cummins Range carbonitite diatreme, is highlighted by a magnetic high (enclosed by a white line) from imaged aeromagnetic data (modified after Navigator Resources, 2007)

Brockman

Situated 18 km southeast of Halls Creek, the Brockman polymetallic deposit, is hosted by a fine-grained silica–sericite rock that has been identified as a hydrothermally altered trachyte. Mineralization comprising Zr–REE–Nb–Ta is confined to two units that together comprise the 'Niobium Tuff' of the Butchers Gully Member. The lower unit is a crystal-rich (albite-bearing) ashflow tuff and the upper unit is an albite-free, pumice-rich tuff. Closely spaced pyroclastic flows sourced from a trachytic magma, highly enriched in REE and other incompatible elements, is considered to be the source of the mineralization.

In mid-2004, project operators Brockman Minerals Pty Ltd (ABM Resources NL, and Aztec Resources Ltd) released an upgraded measured, indicated, and inferred resource totalling 50 Mt grading 0.090% REO, 1.040% ZrO_2, 0.440% Nb_2O_3, and 0.027% Ta_2O_5 (Aztec Resources, 2003). In late 2005, a program of metallurgical test work involving heavy liquid mineral separation was initiated. The completed report on this research program was due for completion late in 2006 (ABM Resources, 2006) but, to date, no further results of the testwork have been announced.

Following a takeover of Aztec Resources in January 2007, the Brockman Rare Earth project is currently 100% owned by Mount Gibson Iron Ltd.

John Galt and Corkwood Yard

The John Galt REE and yttrium deposit, and the adjacent Corkwood Yard REE alluvial prospect are currently owned by AJ Exploration Geology Pty Ltd and Panoramic Resources Ltd (formerly Sally Malay Exploration Pty Ltd) respectively. These sites are located at the western end of the Osmond Range, about 120 km north-northeast of Halls Creek. At John Galt deposit the REE mineralization occurs within xenotime, which forms disseminations in lithic quartz sandstone of the Proterozoic Red Rock Formation, as well as in joint- and fault-controlled veins up to 30 cm wide. Inferred resources of 0.359 Mt at 0.001% REO were calculated for Corkwood Yard alluvial prospect (Ceplecha,1988), and 0.051 Mt at 0.35% REO for the John Galt deposit (Noble Resources, 1992). There has been no further exploration, probably because of assessments that deemed the project subeconomic at prices prevailing at that time.

Salt

Onslow salt project

In May 2007, Polaris Metals NL announced they were examining the potential for a second solar salt project in the Onslow area on the northwest coast. The company had recently applied for four extensive exploration licences along the coast to the northeast and southwest of the town of Onslow and adjoining the operating Onslow salt field owned by Mitsui & Co. Ltd. One of these exploration licences (E08/1524) has already been granted.

Polaris Metals have commissioned a $50 000 scoping study with consulting engineers Project Development and Management Services Pty Ltd. This study, which is currently underway, will evaluate the potential for the development of a new solar salt operation. One of the key drivers under investigation is the development of major markets in China given the country's rapidly developing economy and the project's favourable proximity to China and other South East Asian markets (Polaris Metals, 2007).

Yannarie salt project

The proposed area of the Yannarie solar salt project extends in a strip averaging 12 km wide for almost 70 km following the eastern shoreline of Exmouth Gulf. Project owners, Straits Resources Ltd, have divided the project area into northern and southern crystallizer ponds with a proposed central handling facility and port at Hope Island, about 90 km southwest of Onslow. The company is currently conducting feasibility studies to assess the viability of producing up to 10 Mtpa of solar salt from this area.

In March 2007, following the end of the period for public submissions to the Environmental Review and Management Program (ERMP), the company has been carrying out additional environmental research prior to a formal assessment of the project by the Environmental Protection Authority. If approval is granted to proceed with the project, it appears that it will take about 2–3 years to bring the project into operation with an initial production of 3 Mtpa (Straits Resources, 2006; Prospect, 2007a).

Semiprecious stones

Edmund Basin

Waldburg variscite

In 2005, a new deposit of variscite (hydrated aluminium phosphate) was discovered by prospectors in the Waldburg Range on Woodlands Station, about 230 km north-northwest of Meekatharra. The variscite mineralization occurs within an 0.5 m-wide zone as a number of conformable, subhorizontal veins within brecciated shale and siltstone of the Mesoproterozoic Edmund Group.

Within the mineralized zone, variscite veins are generally less than 70 mm wide but the zone can be traced for about 1.0 km along strike. The veins comprise both massive and spindle-shaped variscite together with secondary phosphatic minerals, plus alunite, jarosite, kaolinite, and iron hydroxides. The high-quality gem variscite is translucent with a dark emerald green colour (derived from about 0.5% chromium substitution). Also, the mineral has been shown to have an association with gold that varies from fine grains to visible concentrations within the variscite spindles (Hancock, 2008).

Bulk samples extracted during 2006 revealed a range of colours in the variscite from pale lime green to mid-green (similar to high-quality green chrysoprase), to translucent emerald green. Some of the variscite has a 'webbed' texture of subrounded variscite masses, up to 1–2 cm

diameter separated from each other by a narrow, pale yellow fringing margin. Trial batches of polished Waldburg variscite, mainly as slabs, cabochons and carvings, were recently displayed to some acclaim at an international gem trade fair in Tucson in the US (frontispiece).

Tantalum and lithium

Halls Creek Orogen

Brockman

As previously mentioned under Brockman rare earth element exploration, the Brockman polymetallic deposit, 18 km southeast of Halls Creek, has an upgraded, measured, indicated, and inferred resource totalling 50 Mt grading 0.090% REO at 1.040% ZrO_2, 0.440% Nb_2O_3, and 0.027% Ta_2O_5 (Aztec Resources, 2003). In late 2005, the project operators Brockman Minerals Pty Ltd (ABM Resources NL, and Aztec Resources Ltd) announced that a program of metallurgical test work involving heavy liquid mineral separation had been initiated. The completed report on this research program was due for completion late in 2006 (ABM Resources, 2006) but, to date, no further results of the testwork have been announced. Following a takeover of Aztec Resources in January 2007, the Brockman Rare Earth project is currently 100% owned by Mount Gibson Iron Ltd.

Pilbara Craton

East Pilbara region

Australian Tantalum Pty Ltd, a wholly owned subsidiary of Haddington Resources Ltd, has six tantalum prospects in the East Pilbara region between 50 and 200 km southeast of Port Hedland including Pilgangoora, Crawford Bore, Woodstock, Pinga, and Shaw River. Another prospect at Moolyella is located in the Marble Bar district. Most of these prospects are discussed in Fetherston (2004).

Initial exploration of the East Pilbara prospects in 2005–06, focused on the Pilgangoora prospect where 97 geochemical samples were collected. Of these, 14 returned values between 0.010 abd 0.039% Ta_2O_5 with samples from many other pegmatites returning Ta_2O_5 values well above 0.005%. A number of large pegmatites have been identified for follow-up work, especially those parallel to, and within 1.0 km of, the granite–greenstone contact (Haddington Resources, 2005, 2006a).

Yilgarn Craton – Eastern Goldfields Terrane

Bald Hill exploration area

Tantalum exploration continued until late 2006 on Haddington Resources Ltd Bald Hill exploration licence tenements 50–60 km southeast of Kambalda following the shut down of the Bald Hill mine and processing plant in December 2005.

Over the years, a vigorous exploration program had been pursued by the company to extend the future available tantalum resource for the Bald Hill mine. In 2005, the company held numerous exploration and prospecting licences in the area with most exploratory work being carried out close to the Bald Hill mine, and on the Bald Hill Extended, Madoonia, and Sinclair exploration areas (Fig. 20). Work was also carried out on the Yallaburra exploration area located immediately west and northwest of the Bald Hill tenements (Haddington Resources, 2005, 2006a,c). Exploration highlights during 2005–06 included:

- Bald Hill Extended (E15/798 and E15/813)
  The Creekside deposit, about 2.0 km southwest of the Bald Hill mine, was drilled in 2005 with around 50% of drillholes intersecting pegmatite of at least 3.0 m thickness. Further drilling confirmed a resource of 0.204 Mt at 0.044% Ta_2O_5. A follow-up study indicated that under prevailing low prices for tantalite concentrate the deposit was uneconomic at that time. Also in the Bald Hill Extended area, three new prospects were investigated. Drilling at the Access Road, Cotters, and Bulloak Dam prospects intersected pegmatites with thicknesses of up to 33 m. The Access Road prospect contains multiple, narrow vein pegmatites containing indications of high-grade values for Ta_2O_5. At Cotters prospect, pegmatites appear to form part of a larger system comprising narrow veins and broad, flat sheets. Initial drilling results indicate the possibility of a significant lower grade resource with Ta_2O_5 values between 0.008 and 0.016%. At Bulloak Dam, surface outcrops of pegmatite indicate a strike length of at least 150 m. A 12 m drillhole in this vein gave average Ta_2O_5 values of 0.029%. Also, a geochemical sample taken 450 m north of Bulloak Dam yielded a Ta_2O_5 value of 0.133%. Further drilling and trenching is required at each prospect to confirm these observations.
- Madoonia area (E15/665)
  Results from 253 broadly spaced geochemical drillholes, identified two new mineralized pegmatites at the Madoonia and Claypan prospects, 20 and 6 km northeast of Bald Hill respectively. At the Madoonia prospect, 14 drillholes intersected six pegmatites with Ta_2O_5 grades from 0.006 to 0.013% over thicknesses of 1–5 m. At the Claypan prospect, over 40 northwest-trending, mostly thin pegmatites were identified with the largest being over 600 m in length. Of these, six pegmatites were selected for drilling with disappointing results ranging from 0.006 to 0.017% Ta_2O_5 over widths ranging from 2 to 5 m.
- Yallaburra area (E15/791)
  At the Cotters North prospect, seven reverse circulation holes for a total of 128 m yielded Ta_2O_5 values from 0.008 to 0.024% over thicknesses of 1–5 m. Also within the Yallaburra area, a program of 273 RAB holes was completed. Pegmatites up to 4.0 m thick were intersected with grades ranging fron 0.002 to 0.024% Ta_2O_5.

Mount Weld

At the Mount Weld REO deposit, located about 35 km south-southeast of Laverton, deposits of rare metals, principally tantalum–niobium and zirconium, are contained within lacustrine sediments overlying areas in the northern

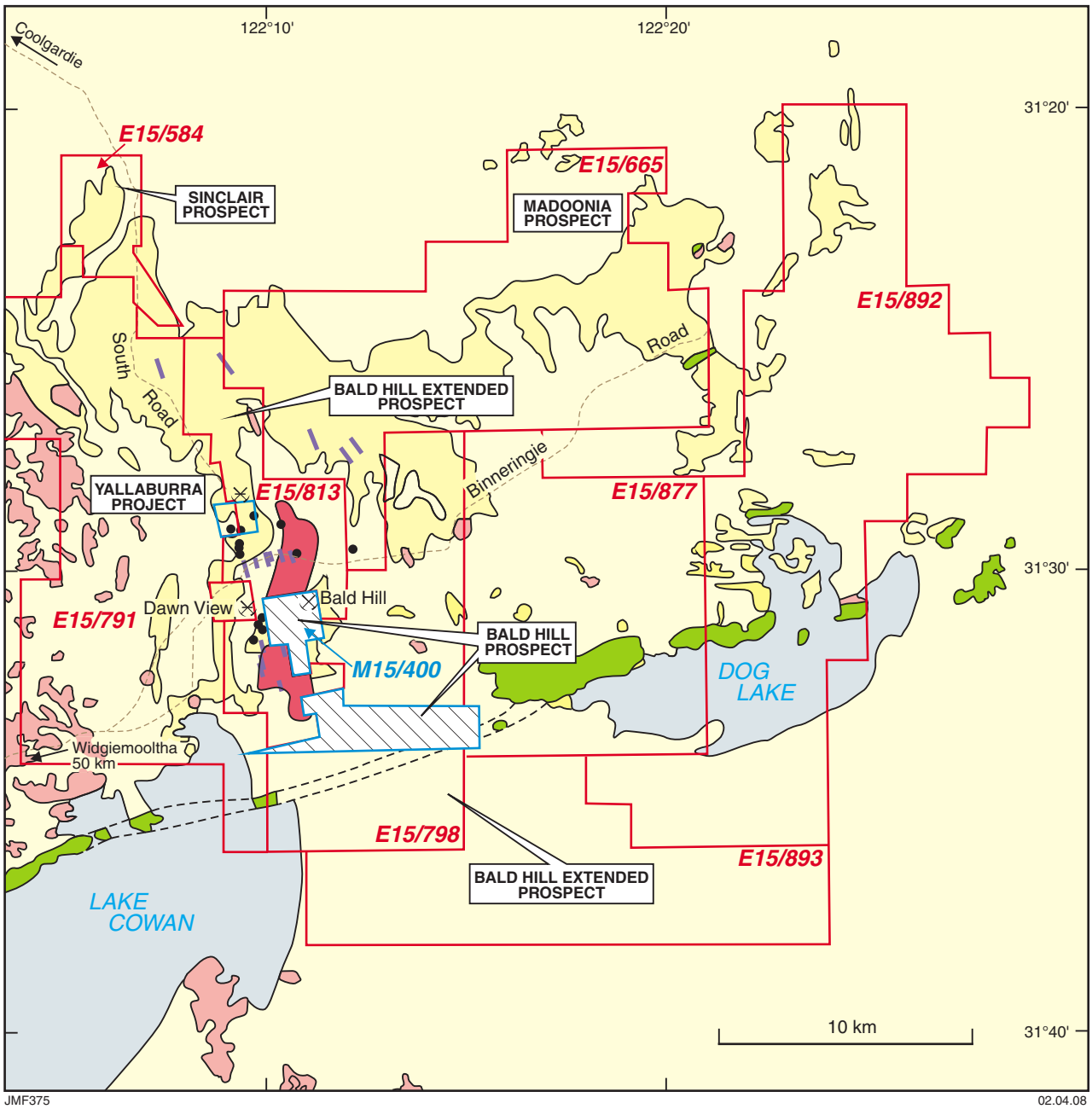

Figure 20. Tantalum exploration prospects and mining area at Bald Hill about 55 km southeast of Kambalda (modified after Haddington Resources, 2005)

and southern sectors of the polymetallic carbonatite pipe (Fig. 15; Fetherston, 2004).

