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Australia’s potential to supply global demand

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APPLYING GEOSCIENCE TO AUSTRALIA’S MOST IMPORTANT CHALLENGES

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Geoscience Australia
Chief Executive Officer: Dr Chris Pigram

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ISSN 1448-2177

ISBN 978-1-922201-43-0

GeoCat # 76526

GA 13-7166

Bibliographic reference: Skirrow, R.G., Huston, D.L., Mernagh, T.P., Thorne, J.P., Dulfer, H., & Senior, A.B. 2013. *Critical commodities for a high-tech world: Australia's potential to supply global demand*. Geoscience Australia, Canberra.

Cover image: Nickel mine in Western Australia. Image courtesy of Thiess Pty Ltd.

Executive Summary

The availability of metal, non-metal and mineral raw materials, particularly those that underpin high-technology industries are important for the ongoing development of these industries. Several countries have developed risk lists of metals and minerals that are considered to be critical. The level of criticality of a commodity reflects the combination of risk of supply and the importance of the particular commodity.

Australia is a major exporter of mineral commodities but is a relatively small consumer. Therefore the critical commodities for other countries are not critical at present for Australian industries, with a small number of possible exceptions relating to the agricultural sector (phosphate and potash).

This report examines critical commodities from an Australian perspective and presents comprehensive technical (geological) information on Australia's resources and resource potential for these critical commodities. The report comprises two parts: Part 1 summarises assessment of critical commodity reports; Part 2 is a technical presentation of geological information on critical commodities. The full report is available at www.ga.gov.au.

Part 1 assesses the EU, Japan, South Korea, UK and US critical commodity reports, and identifies current and potential commodity resources in Australia.

Critical commodities assessed as having category one (high) resource potential in Australia are (in alphabetical order): **chromium**, **cobalt**, **copper**, **nickel**, **platinum-group elements (PGE)**, **rare-earth elements (REE)**, and **zirconium**. Of these seven commodities, five are ranked in the group considered as most critical by the EU, Japan, South Korea, UK and US (i.e., excluding copper and zirconium which are of category three and category two criticality, respectively).

Critical commodities assessed as having category two resource potential in Australia are (in alphabetical order): **antimony**, **beryllium**, **bismuth**, **graphite**, **helium**, **indium**, **lithium**, **manganese**, **molybdenum**, **niobium**, **tantalum**, **thorium**, **tin**, **titanium**, and **tungsten**. Of these 15 commodities, eight are considered to be of highest criticality by the EU, Japan, South Korea, UK and US. This assessment of resource potential does not consider non-critical commodities such as base metals, ferrous