In October 2004, Lynas Corporation Ltd announced an upgraded resource for rare metals contained in the Coors and Crown deposits located in the northern sector of the Mount Weld pipe. The indicated and inferred resources for these deposits totalling 37.7 Mt were estimated to contain rare metals: 0.024% Ta_2O_5, 1.07% Nb_2O_5, and 0.30% ZrO_2, and also 0.09% Y_2O_3, 1.16% REO, 4.0% TiO_2, 8.0% P_2O_5, 11.3% Al_2O_3, and 42.8% Fe_2O_3.

A subsequent scoping study identified a future openpit between 30 and 60 m depth, that would produce about 1 Mtpa over a mine life in excess of 35 years. This operation would focus mainly on the production of niobium concentrate that could be exported to China largely for the production of ferro-niobium alloys. It is envisaged that a pre-feasibility study, including research on the mineralogy and metallurgy of the rare-metal ore, will commence following the commissioning of the REO mine and plant at the Central Lanthanide REO deposit currently under development (Lynas Corporation, 2004).

Yilgarn Craton – Murchison Terrane

Niobe

Located about 70 km northwest of Mount Magnet and 7 km east of the abandoned Dalgaranga tantalum mine, the Niobe deposit was first mined in 1995. At that time the deposit, known then as Mount Farmer, produced almost 19 000 t of ore that yielded 38.9 t at 0.05% Ta_2O_5.

About 2000–01, Tantalum Australia NL carried out several drilling programs at Niobe and the adjacent Niobe East prospect along strike. These drilling programs provided sufficient information to estimate a measured, downdip resource of 57 550 t at 0.024% Ta_2O_5. The deposit also has surrounding waste dumps containing lower grade ore estimated to contain an additional 36 000 t at 0.031% Ta_2O_5 (Fetherston, 2004).

In 2002–03, Tantalum Australia targeted Niobe as its next mining project in view of the depletion of ore from its Dalgaranga mine. However, the company was apparently unable to secure an operational mining lease over the Niobe deposit and the project lapsed.

Yilgarn Craton – Southern Cross Terrane

Mount Cattlin

The Mount Cattlin tantalum–lithium deposit (formerly Cattlin Creek) was investigated by Haddington Resources Ltd in 2002. At that time, the company's resource evaluation of mining lease M74/12 was downgraded to 170 000 t at 0.054% Ta_2O_5, with the result that the deposit was put on hold in terms of development (Fetherston and Searston, 2004).

Galaxy Resources Ltd was listed on the ASX in February 2007. The company had acquired the above mentioned tenement at Mount Cattlin and embarked on an intensive drilling program of 350 holes between March and July to further evaluate the resource. Final assay results announced in October 2007 yielded some very high values for tantalum and lithium. In nine significant holes, intercepts of 3–10 m returned average grades of 0.062% Ta_2O_5, and 1.4% Li_2O (20% spodumene equivalent). Maximum values from these holes reached 0.156% Ta_2O_5, and 2.21% Li_2O (32.4% spodumene equivalent) over 5 and 4 m respectively. Drilling results to date indicate the pegmatite orebody is a relatively flat-lying, sheet-like structure, situated generally between 50 and 100 m below surface but also outcropping in a number of places. A wireframe geological model of the orebody is currently being investigated as part of the continuing estimation of resources (Galaxy Resources, 2007a).

In October 2007, Galaxy Resources announced an initial resource for Mount Cattlin of 28.4 Mt at 0.012% Ta_2O_5 and 8.2% spodumene (0.56% Li_2O) for 3000 t of contained Ta_2O_5 and 2.03 Mt spodumene. Follow-up exploratory drilling on other pegmatite targets is planned commencing early in 2008. This was followed in December 2007 by a pre-feasibility study indicating that a concentrate production of 364 tpa tantalum at 25% Ta_2O_5, and 0.12 Mtpa spodumene (6.0% Li_2O) could be achieved over a ten-year mine life (MiningNews.net, 2007; Galaxy Resources, 2007b).

Galaxy Resources also has pending applications for four additional mining leases surrounding the Mount Cattlin property including M74/155, immediately to the northeast. This area overlies the North Ravensthorpe tantalum deposit, evaluated by Galaxy Resources in 2001. At that time the company drilled 116 holes and subsequently announced a measured and indicated resource totalling 0.85 Mt at 0.039% Ta_2O_5 together with an inferred resource of 0.21 Mt at 0.035% Ta_2O_5 (Fetherston, 2004).

In March 2008, the company announced that it was considering the downstream processing of spodumene from Mount Cattlin into lithium carbonate.

Other tantalum prospects

In 2006, as part of its strategy to discontinue tantalum mining and exploration activities in the Yilgarn Craton, ABM Resources NL (formerly Tantalum Australia NL) sold the Binneringie (60 km southeast of Kambalda), and Mount Deans (10 km south of Norseman) deposits to Haddington Resources Ltd. Also, the company's Norseman ball mill was sold and arrangements were in place for the disposal of plant and equipment from the Dalgaranga mine and Balcatta tantalum processing plant (Tantalum Australia, 2006). About the same time, focus on tantalum exploration in the Yinnietharra region of the Gascoyne Complex at Arthur River, Beryl Hill and other locations around 220 km east-northeast of Carnarvon appears to have shifted to uranium and rare metals (Hazelwood Resources, 2007).

Detailed accounts of previous exploration at these sites and many other tantalum deposits and prospects in the State are given in Fetherston (2004).

Titanium minerals and zircon

Perth Basin

The mid-west coastal plain

Cataby

The Cataby heavy mineral sands deposit, located about 150 km north of Perth, is owned by Iluka Resources Ltd. The deposit consists of a series of discontinuous, north-northwesterly trending strandlines extending over 20 km adjacent to the Brand Highway. This deposit was evaluated by the company in 2005 as a potential mine consisting of 13 openpits capable of producing up to 0.78 Mtpa mineral sands over a five-year period. In 2006, environmental approval was received for the project to proceed with production expected to commence in 2008. In 2007, the company was reported to be re-evaluating the deposit by drilling and bulk sampling with a view to upgrading the resource for JORC classification (Australian Mines Atlas, 2007).

Cooljarloo–Gingin

Over the last few years, Image Resources NL has applied for ten areas prospective for heavy mineral sand exploration extending over 160 km from north of the existing TiWest Cooljarloo mine to south of Gingin on the Swan Coastal Plain. Of these areas, exploration licences have been granted to date for the Cooljarloo North, Cooljarloo, and Bidaminna prospects. Preliminary ground magnetic surveys have also been carried out in the proposed Bootine, Cataby West, and Quinns Hill exploration areas, while other pending licence areas include Cowalla, Wannamal, Gingin, and McKinley prospects.

Cooljarloo North prospect

During 2006–07, ground magnetic surveys at Cooljarloo North, about 180 km north-northwest of Perth, revealed the presence of numerous, north-northwesterly trending magnetic anomalies representing possible mineralized paleostrandlines. This was confirmed by follow-up drilling traverses across seven anomalies at 200 m intervals. Of these, two highly mineralized strandline systems (Targets 1 and 2) were each found to extend continuously over 4.5 km. Target 2 is located in the north of the exploration area and comprises three subparallel strandlines. This mineralized area has produced consistently high-grade drill intersections mostly in excess of 5% heavy minerals with a maximum around 20%. Smaller Targets 3 and 5 farther west have also yielded significant preliminary results, including one intersection of 2 m at 17.8% heavy minerals from 6 m.

In mid-2007, Target 1 was renamed Hyperion Prospect (Fig. 21). Located in the southwest of the exploration licence, Hyperion has been redrilled with 259 holes on a 20 × 100 m grid to provide sufficient data for a resource estimation. Results to date indicate the strandline averages 40–60 m in width (maximum 120 m) with an average thickness of 5.0 m beneath 4.0 m of overburden. Assay results provided 530 samples in excess of 2.0% heavy minerals with 12 samples exceeding 50% (maximum 76.2%). Further assay work is continuing and Image Resources is confident that the Hyperion Prospect will prove to be an economic heavy mineral sands deposit (Image Resources, 2007a).

Cooljarloo prospect

The Cooljarloo prospect adjoins the ground held by TiWest's Cooljarloo heavy mineral sands mine and is situated on heavy mineral strand lines extending northwest from the mine. This area has yielded a total of 95 km of strandline targets identified by ground magnetic surveys and follow-up aircore drilling. This program has identified a possible new channel-style mineralization situated beneath existing mineralized strandlines. In this model, steep-sided, mineralized channels at least 200 m wide have the potential for large tonnages of contained heavy minerals. These channels were discovered by scout drilling, which identified an upper strandline zone that included intersections of 2.0 m at 9.2% heavy minerals from 16 m. The upper zone was found to overlie channels about 200 m wide that contained up to 12 m of channel sand at 2.7% heavy minerals from 28 m (Image Resources, 2006).

By May 2007, drilling had identified mineralized strandlines over 22 km of strike. Some of the better intersections yielded zones of 5, 3, and 2 m with heavy mineral grades of 42.6, 41.7, and 45% respectively. The exploration program is continuing (Garvey, 2007).

Bidaminna prospect

The Bidaminna prospect, about 25 km northwest of Gingin, contains four strandline systems named Callisto, Amalthea, Europa, and Ganymede. Follow-up drilling has identified a central high-grade mineralized zone in the Callisto and adjoining Ganymede strandlines, as well as an additional high-grade zone in the south of Callisto. In these target areas, grades were consistently above 2.5% contained heavy minerals. A 500 m wide zone in the north of the exploration area yielded the best intersection of 12 m at 5.4% heavy minerals from 34 m (Image Resources, 2006).

Bootine prospect

At the Bootine prospect, about 22 km north-northwest of Gingin, a recently-flown aeromagnetic survey identified over 30 northwest-trending, heavy mineral sand targets with a total length in excess of 87 km. It is thought that the mineralized strandline currently being mined at the Gingin mine may extend into the Bootine prospect. Image Resources is currently conducting a follow-up ground magnetic survey with 120 km of line surveying having been completed to date (Image Resources, 2007b).

The southwest coastal plain

Exploration by Bemax Resources

Bemax Resources Ltd currently holds tenements over a number of mineral sands deposits in the southwest coastal plain including Kemerton, Hopelands East, Jangardup

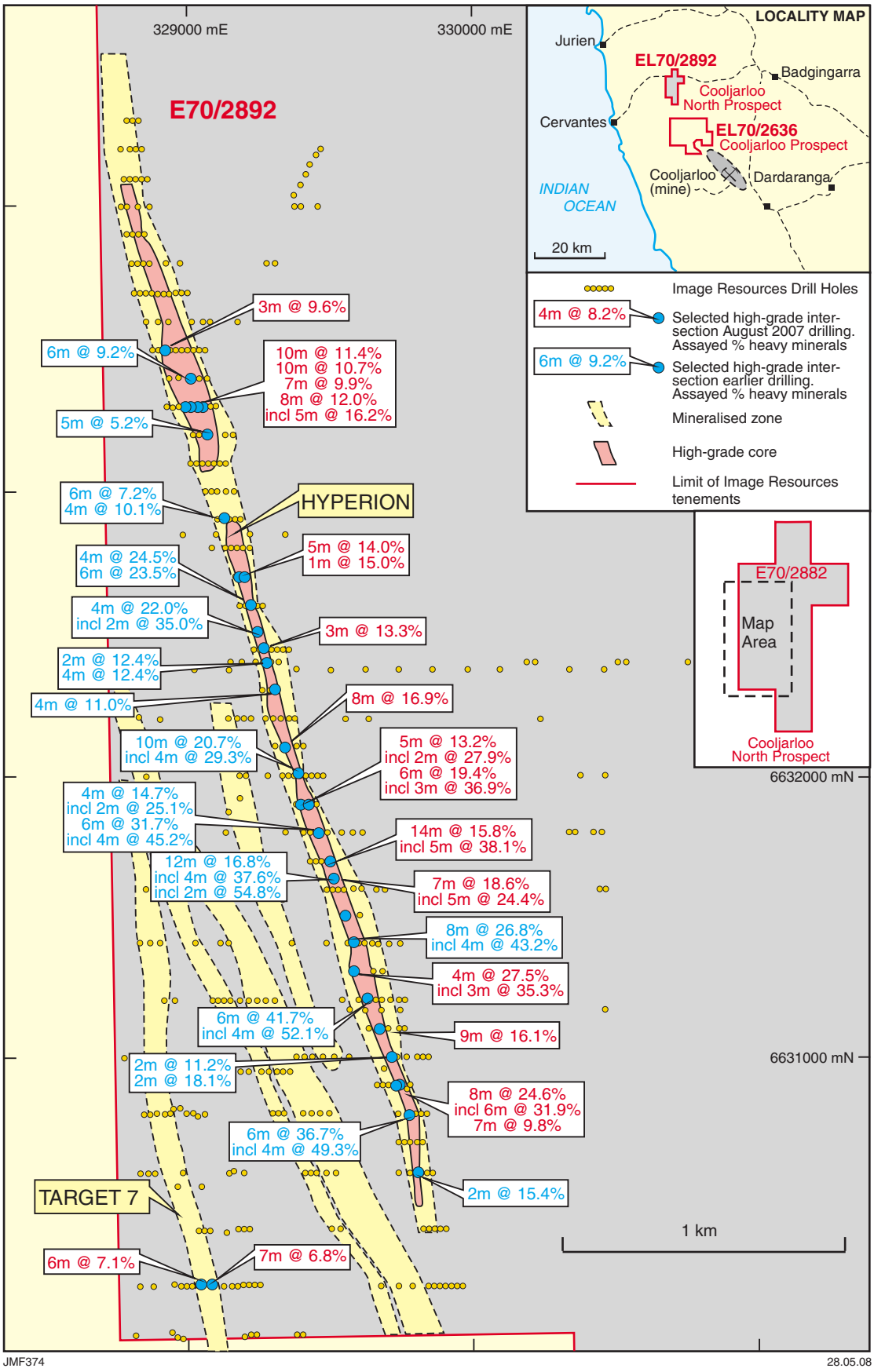

Figure 21. High-grade mineral sands drillhole intersections from the Hyperion prospect in the Cooljarloo North exploration area (modified after Image Resources, 2007a)

Table 2. Bemax Resources exploration areas, 2006

Deposit	*Location*	*Tenement numbers*	*Resources*	*Heav mineral grade (%)*
Kemerton	6 km southeast of Binningup	M70/871, 986–987	8 Mt (measured and indicated)	12.15 (average)
Hopelands East	22 km southeast of Rockingham	M70/599–603	19 Mt (indicated)	10.6
Hassell Beach	50 km east of Albany	M70/562	4 Mt (indicated)	11.9
Jangardup South	47 km east-southeast of Augusta	E70/588–589, M70/993	25 Mt (measured)	10.4
Four Acres	8 km northwest of Jangardup minesite	R70/22	1 Mt (indicated)	11.0

SOURCE: Bemax Resources (2006)

South and Four Acres, as well as Hassell Beach east of Albany in the Albany–Fraser Orogen, that were explored prior to 2004. These deposits, averaging 80% ilmenite and 10% zircon, have been retained by the company as additional resources that may be accessed in future years and are listed in Table 2 (Bemax, 2006).

Exploration by Iluka Resources

Exploration by the Illuka Resources Ltd in the southwest region has continued over the years at Hopelands, Dardanup and Elgin, and more recently in 2007 at Tutanup South, where exploration drilling was scheduled to take place. To date, no details have been released.

Exploration by Olympia Resources

Keysbrook South and Coolup deposits

Discovered by Olympia Resources Ltd in 2005, the Keysbrook South and Coolup deposits are located respectively 10 km northeast and 14 km south-southeast of Pinjarra. These deposits, discovered during a 556 drillhole exploration program, were found to contain grades similar to those of the Keysbrook deposit, with indicated resources of 13.6 Mt at 2.24% heavy mineral sands for 0.31 Mt contained heavy minerals at Keysbrook South, and 2.0 Mt at 6.0% heavy mineral sands for 0.12 Mt contained heavy minerals at Coolup. The company intends to use the combined resources from these deposits (totalling 15.6 Mt at 2.7% at a 1.5% heavy mineral cutoff grade) to extend the estimated eight-year life of the Keysbrook mine by an additional three years (Olympia Resources, 2005b).

Pinjarra

Located east of Pinjarra and 20 km south of the Keysbrook deposit, this heavy mineral prospect was discovered by an initial drilling program in 2005. This exploration indicated that mineralization in this prospect appears similar to that in the nearby Keysbrook deposit. Further drilling to define a resource for the Pinjarra prospect was due to commence in 2006 (Olympia Resources, 2005c), but no information has been announced since then.

Yalyalup

Prospected in 2006, the Yalyalup deposit located 14 km southeast of Busselton, has the potential to be an operating mine with a 5–10 year mine life pending the successful outcome of further drilling and metallurgical work. An initial drilling program of 36 holes outlined an inferred resource of 19.9 Mt at 5.5% heavy minerals sands for 1.1 Mt contained heavy minerals using a 2% cutoff grade. Exploration of the site indicated that mineralization was contained in two paleostrandlines with average heavy mineral contents for ilmenite and altered ilmenite (21%), leucoxene (41%), and zircon (13%). The strandlines were found to be separated by a strongly mineralized beach placer environment with an average heavy mineral content for ilmenite and altered ilmenite (85%) and zircon (8%; Olympia Resources, 2006b).

Capel North and South

Olympia Resources owns four exploration licences in areas around Capel and Busselton. The Capel North prospect extends northeast from Capel to Boyanup whereas the Capel South prospect surrounds the Yalyalup deposit east of Busselton. These exploration areas contain a number of exploration targets identified from local geomorphology, and follow-up drilling will be undertaken as access agreements and approvals are obtained. In the June quarter of 2006, some drilling was carried out east of Elgin in the Capel North exploration area, but results are yet to be announced (Olympia Resources, 2007b).

Other deposits

Olympia Resources also owns a number of heavy mineral sand deposits with defined resources in the Southwest on which little follow-up activity appears to have occurred. These properties include Ambergate, with measured and indicated resources of 6.82 Mt at 6.1% heavy minerals sands for 0.41 Mt contained heavy minerals, The Loop with inferred resources of 11.5 Mt at 7.2% heavy minerals sands for 0.82 Mt contained heavy minerals, and North Dandalup with inferred resources of 9.7 Mt at 4.5% heavy minerals sands for 0.49 Mt contained heavy minerals (Olympia Resources, 2005b).

Eucla Basin

Balladonia–Esperance

In this area, situated on the western margin of the Eucla Basin, Mineral Sands Ltd currently holds extensive

areas of ground under exploration licences in the search for heavy mineral sand deposits. The first of these exploration projects, known as 'Pioneer', is centred on an area approximately 60 km north of the Balladonia Hotel located on the Eyre Highway. The second project, named 'Newmont', is located around 160 km northeast of Esperance.

Pioneer project

In March 2007, Mineral Sands completed a reconnaissance aircore drilling program of 100 holes on the Pioneer tenements (E28/1554, 1601 and 2089). Results from the analysis of samples collected gave 28 holes returning grades of between 1.00 and 4.26% heavy minerals. Of these, 14 holes returned grades of >10% zircon, and six holes >20% zircon, both contained in the heavy mineral fraction. Maximum recorded value for contained zircon in the heavy mineral fraction was 42.4% in one sample. The drilling program delineated at least two zones of heavy minerals associated with a sand accumulation against a basement high, similar to the exploration model present at the zircon-rich Jacinth and Ambrosia deposits on the eastern margin of the Eucla Basin (Mineral Sands, 2007a).

Following the successful drilling program, Mineral Sands Ltd and Olympia Resources Ltd formed a joint venture in September 2007 to continue the exploration of three contiguous exploration licences (E69/2090–2092) for zircon-rich mineral sands (Industrial Minerals, 2007).

Newmont project

Based on previous drillhole intersections of 1.5% heavy minerals, containing up to 26.3% zircon from this area and following the granting of three new exploration licences, Mineral Sands Ltd announced it was embarking on an extensive drilling program commencing in the third quarter of 2007 to test for zircon-rich, paleobeach heavy mineral deposits related to headland trap sites (Mineral Sands, 2007b).

Wanna Lakes

In May 2007, Diatreme Resources Ltd in a joint venture with Minerals Corporation Ltd (75% and 25% respectively) announced the commencement of a drilling program for heavy mineral sands at their Wanna Lakes deposit, situated on the northern fringe of the Eucla Basin about 60 km west of the South Australian border and 700 km east-northeast of Kalgoorlie. In this area the Company holds a northeast-trending exploration licence almost 40 km in length (E69/1920) that follows interpreted heavy mineral strandlines along the paleoshoreline of the Eucla Basin.

By July 2007, reconnaissance air core drilling indicated the presence of two heavy mineral sand line systems; at the Cyclone deposit in the southeast of the exploration area, and the Hurricane prospect about 25 km to the northwest. At Cyclone, 100 m-spaced drilling indicated the presence of high-grade zircon-rich mineralization over 2.3 km within 15–17 m of the surface. Several high-grade cores comprised 40% heavy mineral content with zircon estimated up to 50% of the heavy minerals. The high-grade zones appear to be surrounded by a 20 m-thick envelope averaging 1% heavy minerals. Reconnaissance drilling of a mineralized zone 12 m deeep at Hurricane prospect gave estimated heavy mineral grades of 10% over 2 m, and 3.8% over 4.5 m in two holes 10 km apart (Diatreme Resources, 2007a).

Drilling continued in 2007 at Cyclone deposit, where a high-zircon concentration of heavy minerals was encountered over 1.5 km in length in drillhole Line 6. In this zone 52 samples averaged 40.02% zircon, 37.99% leucoxene, 3.12% rutile, 10.7% 'pseudo-rutile', 0.26% monazite, minor ilmenite, and low slimes (3%). In October 2007, the company announced that of the 276 holes drilled, 117 holes recorded heavy mineral contents >1% with the highest assay reaching 18.3% (Diatreme Resources, 2007b). Interpretation of drillhole data at Cyclone has indicated the presence of two mineralized, parallel beach strand lines separated by a partially mineralized barrier dune (Dune T1). The western transgressive beach line (Beach T1) is 1 km wide, ranges from 4 to 35 m thick, and represents the target horizon for heavy minerals. On the eastern side of Dune T1 a regressive beach line has been identified (Beach R2) at least 1 km wide (Fig. 22). Several kilometres farther east, another parallel, regressive beach has been located (Beach R3). This regressive, high-stand beach has been interpreted from digital terrain modelling and is yet to be investigated (Diatreme Resources, 2007c).

In February 2008, the company announced an inferred resource for Cyclone of 60 Mt at 3.1% heavy minerals. The heavy mineral content of this resource was estimated at 1.8 Mt with a heavy mineral concentrate assemblage of zircon (41%), leucoxene (42%), ilmenite (10%), rutile (3%), and waste (4%; Diatreme Resources, 2008).

In mid-2008, Diatreme Resources was granted a second contiguous exploration licence (E69/2408) of similar size along the northeast boundary of E69/1920. The company also has a number of other exploration licence applications in the Wanna Lakes area and also 80 km to the south-southeast at Forrest Lakes for future exploration.

Southern Carnarvon Basin

Yaringa

The Yaringa mineral sands exploration area, located about 250 km north of Geraldton, comprises eight exploration licences that lie immediately east and southeast of the Coburn mineral sands project in the Shark Bay area. The area was formerly held by Mineral Securities Ltd from 2004 to 2006 based on a pre-exploration, indicated–inferred resource estimate of 710 Mt at 1.4% heavy minerals containing 24% zircon (Register of Australian Mining, 2006/07).

In 2007, the project was taken over by Mineral Sands Ltd. In May of that year the company carried out an 84-hole drilling program focusing potential barrier beach systems similar to those present in the nearby Amy Zone of the

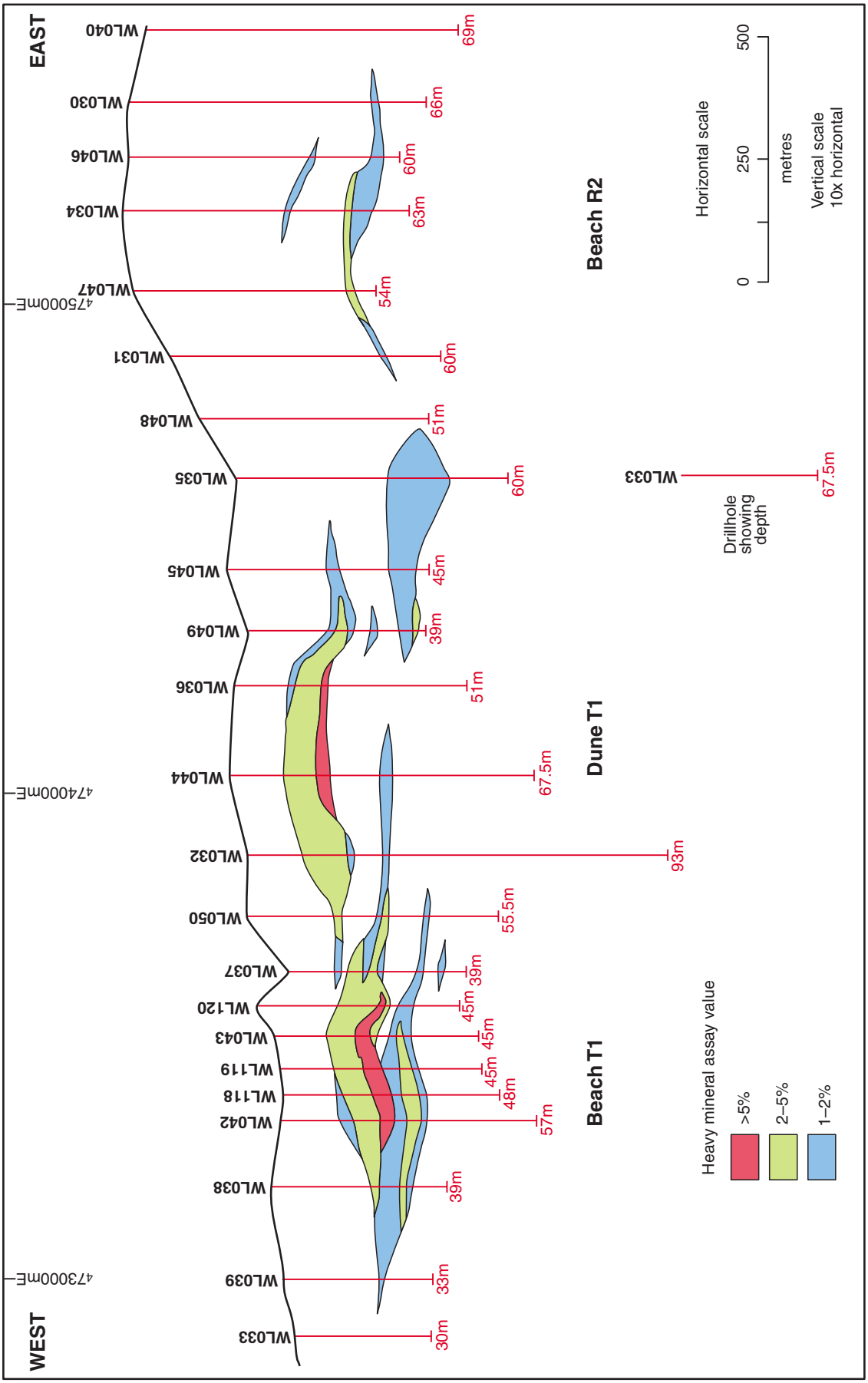

Figure 22. Cross section along drill line 6, at Cyclone mineral sands prospect at Wanna Lakes, northern Eucla Basin. Section shows zircon-rich, mineralized beach strand lines and barrier dune (modified after Diatreme Resources, 2007b)

Coburn mineral sands project. Of the 1495 m drilled, only a few low-grade mineralized areas were located with maximum grades between 1.0–1.6% heavy minerals, but no substantial mineralized beach systems were found and the tenements were subsequently relinquished (Mineral Sands, 2007c).

Canning Basin

Pender

Matilda Minerals Ltd currently has seven granted exploration licences plus an additional two applications covering 1600 km^2 of the Pender Peninsula from 60 km north of Broome and extending 130 km north-northeast to Cape Leveque. In this region, inland from modern coastal shoreline deposits, is an area of sand plain comprising older Cenozoic strandline and beach dunal environments. Based on earlier reports of a site containing a substantial concentration of heavy minerals with elevated zircon and rutile levels, it is possible the region may host paleostrandlines with significant heavy mineral content. The company is currently negotiating with government agencies and the Kimberley Land Council over issues relating to access and heritage surveys (Matilda Minerals, 2006).

King Sound

Samples taken by Carr Boyd Minerals in 1971 from the southern end of King Sound were found to contain heavy minerals up to 22.7% comprising 12.1% ilmenite, 3.5% zircon and 1.1% magnetite. High values for heavy minerals in the area were confirmed by an auger-hole survey conducted by Metal Investment Pty Ltd in that same year. To follow up on this earlier heavy mineral exploration, Strike Resources Ltd has applied for three exploration licences over the southern extent of King Sound and surrounding land about 15 km southwest of Derby (Strike Resources, 2007).

Kimberley Basin

Durack Range

Following a reconnaissance sampling program, Northern Mining Ltd in association with Quaalup Investments Pty Ltd have announced the discovery of heavy mineral concentrations of up to 19.3% TiO_2 and 7.34% ZrO_2 contained in an extensive purple sandstone unit within the Proterozoic Carson Volcanics in the Durack Range about 125 km north-northwest of Halls Creek. The sandstone unit also contains anomalous values for molybdenum of up to 0.3% (Northern Mining, 2007).

Ord Basin

Ord River project

Matilda Minerals is to explore an area of the floodplain surrounding the Ord River, 35 km upstream from Lake Argyle, and about 120 km south of Kununurra. The Ord River project area covering 150 km^2, will be focused on the search for paleochannels containing large tonnage, moderate-grade heavy mineral deposits. Previous exploration in 1989 located numerous, variable surface concentrations of heavy minerals with an average grade varying between 5 and 15%. Preliminary investigations by Matilda Minerals indicate the two main minerals present in this section of the floodplain are ilmenite (46%) and zircon (7%) (Matilda Minerals, 2007).

Southern Bonaparte Basin

Medusa Banks

Matilda Minerals has an exploration licence 110 km north-northwest of Kununurra on Cambridge Gulf near the mouth of the Ord River. This exploration area, known as the Medusa Banks project, is situated in an area of coastal strandlines that were identified in 1970 as a source of ilmenite, zircon and rutile possibly derived from Archean and Proterozoic metamorphic rocks in the region. At that time, heavy mineral concentrations, some as high as 5–8%, were found in this environment (Matilda Minerals, 2007).

Vanadium

Yilgarn Craton – Murchison Terrane

Barrambie

During 2005, a substantial increase in the price of vanadium on world markets caused Reed Resources Ltd to re-assess the Barrambie deposit, located 115 km southeast of Meekatharra, as a recoverable vanadium deposit with titanium as a byproduct.

At Barrambie, vanadium–titanium mineralization is associated with the 400 m-thick Archean Barrambie Igneous Complex, a layered, anorthosite–gabbro intrusion. In this structucture, mineralization is contained within a series of parallel, steeply dipping, north-northwesterly trending magnetite-rich bands that extend over a strike length in excess of 11 km. Along its length, the structure has been dislocated in places by minor faulting. Within the magnetite bands, vanadium–titanium mineralization is developed as two distinct ore types. The first of these, comprising the Main Zone, consists of a massive, vanadiferous magnetite–ilmenite as cumulative segregations of approximately 80% magnetite and ilmenite in bands and lenses ranging from <1 to >20 m thick. The second ore type, in the massive Eastern Zone, is dispersed throughout the basal anorthosite gabbro as disseminated and massive vanadiferous granular magnetite–ilmenite (Fig. 23; Collins, 2005).

During the first half of 2007, an intensive drilling program focused on the Eastern and Central magnetite bands within the Bay and Cove segments in the southern half of the orebody. Total indicated and inferred resources to date are 23.6 Mt at 0.82% V_2O_5, 17.9% TiO_2, and 48.5% Fe_2O_3 at a block cutoff grade of 0.5% V_2O_5 (Reed Resources, 2007).

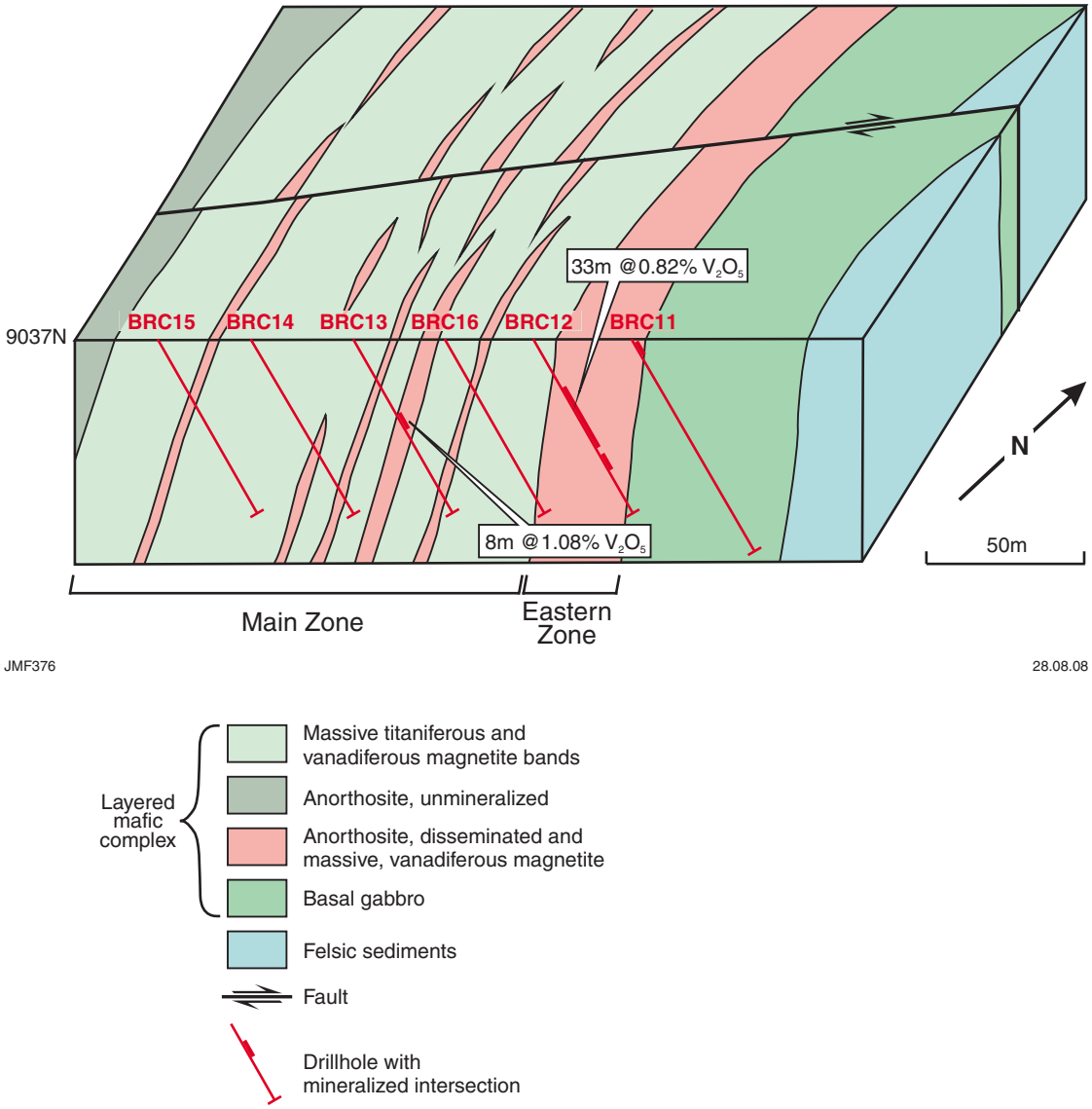

Figure 23. Two styles of mineralization present at Barrambie vanadium deposit: a) Main zone: massive titaniferous and vanadiferous magnetite bands; b) Eastern zone: disseminated and massive vanadiferous granular magnetite–ilmenite dispersed throughout the basal anorthosite gabbro (modified after Collins, 2005)

Gabanintha

Gabanintha, 48 km southeast of Meekatharra, formerly owned by Greater Pacific Gold Ltd, entered a new exploration phase early in 2007 with new owners Yellow Rock Resources Ltd. Following a detailed aeromagnetic survey flown over the orebody in 2006, Yellow Rock Resources completed a new drilling program to determine the indicated resource over 9.5 km of the orebody within their exploration tenements.

The Gabanintha orebody has been described as a magnetite–vanadiferous ilmenite hosted by an anorthositic gabbro that was intruded along the boundary of an Archean sequence between a massive basalt and intermediate to felsic volcanic and sedimentary rocks. The structure containing the gabbro, extends in a north-northwesterly direction for over 14 km, dipping to the southwest between 50–60° (Yellow Rock Resources, 2006). Within the gabbro, the vanadium mineralization is contained within a series of two or three extensive titaniferous magnetite bands and elongated lenses orientated roughly parallel to the structural alignment of the gabbro.

In July 2007, Yellow Rock Resources Ltd completed a 42-hole reverse circulation drilling program over 3876 m. This drilling program, combined with data obtained from previous exploration programs, provided sufficient information to construct an initial block model of the orebody over 9.5 km of strike followed by an estimate of indicated resources of 92.5 Mt at 0.81% V_2O_5, 9.81% TiO_2, and 51.20% Fe_2O_3 (Yellow Rock Resources, 2007).

Pilbara Craton

Balla Balla

The Balla Balla vanadium–magnetite project, currently owned by Aurox Resources Ltd, is located about 100 km southwest of Port Hedland and 10 km north-northwest of Whim Creek. The Balla Balla project now incorporates the Don Well deposit formerly owned by Ashbridge Holdings Pty Ltd.

Currently Australia's largest vanadium–titanomagnetite deposit, the Balla Balla structure is an irregular, faulted, tabular body of vanadiferous titanomagnetite (containing significant quantities of ilmenite) that extends for about 16 km in an east–west direction. The magnetite-rich orebody is between 18 and 35 m thick and dips 20–50° to the northeast. In the upper 15 m regolith zone, weathering has partially altered the magnetite to hematite. On its eastern end the orebody has been subdivided into the Western, Central, and Eastern deposits (Murphy, 2002). The orebody is estimated to contain overall resources of 303 Mt at 0.65% V_2O_5, 43% Fe and 13% Ti (Mining Journal, 2006).

In late 2006, Aurox Resources completed a detailed test drilling program focused on a 5 km east–west section of the orebody, containing their bankable feasibility study (BFS) area incorporating the Western and Central deposits. The drilling program resulted in a substantial increase in ore reserves to proven and probable JORC-compliant reserves of 103.9 Mt at 45.7% Fe and 0.63% V_2O_5.

Early in 2007, it was announced the project would be developed in two stages with the first stage involving the development and operation of an on-site 3 Mtpa titanomagnetite concentration plant. The second stage will involve the construction and operation of a vanadium concentration circuit that will run alongside the titanomagnetite plant. At that time, the company also signed an offtake agreement with Chengde Iron and Steel, a Chinese steel–vanadium producer, for 3 Mtpa over 15 years. The bankable feasibility study in support of this agreement covering mining, production and transport of 3 Mtpa of iron ore concentrate from the BFS his area was completed in mid-2007 (Aurox Resources, 2007a).

In July 2007, the company announced a second 3 Mtpa off-take agreement with RockCheck Steel Group. This brings the total amount of contracted concentrate to 6 Mtpa and Aurox Resources is currently upgrading its bankable feasibility study to reflect the required doubling of output (Aurox Resources, 2007b).

Other deposits

Other vanadium deposits investigated pre-2002 include Unaly Hill, about 115 km east-southeast of Mount Magnet, Youanmi, 120 km southeast of Mount Magnet, Buddadoo, 130 km west-northwest of Paynes Find, and Nowthanna, about 55 km southeast of Meekatharra. Some of these deposits are summarized in Fetherston and Abeysinghe (2000) and Fetherston and Searston (2004).

Summary

Western Australia is the nation's most resource-rich State, with a diversity of significant mineral output that is almost unequalled in the world marketplace. In 2006–07, the State's industrial mineral production was valued at approximately $2558 million. This represents about 7% of the value of total mineral production (excluding petroleum) for the State in that year.

Western Australia is a leading world producer of many industrial minerals. For example, in 2007 the State was the world's largest producer by weight of tantalite (61%), zircon (25%) and the titanium mineral rutile (22%). The State was also the second-largest world producer of the lithium mineral, spodumene (22%), industrial diamonds (21%), and the titanium mineral ilmenite (13%). Another key industrial mineral was salt (sixth-largest world producer at 4%).

Geologically, the State has major untapped potential for industrial minerals in a variety of settings, and a number of identified deposits are targets for current and future development. Currently, Bemax Resource's Gwindinup and Happy Valley mineral sand operations in the Bunbury area are ramping up initial production. Significant projects coming into production include Lynas Corporation's Mount Weld rare earths deposit near Laverton, with resources totalling around 15 Mt rare earth oxides. In full production, this operation should make Western Australia the world's second-largest producer of rare earth oxides. Also included is Windimurra Vanadium's recommissioning of the Windimurra vanadium deposit in the Mount Magnet region, and south of Shark Bay, Gunson Resources zircon-rich Coburn mineral sands project is in final feasibility stage. Other projects currently under consideration include the Ant Hill and Sunday Hill manganese deposit in the East Pilbara, the Mount Cattlin tantalum deposit at Ravensthorpe, and mineral sand deposits at Cataby and the Hyperion deposit at Cooljarloo North.

In Western Australia, virtually all near-surface rocks have been affected to some degree by deep-weathering processes that have controlled landscape evolution since at least the end of the Permian. As a result, much of the State's fresh bedrock is covered by regolith of varying thickness. In many places, deep-weathering profiles in excess of 40 m have developed. The development of most industrial mineral deposits has in some way been affected by regolith processes, sometimes resulting in enrichment of orebodies. In general, most of the State's industrial mineral deposits have evolved within three broad regolith types: residual or relict ferruginous duricrusts; alluvial/fluvial and lacustrine paleodrainage deposits; and Cenozoic coastal regolith deposits.

Major industrial minerals produced in Western Australia include titanium minerals, zircon, diamond, salt, manganese, tantalum, speciality aluminas, spodumene, garnet, and gypsum. A number of other minerals are also mined to service key markets both locally and overseas. These include limestone and limesand supplying the cement, mining, agriculture, and building

stone industries. High-grade silica rock is used for the manufacture of silicon metal, which is then largely alloyed with aluminium for applications in the automotive and aerospace industries. Silica sand is exported to South East Asia for the glass, ceramic, foundry, and silicon chemical industries. Talc mined from two centres has found applications in paint, paper, plastic, and cosmetic industries in a number of overseas and domestic markets. Two forms of clays, attapulgite and bentonite, find uses as industrial and domestic absorbents, geotechnical sealants, and soil conditioners. Other industrial mineral industries include dimension stone that is current showing signs of a resurgence in demand, as well as iron oxide pigments for the paint industry, and a variety of spectacular semiprecious stones.

Since 2006, major exploration projects have included extensive exploration for heavy mineral sands deposits, particularly for those rich in zircon. The main focus by explorers has been in the Cooljarloo area in the mid-west coastal plain of the Perth Basin. Deposits such as Cataby have been identified for future mining, and the new Hyperion deposit at Cooljarloo North appears extremely prospective. Other areas of interest include the Cooljarloo prospect, as well as mineral sands targets around Biddaminna and Bootine. Another newly discovered, zircon-rich mineral sand is contained within the prospective Cyclone deposit at Wanna Lakes in the Eucla Basin, close to the border with South Australia.

Considerable interest has been shown in the exploration for manganese, particularly in the east Pilbara manganese province. Exploration in this area has been focused on the deposits at Ant Hill and Sunday Hill with a view to establishing an offshore, downstream electrolytic manganese dioxide (EMD) plant for the manufacture of advanced dry-cell batteries. Other areas of interest for manganese have included the South Woodie Woodie deposit, and in the Bryah Basin to the south, around the old Horseshoe South deposit.

The interest in exploration for rare earth elements continued in 2007–08 at the Cummins Range carbonatite deposit, south-southeast of Halls Creek in the east Kimberley region. Recent exploration has identified a high-grade, open-ended zone with estimated resources in excess of 1.0 Mt of predominantly light rare earths.

In 2007, a new drilling program was initiated at at the Mount Cattlin tantalum–spodumene deposit, near Ravensthorpe in the far south of the State. Data from significant drillholes provided an initial resource estimate of 28.4 Mt of tantalite (Ta_2O_5) and spodumene (Li_2O). Feasibility studies are continuing.

The search for commercial vanadium deposits accelerated in 2006–07 with three deposits reporting substantial resources. Balla Balla, Australia's largest vanadium–titanomagnetite deposit, located near Whim Creek in the Pilbara region, reported overall resources of 303 Mt at 0.65% V_2O_5. Farther south in the Yilgarn Craton, two vanadium-rich titanomagnetite deposits located in the Meekatharra region are the Barrambie and Gabanintha deposits with resources of 23.6 Mt at 0.82%, and 92.5 Mt at 0.81% V_2O_5 respectively.

The most encouraging results in diamond exploration in 2006–07 were obtained at the Blacktop 1 kimberlite dyke south of Karratha in the Pilbara Craton. At this location, 2320 diamonds were recovered with a total weight of 163.89 ct with the largest stone weighing 1.41 ct. Since that time, exploration has targeted two new kimberlite dykes at Blacktop East.

In 2007, feasibility studies into two new solar salt projects on the Pilbara coast were announced. The first of these, the Onslow salt project covers extensive areas of the coast in the Onslow area and adjoins the existing Onslow salt field operated by Mitsui & Co Ltd. The second project, at Yannerie, is situated along 70 km of the eastern shoreline of Exmouth Gulf. It is proposed to develop this project as a 10 Mtpa salt field with a central handling facility and port at Hope Island. Investigations on the feasibility of both projects are continuing.

Other exploration programs of significance since 2006, included the re-examination of the Speewah fluorite deposit in the East Kimberley region that resulted in some notable drillhole intersections for fluorite. Pilot plant trials were successfully completed for high-quality kaolin from the Meckering and Jacobs Well areas in the South West Terrane of the Yilgarn Craton for potential paper- and ceramic-grade applications. Exploration for new sources of marble as dimension stone was carried out in the Edmund Basin resulting in the discovery of visually attractive cream and pink marbles in the Nanutarra area, and pale-green marbles at Maroonah Station. An unusual form of exploration for potash took place at Lake Disappointment in the Officer Basin. This program involved the drilling of muddy lake sediments to successfully establish an upper potash resource estimate of 8635 Mt at 3.17 kg/t.

There are abundant opportunities for the development of industrial mineral projects in Western Australia. Currently, a number of key industries are carrying out downstream mineral processing, particularly in the mineral sands industry, resulting in the processing of white titanium pigment, fused zirconia and zirconium chemicals. Other advanced processing includes the manufacture of silicon metal, and calcined, hydrated and fused aluminas, as well as high-grade concentrates of tantalite, spodumene, garnet, and silica sand destined mainly for export. The ready availability of natural gas to preferred industrial development areas of the South West, especially the Perth–Bunbury region, and resource-rich areas in the rapidly developing Pilbara and Eastern Goldfields, is already making substantial improvements to the State's mineral-processing potential.

Cost-efficient container and bulk-handling shipping facilities have been important factors in establishing export competitiveness. In recent years, handling facilities at a number of the State's ports have been upgraded, with a substantial upgrade completed at Geraldton in 2007. In addition, the proposed port of Oakajee, a few kilometres north of Geraldton, will greatly enhance the region's bulk

handling capacity for minerals when completed. Other strategically located ports of Esperance, Albany, Bunbury, Fremantle, Kwinana, Dampier, Port Hedland, Broome, and Wyndham, continue to provide efficient facilities for shipping around the State's coastline.

Considerable effort is being applied to promoting industrial mineral developments by industry groups such as the Western Australian Chamber of Minerals and Energy, and the Chamber of Commerce and Industry, and by the Western Australian State Government through regional development agencies, and the Department of Industry and Resources through assistance in research, market development and promotion of the State's diverse industrial mineral sector.

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Appendix 1

Location of mines, quarries, and exploration project areas

Name	*Operation*	*Status*	*Location*	*MGA zone*	*Easting*	*Northing*
CLAYS						
Attapulgite						
Yilgarn Craton–Murchison Terrane						
Lake Nerramyne	Quarry	Operating	140 km northeast of Geraldton	50	346353	6926091
Bentonite						
Pinjarra Orogen						
Watheroo Lake A	Quarry	Operating	21 km north-northwest of Watheroo	50	401525	6667185
Watheroo Lake E	Quarry	Operating	19 km north-northwest of Watheroo	50	399530	6663445
Construction clay						
Perth Basin						
Bullsbrook	Quarry	Operating	45 km northeast of Perth	50	409755	6495841
Byford	Quarry	Operating	35 km southeast of Perth	50	407583	6430384
Muchea	Quarry	Operating	55 km north-northeast of Perth	50	407009	6509901
Swan Valley	Quarries	Operating	35 km northeast of Perth	50	[(a)]408258	[(a)]6485312
Yilgarn Craton–South West Terrane						
Bakers Hill	Quarries	Operating	70 km east-northeast of Perth	50	448682	6497113
Goomalling	Quarry	Closed	115 km northeast of Perth	50	467184	6536089
Jimperding Hill	Quarries	Operating	70 km northeast of Perth	50	[(a)]436963	[(a)]6503343
Mount Kokeby	Quarry	Operating	105 km east-southeast of Perth	50	488935	6429214
Kaolin						
Yilgarn Craton–Murchison Terrane						
Mount Gibson	Deposit	Exploration pre-2000	175 km northeast of Moora	50	533842	6727356
Mullewa	Deposit	Exploration pre-2000	100 km east-northeast of Geraldton	50	357929	6849605
Yilgarn Craton–South West Terrane						
Gabbin	Deposit	Exploration pre-2000	115 km west-northwest of Merredin	50	561650	6615609
Goomalling	Deposit	Care and maintenance	132 km northeast of Perth	50	–	–
Jacobs Well	Prospect	Pilot plant trials	125 km east of Perth	50	513983	6454990
Jacobs Well South	Prospect	Pilot plant trials	125 km east of Perth	50	513394	6448337
Jubuk	Deposit	Exploration pre-2000	185 km east-southeast of Perth	50	565000	6413215
Kerrigan	Deposit	Exploration pre-2000	160 km east-northeast of Narrogin	50	671742	6384857
Meckering Trial Pit	Deposit	Pilot plant trials	125 km northeast of Perth	50	505540	6494949
Mount Kokeby	Deposit	Abandoned	105 km east-southeast of Perth	50	487530	6427960
Ockley–Wickepin	Deposit	Exploration pre-2000	50 km east-northeast of Narrogin	50	567999	6367501
Tambellup	Deposit	Exploration pre-2000	110 km north-northwest of Albany	50	554125	6231857
DIAMOND						
Canning Basin						
Leonard Shelf						
Ellendale 4	Mine	Operating	140 km east-southeast of Derby	51	704083	8045035
Ellendale 9	Mine	Operating	140 km east-southeast of Derby	51	696953	8057143
Walgidgee Hills	Prospect	Exploration 2008	170 km southeast of Derby	51	697260	7974548
Edmund Basin						
Ullawarra	Prospect	Exploration 2005	170 km west-southwest of Paraburdoo	50	407425	7402438

Halls Creek Orogen						
Argyle	Mine	Operating	120 km south-southwest of Kununurra	52	434750	8152221
Wood River	Prospect	Exploration 2008	180 km west Argyle mine	52	[a]291625	[a]8147968
Kimberley Basin						
Moonlight Valley	Prospect	Exploration 2006	150 km north-northeast of Fitzroy Crossing	52	193653	8123147
Phillips Range	Deposit	Exploration 2005	150 km north-northeast of Fitzroy Crossing	52	194294	8129598
Paterson Orogen						
Runton	Prospect	Exploration 2005	375 km east of Newman	51	[a]533750	[a]7433195
Pilbara Craton						
Hamersley Basin						
Blacktop	Prospect	Exploration 2006	90 km south-southwest of Karratha	50	459651	7623193
Caduceus	Prospect	Exploration 2006	70 km north-northwest of Tom Price	50	550460	7554163
DIATOMITE						
Perth Basin						
Badgingarra	Mine	Care and maintenance	75 km west-northwest of Moora	50	342395	6646021
Dongara	Deposit	Exploration pre-2000	25 km southeast of Dongara	50	318407	6749292
Drak	Deposit	Exploration pre-2000	65 km west-northwest of Moora	50	349211	6642938
Mathawandry	Prospect	Exploration pre-2000	30 km west-northwest of Moora	50	379148	6619568
Tara 1	Deposit	Exploration pre-2000	25 km southwest of Moora	50	386748	6590766
Tara 2	Deposit	Exploration pre-2000	25 km southwest of Moora	50	386303	6590503
Yeal Swamp	Prospect	Exploration pre-2000	60 km north of Perth	50	382304	6518917
Yere Yere	Deposit	Exploration pre-2000	30 km west-northwest of Moora	50	377664	6616600
DIMENSION STONE						
Black granite						
King Leopold Orogen						
Wombarella Creek						
Kimberley Black	Quarry	Care and maintenance	150 km east-northeast of Derby	51	703448	8095004
Granite						
Albany–Fraser Orogen						
Albany						
Willyung Hill Granite	Quarry	Operating	10 km north-northwest of Albany	50	577586	6132791
Esperance						
Desert Brown	Quarry	Operating	14 km east-northeast of Esperance	51	410430	6259956
Fraser Range						
Garnet Ice	Quarry	Care and maintenance	85 km east-northeast of Norseman	51	468506	6450470
Verde Austral	Quarry	Operating	100 km east of Norseman	51	485027	6435557
King Leopold Orogen						
Wombarella Creek						
Kimberley Pearl	Quarry	Care and maintenance	150 km east-northeast of Derby	51	702459	8094035
Kimberley Storm	Quarry	Care and maintenance	150 km east-northeast of Derby	51	702512	8093613
Yilgarn Craton–Murchison Terrane						
Boogardie	Quarry	Care and maintenance	35 km west of Mount Magnet	50	547729	6895980
Yilgarn Craton–South West Terrane						
Albany Green	Quarry	Care and maintenance	10 km west-southwest of Jerramungup	50	665181	6235626
Austral Juperana	Quarry	Operating	220 km east of Perth	50	613719	6454019
Austral Waterfall	Quarry	Operating	220 km east of Perth	50	613378	6453655
Laguna Green	Quarry	Care and maintenance	20 km south of Jerramungup	50	685224	6222767
Mulroy Green	Quarry	Care and maintenance	30 km north-northeast of Moora	50	409679	6638521
Valmere Green	Quarry	Care and maintenance	40 km north-northeast of Moora	50	408475	6649865
Verde Lope	Quarry	Care and maintenance	40 km north-northeast of Moora	50	412106	6644732

Appendix 1 (continued)

Name	Operation	Status	Location	MGA zone	Easting	Northing
JASPER						
Hamersley Basin						
Mount Brockman	Prospect	Exploration 2005	55 km northwest of Tom Price	50	544356	7531082
Yilgarn Craton–Murchison Terrane						
Fields Find	Prospect	Exploration 2007	50 km northwest of Paynes Find	50	524515	6787455
LIMESTONE						
Perth Basin						
Cutler Road	Quarry	Operating	40 km north-northwest of Perth	50	381750	6502380
Hopkins Road	Quarry	Operating	40 km north-northwest of Perth	50	382269	6502245
Moore River	Quarry	Operating	4 km north-northeast of Guilderton	50	359143	6533845
Wattle Avenue	Quarry	Operating	33 km north-northwest of Perth	50	383820	6497258
Wesco Road	Quarry	Operating	36 km north-northwest of Perth	50	382761	6498249
Wesco Road North	Quarry	Operating	37 km north-northwest of Perth	50	382352	6499805
Yanchep	Quarry	Operating	60 km north-northwest of Perth	50	373787	6521478
MARBLE						
Edmund Basin						
Maroonah						
Belloti and Pindanni	Prospects	Exploration 2008	12 km northwest of Pilbara Green	50	368742	7406894
Pilbara Green	Quarries	Operating	220 km southeast of Onslow	50	377164	7397538
Nanutarra						
Rosso Venezia	Quarry	Operating	120 km southeast of Onslow	50	369303	7488285
Austral Pearl, Austral Dream, and Austral Brown	Quarry	Operating	120 km southeast of Onslow	50	369550	7488381
Parry Range						
Bluff Well	Prospect	Exploration 2007	20 km east of Nanutarra	50	366633	7506576
Motin Bore	Prospect	Exploration 2007	33 km southeast of Nanutarra	50	373496	7489701
Wadrah Bore	Prospect	Exploration 2007	30 km southeast of Nanutarra	50	369596	7489344
QUARTZITE						
Yilgarn Craton–South West Terrane						
Toodyay						
Black and Tan	Quarry	Operating	8 km southwest of Toodyay	50	443590	6503694
Lovers Lane	Quarry	Operating	8 km southwest of Toodyay	50	442970	6503380
Salt Valley Road	Quarry	Operating	10 km south-southwest of Toodyay	50	446542	6500089
SANDSTONE						
Canning Basin						
Mount Jowlaenga						
Argyle White	Quarry	Operating	65 km west-southwest of Derby	51	506280	8064678
Kimberley Sandstone	Quarry	Operating	65 km west-southwest of Derby	51	503445	8067412
Kimberley Quartzite	Quarry	Operating	65 km west-southwest of Derby	51	508273	8041339
Hamersley Basin						
Pinderi Hills						
Karratha Stone	Quarry	Operating	40 km south-southeast of Karratha	50	494639	7671332
Perth Basin						
Donnybrook						
Acrogem	Quarry	Operating	5 km north of Donnybrook	50	391622	6289852
Beelerup	Quarry	Operating	5 km northeast of Donnybrook	50	393353	6288384
Donnybrook Stone	Quarry	Operating	4 km south of Donnybrook	50	390091	6280633

TIGER IRON						
Pilbara Craton						
Ord Ranges	Quarry	Care and maintenance	60 km east of Port Hedland	50	724651	7754851
FELDSPAR						
Yilgarn Craton–Murchison Terrane						
Mukinbudin	Mine	Care and maintenance	6 km west-northwest of Mukinbudin	50	609153	6581999
Pilbara Craton						
Pippingarra	Mine	Care and maintenance	33 km south-southeast of Port Hedland	50	683759	7724171
FLUORITE						
Halls Creek Orogen						
Speewah	Deposit	Exploration 2007	90 km south of Wyndham	52	390985	8186058
GARNET						
Southern Carnarvon Basin						
Port Gregory	Mine	Operating	85 km north-northwest of Geraldton	50	226141	6889390
GYPSUM						
Cowcowing Lakes	Mine	Operating	95 km northeast of Northam	50	532945	6568491
Jurien Bay North	Mine	Operating	12 km north-northwest of Jurien Bay	50	308250	6657450
Lake Brown	Mine	Operating	40 km north of Merredin	50	624919	6559360
Lake Cowan	Mine	Operating	5 km southwest of Norseman	51	381372	6433020
Lake Goorly South	Mine	Operating	120 km northeast of Moora	50	500838	6680581
Lake Hillman	Mine	Operating	120 km east-northeast of Moora	50	516521	6646323
Lake MacLeod	Mine	Operating	80 km north of Carnarvon	49	771088	7324884
Scaddan	Mine	Operating	60 km north of Esperance	51	381841	6310937
LIMESTONE AND LIMESAND						
Albany–Fraser Orogen						
LIMESTONE						
Point D'Entrecasteaux	Mine	Operating	65 km south-southwest of Manjimup	50	409783	6145508
LIMESAND						
Ocean Beach	Mine	Operating	8 km south-southwest of Denmark	50	529656	6123400
Eucla Basin						
LIMESTONE						
Rawlinna	Mine	Operating	2 km north of Rawlinna Siding	51	722549	6569513
Northern Carnarvon Basin						
LIMESTONE						
Exmouth	Mine	Operating	5 km south-southwest of Exmouth	50	201957	7567011
Perth Basin						
LIMESTONE						
Abercrombie Road (See **Dimension stone: limestone, Perth Basin**)	Mine	Operating	3 km north-northwest of Kwinana	50	387096	6434916
LIMESAND						
Cervantes	Mine	Operating	3 km northeast of Cervantes	50	316794	6625198
Cockburn Sound	Mine	Operating	6 km southwest of Fremantle	50	377941	6448199
Coolimba	Mine	Operating	65 km south of Dongara	50	305337	6698157
Denison Westdeen	Mine	Operating	4 km south of Dongara	50	298528	6758997
Denison Cockburn	Mine	Operating	5 km south of Dongara	50	299380	6757927
Green Head	Mine	Operating	6 km south-southeast of Green Head	50	307620	6666875
Lancelin North	Mine	Operating	3 km north of Lancelin	50	340401	6569609
Lancelin South	Mine	Operating	2 km south of Lancelin	50	342328	6565662
Sandy Point	Mine	Operating	13 km north of Jurien Bay	50	307905	6658888

Appendix 1 (continued)

Name	*Operation*	*Status*	*Location*	*MGA zone*	*Easting*	*Northing*
Southern Bonaparte Basin						
LIMESTONE						
Jeremiah Hills	Mine	Operating	45 km north of Kunurra	52	471608	8297667
Southern Carnarvon Basin						
Scrubby Hill	Mine	Operating	14 km northeast of Carnarvon	49	776285	7257297
LIMESAND (COQUINA)						
L'Haridon Bight	Mine	Operating	40 km southeast of Denham	49	785309	7108730
LIMESTONE (CALCRETE)						
Yilgarn Craton–Eastern Goldfields Terrane						
Windarra	Mine	Operating	35 km northwest of Laverton	51	415001	6849506
MANGANESE						
Bryah Basin						
South Horshoe	Prospect	Exploration 2008	130 km north of Meekatharra	50	656681	7185062
Hamersley Basin						
Ant Hill	Prospect	Exploration 2008	85 km southwest of Woodie Woodie	51	252073	7555612
Skull Springs	Prospect	Exploration 2008	38 km southwest of Woodie Woodie	51	297241	7581940
South Woodie Woodie	Prospect	Exploration 2008	50 km south of Woodie Woodie	51	314149	7551137
Sunday Hill	Prospect	Exploration 2008	85 km southwest of Woodie Woodie	51	246813	7559292
Woodie Woodie	Mines and prospects	Operating exploration 2008	325 km southeast of Port Hedland	51	318010	7607088
Northwest Officer Basin						
Table Hill	Prospect	Exploration 2007	180 km southeast of Newman	51	340650	7369385
Padbury Basin						
Mount Padbury	Prospect	Exploration 2008	120 km north-northwest of Meekatharra	50	635003	7165223
Yilgarn Craton–Eastern Goldfields Terrane						
Mount Thirsty	Prospect	Exploration 2007	20 km north-northwest of Norseman	51	372407	6447472
PHOSPHATE						
Southern Carnarvon Basin						
Cardabia	Prospect	Exploration 2008	125 km south of Exmouth	50	210825	7448134
Yilgarn Craton–Eastern Goldfields Terrane						
Mount Weld	Deposit	Exploration 2000	35 km southeast of Laverton	51	456155	6807847
PIGMENT (IRON OXIDE)						
Yilgarn Craton–Murchison Terrane						
Little Wilgie Mia	Mine	Care and maintenance	330 km east-northeast of Geraldton	50	567857	7019585
Narryer Terrane						
Mount Gould	Mine	Care and maintenance	160 km northwest of Meekatharra	50	534083	7146486
POTASH						
Officer Basin						
Lake Disappointment	Deposit	Exploration 2007	300 km east of Newman	51	474197	7406724
Canning Basin						
Lake Auld	Prospect	Exploration 2006	430 km east-northeast of Newman	51	581739	7537153

RARE EARTH ELEMENTS						
Gascoyne Complex						
Yangibana	Deposit	Exploration 1988	280 km east-northeast of Carnarvon	50	418278	7357422
Halls Creek Orogen						
Brockman	Deposit	Exploration 2006	18 km southeast of Halls Creek	52	371443	7973892
Corkwood Yard	Deposit	Exploration 1992	120 km north-northeast of Halls Creek	52	415029	8086160
Cummins Range	Deposit	Exploration 2008	130 km south-southwest of Halls Creek	52	307231	7866662
John Galt	Deposit	Exploration 1992	120 km north-northeast of Halls Creek	52	417728	8087640
Yilgarn Craton–Eastern Goldfields Terrane						
Mount Weld	Mine	Under development	35 km southeast of Laverton	51	456155	6807847
SALT						
Dampier	Solar salt ponds	Operating	5 km south of Dampier	50	471883	7707630
Lake MacLeod	Solar salt ponds	Operating	80 km north of Carnarvon	49	758683	7293953
Lake Deborah	Solar salt ponds	Operating	65 km north of Southern Cross	50	730590	6604791
Onslow	Solar salt ponds	Operating	12 km east of Onslow	50	299496	7596499
Onslow Salt Prospect	Prospect	Feasibility studies	30 km east-northeast of Onslow	50	334553	7613855
Pink Lake	Solar salt ponds	Operating	5 km northwest of Esperance	51	393419	6255809
Port Hedland	Solar salt ponds	Operating	30 km east of Port Hedland	50	699586	7759668
Shark Bay	Solar salt ponds	Operating	140 km south of Carnarvon	49	740208	7105851
Yannarie	Prospect	Feasibility studies	90 km southwest of Onslow	50	238381	7546793
SEMIPRECIOUS STONES						
Edmund Basin						
Waldburg variscite	Prospect	Exploration 2006	230 km north-northwest of Meekatharra	50	567099	7272576
Gascoyne Complex						
Gascoyne amethyst	Mine	Operating	290 km east-northeast of Carnarvon	50	445919	7292796
Injinu Hills rose quartz	Mine	Operating	280 km east-northeast of Carnarvon	50	437681	7267255
Yinnietharra dravite (tourmaline)	Mine	Operating	260 km east-northeast of Carnarvon	50	416514	7282081
Hamersley Basin						
Snowy Mount and Divide Creek jaspers	Mines	Operating	100 km south-southeast of Tom Price	50	640730	7408082
Marillana crazy lace agate	Mine	Operating	75 km north-northwest of Newman	50	763216	7488784
Roy Hill jasper	Mine	Operating	100 km north-northeast of Newman	51	201359	7511703
Pilbara Craton						
Ord Ranges tiger eye	Mine	Care and maintenance	55 km east of Port Hedland	50	723452	7755368
Pear Creek jade (chert)	Mine	Care and maintenance	120 km southeast of Port Hedland	50	769444	7692216
Southern Carnarvon Basin						
Mooka chalcedony (mookaite)	Mines	Operating	135 km east of Carnarvon	50	293578	7245414
Yilgarn Craton – Murchison Terrane						
Warriedar tourmaline	Mine	Care and maintenance	45 km west-northwest of Paynes Find	50	524806	6778165
Eastern Goldfields Terrane						
Binti Binti magnesite	Mine	Operating	80 km northeast of Kalgoorlie	51	394272	6666882
Marshall Creek chrysoprase	Mine	Care and maintenance	70 km north-northwest of Leonora	51	302530	6865857
Yerilla chrysoprase and magnesite	Mine	Operating	140 km north-northeast of Kalgoorlie	51	396007	6731645
SILICA AND SILICA SAND						
Kemerton smelter	Silicon smelter	Operating	20 km northeast of Bunbury	50	383377	6323605
Albany–Fraser Orogen						
Mindijup	Mine	Operating	40 km northeast of Albany	50	596906	6154401
Perth Basin						
Kemerton	Mine	Operating	30 km northeast of Bunbury	50	387353	6333252
Lexia	Mine	Operating	20 km north-northeast of Perth	50	399961	6482959

Appendix 1 (continued)

Name	*Operation*	*Status*	*Location*	*MGA zone*	*Easting*	*Northing*
Pinjarra Orogen						
Moora	Mine	Operating	12 km north of Moora	50	407556	6623608
Yilgarn Craton–Eastern Goldfields Terrane						
Mount Burges	Mine	Operating	20 km northwest of Coolgardie	51	312520	6591027
SPODUMENE (LITHIUM)						
Yilgarn Craton–Eastern Goldfields Terrane						
Mount Cattlin	Deposit	Exploration 2007	2 km north of Ravensthorpe		225020	6282433
Yilgarn Craton–South West Terrane						
Greenbushes	Mine	Operating	70 km south-southeast of Bunbury	50	413623	6253109
SPONGOLITE						
Bremer Basin						
Mount Barker	Mine	Care and maintenance	12 km east of Mount Barker	50	573205	6167515
Red Gum	Mine	Operating	20 km northeast of Mount Barker	50	567085	6186668
Woogenilup	Mine	Care and maintenance	17 km northeast of Mount Barker	50	573851	6179058
TALC						
Capricorn Orogen						
Mount Seabrook	Mine	Operating	460 km northeast of Geraldton	50	572753	7168259
Pinjarra Orogen						
Three Springs	Mine	Operating	275 km north of Perth	50	389597	6735563
TANTALUM						
Halls Creek Orogen						
Brockman	Deposit	Exploration 2006	18 km southeast of Halls Creek	52	371443	7973892
Gascoyne Complex						
Arthur River	Deposit	Exploration 2000	212 km east-northeast of Carnarvon	50	373575	7273989
Beryl Hill	Prospect	Exploration 1999	240 km east-northeast of Carnarvon	50	405519	7288933
Pilbara Craton						
Crawford Bore	Prospect	Exploration 2005–06	67 km southeast of Port Hedland	50	711725	7696006
Moolyella	Prospect	Exploration 2005–06	165 km east-southeast of Port Hedland	50	803499	7656243
Mount Francisco	Prospect	No recent exploration	20 km south-southwest of Wodgina mine	50	[a]660229	[a]7635531
Pilgangoora	Prospect	Exploration 2005–06	80 km south-southeast of Port Hedland	50	[a]695000	[a]7673310
Pinga	Prospect	Exploration 2005–06	134 km south-southeast of Port Hedland	50	685914	7621213
Shaw River	Prospect	Exploration 2005–06	156 km southeast of Port Hedland	50	[a]743764	[a]7615435
West Wodgina	Deposit	Originally mined for tin	4 km west-northwest of Wodgina mine	50	670766	7657139
Wodgina	Mine	Operating	100 km south of Port Hedland	50	673725	7655678
Woodstock	Prospect	Exploration 2005–06	205 km south-southeast of Port Hedland	50	[a]723553	[a]7556345
Yilgarn Craton–Eastern Goldfields Terrane						
Access Road	Prospect	Exploration 2005	2 km north of Bald Hill mine	51	421502	6515190
Bald Hill	Mine	Care and maintenance	55 km east-southeast of Widgiemooltha	51	422069	6512952
Binneringie	Deposit	Exploration 2001	3 km west-northwest of Bald Hill mine	51	420101	6513401
Bulloak Dam	–	–	–	–	421251	6515851
Claypan	Prospect	Exploration 2005	6 km northeast of Bald Hill mine	51	[a]425310	[a]6517924
Cotters	Prospect	Exploration 2005	Approx. 2 km south of Bald Hill mine	51	[a]422358	[a]6510696
Cotters North	Prospect	Exploration 2005	Location not known	–	–	–

Creekside	Deposit	Exploration 2005	2 km southwest of Bald Hill mine	51	420723	6511328
Sinclair	Prospect	Exploration 2005	6 km northeast of Bald Hill mine	51	[a]414444	[a]6529696
Madoonia	Prospect	Exploration 2005	20 km northeast of Bald Hill mine	51	[a]437091	[a]6525063
Mount Cattlin	Deposit	Exploration 2007	2 km north of Ravensthorpe	51	225020	6282433
Mount Deans	Deposit	Exploration 2001	10 km south of Norseman	51	385277	6424942
Mount Weld	Deposit	Exploration 1980s	35 km southeast of Laverton	51	455995	6808238
Yilgarn Craton–Murchison Terrane						
Niobe	Deposit	Exploration 2000	70 km northwest of Mount Magnet	50	526333	6935095
Yilgarn Craton–South West Terrane						
Greenbushes	Mine	Care and maintenance	70 km south-southeast of Bunbury	50	413674	6253170
TITANIUM MINERALS AND ZIRCON						
Albany–Fraser Orogen						
Hassell Beach	Deposit	Exploration pre-2004	50 km east of Albany	50	627665	6144354
Canning Basin						
King Sound	Prospect	ELs pending 2008	15 km southwest of Derby	51	557509	8074895
Pender	Prospect	Pending access issues 2008	60–190 km north-northeast of Broome	51	[a]462775	[a]8104933
Eucla Basin						
Newmont	Prospect	Exploration 2007	160 km northeast of Esperance	51	[a]523099	[a]6348680
Pioneer	Prospect	Exploration 2007	60 km north of Balladonia Hotel	51	[a]555368	[a]6452212
Wanna Lakes						
Cyclone	Deposit	Exploration 2007	700 km east-northeast of Kalgoorlie	52	474848	6811997
Hurricane	Prospect	Exploration 2007	700 km east-northeast of Kalgoorlie	52	455122	6833740
Kimberley Basin						
Durack Range	Prospect	Exploration 2007	125 km north-northwest of Halls Creek	52	324172	8098365
Ord Basin						
Ord River project	Prospect	Exploration pending	120 km south of Kununurra	52	468931	8140453
Perth Basin						
Northwest Coastal Plain						
Biddaminna	Prospect	Exploration 2006	25 km northwest of Gingin	50	376306	6540170
Boonanarring	Prospect	Exploration 2007	16 km northeast of Gingin	50	388791	6545023
Bootine	Prospect	Exploration 2007	22 km north-northwest of Gingin	50	[a]381158	[a]6543741
Cataby	Deposit	Feasibility studies 2007	150 km north of Perth	50	358992	6597950
Cooljarloo	Mine	Operating	170 km north of Perth	50	349527	6610359
Cooljarloo North	Prospect	Exploration 2007	180 km north-northwest of Perth	50	329496	6631702
Cooljarloo Prospect	Prospect	Exploration 2007	170 km north-northwest of Perth	50	337641	6619995
Dongara	Deposit	Resource	37 km southeast of Dongara	50	322161	6739432
Eneabba	Mine	Operating	80 km south-southeast of Dongara	50	336838	6695998
Gingin	Mine	Operating	3 km west of Gingin	50	392911	6534257
Jurien	Deposit	Resource	14 km south-southeast of Jurien Bay	50	325109	6642436
Southwest Coastal Plain						
Capel	Plant	Operating	25 km south-southwest of Bunbury	50	368218	6289945
Ambergate	Deposit	Resource	9 km southwest of Busselton	50	341166	6268233
Cloverdale	Mine	Operating	9 km southeast of Capel	50	369486	6279890
Dardanup	Mine	Operating	17 km east of Bunbury	50	389059	6308824
Coolup	Deposit	Exploration 2005	14 km south-southeast of Pinjarra	50	400098	6376016
Four Acres	Deposit	Exploration pre-2004	8 km northwest of Jangardup minesite	50	369131	6202588
Gwindinup	Mine	Operating	4 km south of Boyanup	50	381812	6290425
Happy Valley	Deposit	Resource	11 km south of Boyanup	50	380817	6287006
Hopelands East	Deposit	Exploration pre-2004	22 km southeast of Rockingham	50	397128	6415112
Jangardup South	Deposit	Exploration pre-2004	47 km east-southeast of Augusta	50	376530	6192649
Kemerton	Deposit	Exploration pre-2004	6 km southeast of Binningup	50	382907	6328261
Keysbrook	Deposit	Resource	55 km south-southeast of Perth	50	400263	6407611

Appendix 1 (continued)

Name	*Operation*	*Status*	*Location*	*MGA zone*	*Easting*	*Northing*
Keysbrook South	Deposit	Exploration 2005	10 km northeast of Pinjarra	50	401035	6397644
Ludlow	Mine	Closed	34 km south-southwest of Bunbury	50	359788	6282322
North Dandalup	Deposit	Resource	11 km northeast of Pinjarra	50	404482	6405685
Pinjarra	Prospect	Exploration 2005	20 km south of Keysbrook deposit—location not known	–	–	–
The Loop	Deposit	Resource	6 km southeast of Pinjarra	50	400741	6386277
Tutunup South	Mine	Closed	20 km south of Capel	50	363183	6268827
Wagerup	Mine	Operating	20 km north of Harvey	50	399335	6359450
Waroona	Mine	Operating	3 km northeast of Waroona	50	399704	6367536
Yalyalup	Prospect	Exploration 2006	13 km south-southeast of Busselton	50	358394	6271199
Southern Bonaparte Basin						
Medusa Banks	Prospect	Exploration pending	110 km north-northwest of Kununurra	52	445038	8364411
Southern Carnarvon Basin						
Coburn	Deposit	Resource	130 km north of Kalbarri	50	214116	7037154
Yaringa	Prospect	Exploration 2007	130 km north of Kalbarri	50	221957	7043748
VANADIUM						
Pilbara Craton						
Balla Balla	Deposit	Resource	10 km north-northwest of Whim Creek	50	580750	7703551
Yilgarn Craton–Murchison Terrane						
Barrambie	Deposit	Exploration 2005	115 km southeast of Meekatharra	50	709564	6964000
Buddadoo	Prospect	Exploration ?	45 km south-southwest of Yalgoo	50	449997	6820005
Gabanintha	Deposit	Exploration 2007	48 km southeast of Meekatharra	50	663315	7016200
Nowthanna	Prospect	Exploration ?	55 km southeast of Meekatharra	50	666635	7012013
Unaly Hill	Deposit	Exploration 2000	115 km east-southeast of Mount Magnet	50	691018	6860168
Windimurra	Mine	Redevelopment phase	70 km southeast of Mount Magnet	50	650484	6868763
Youanmi	Deposit	Exploration 1999	120 km southeast of Mount Magnet	50	[(a)]675802	[(a)]6827091

NOTE: (a) Position approximate

FETHERSTON

Industrial minerals in Western Australia:
The situation in 2008

RECORD 2008/16

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Phone: (08) 9222 3222 Fax: (08) 9222 3444

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REFERENCE

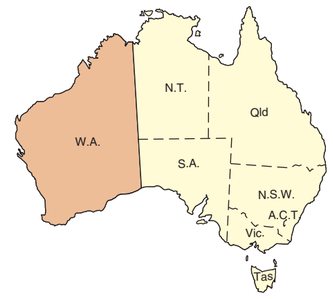
- DIAMOND
  - Dmd Diamond
- SEMIPRECIOUS STONES
  - Aga Agate
  - Chrp Chrysoprase
  - Chrt Chert
  - Clc Chalcedony (mookaite)
  - Jasp Jasper
  - Mgs Magnesite
  - Qtza Amethyst
  - Qtzr Rose quartz
  - Teye Tiger eye
  - Tur Tourmaline
  - Vrs Variscite
- STEEL INDUSTRY METAL
  - Mn Manganese
  - V Vanadium
- SPECIALTY METAL
  - REE Rare earth elements
  - Li Spodumene (lithium)
  - Ta Tantalum
  - Hm Titanium minerals and zircon
- ALUMINIUM
  - Bx Bauxite
- INDUSTRIAL MINERAL
  - Fel Feldspar
  - Fl Fluorite
  - Gp Gypsum
  - Kln Kaolin
  - Lsd Limesand
  - Lst Limestone
  - Mnpg Pigment (iron oxide)
  - Phos Phosphate
  - KSO Potash
  - Salt Salt
  - Sisd Silica sand
  - Tlc Talc
- CONSTRUCTION MATERIAL
  - Dst Dimension stone

Age (Ma)

0	PHANEROZOIC
1000	NEOPROTEROZOIC
	MESOPROTEROZOIC
2000	PALEOPROTEROZOIC
3000	ARCHEAN
4000	

Sedimentary and volcanic rocks; Igneous and metamorphic rocks; Granite–greenstones and gneisses

City or town; Highway; Major road; Railway; Gas pipeline; Industrial mineral mine, deposit, or prospect (Windimurra)



Department of Industry and Resources
Geological Survey of Western Australia

HON. NORMAN MOORE, M.L.C.
MINISTER FOR MINES AND PETROLEUM

TIM GRIFFIN
EXECUTIVE DIRECTOR

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
RECORD 2008/16 PLATE 1

INDUSTRIAL MINERALS IN WESTERN AUSTRALIA MAY 2008

SCALE 1:5 000 000

0 50 100 150 200
Kilometres

Compiled by JM Fetherston
Geology by IM Tyler, and RM Hocking, 2001,
Tectonic units of Western Australia (scale 1:2 500 000):
Western Australia Geological Survey.

Edited by N Tetlaw
Cartography by M Prause

Information on mineral localities from MINEDEX database,
DoIR, at March 2004. Data points filtered for clarity on plate.

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The recommended reference for this map is:
FETHERSTON, JM, 2008, Industrial minerals in Western Australia, May 2008, *in* Industrial minerals in Western Australia: the situation in 2008 *by* JM FETHERSTON: Geological Survey of Western Australia, Record 2008/16, Plate 1.

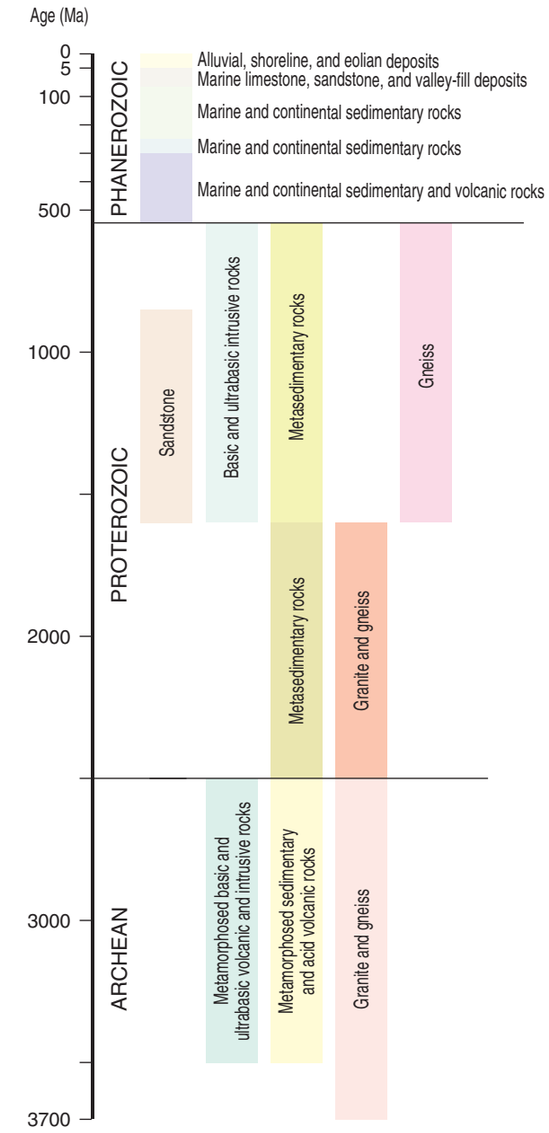
JMF385 23.10.08

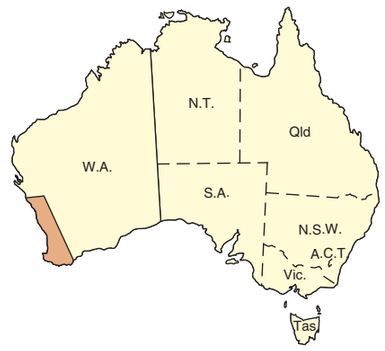
REFERENCE

- SPECIALITY METAL
  - HM Titanium minerals and zircon
  - Li Spodumene (lithium)
  - Ta Tantalum
- ALUMINIUM
  - Bx Bauxite
- INDUSTRIAL MINERAL
  - Atta Attapulgite
  - Bent Bentonite
  - Cc Construction clay
  - Diat Diatomite
  - Gp Gypsum
  - Grt Garnet
  - Kln Kaolin
  - Lsd Limesand
  - Lst Limestone
  - Si Silica (chert)
  - Sisd Silica sand
  - Spon Spongolite
  - Tlc Talc
- CONSTRUCTION MATERIAL
  - Dst Dimension stone

Major road
Formed road
Railway
Gas pipeline
City — PERTH
Townsite
- population 10 000–15 000 — BUSSELTON
- 1 000–10 000 — WAROONA
- less than 1 000 — Jarrahdale

Homestead — Yandi
Locality — Mt Leseur
Mine, deposit, or prospect — Jubuk





Department of Industry and Resources

HON. NORMAN MOORE, M.L.C.
MINISTER FOR MINES AND PETROLEUM

Geological Survey of Western Australia

TIM GRIFFIN
EXECUTIVE DIRECTOR

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
RECORD 2008/16 PLATE 2

INDUSTRIAL MINERALS IN SOUTHWEST WESTERN AUSTRALIA MAY 2008

SCALE 1:2 000 000

0 20 40 60
Kilometres

Compiled by JM Fetherston
Geology by JM Myers and RM Hocking, 1998, as generalized in GSWA, 2003, Western Australian atlas of mineral deposits and petroleum fields 2003.

Edited by N Tetlaw
Cartography by M Prause

Information on mineral localities from MINEDEX database, DoIR, at March 2008. Data points filtered for clarity on plate.

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The recommended reference for this map is:
FETHERSTON, JM, 2008, Industrial minerals in southwest Western Australia, May 2008, *in* Industrial minerals in Western Australia: the situation in 2008 *by* JM FETHERSTON: Geological Survey of Western Australia, Record 2008/16, Plate 2.

JMF384 23.10.08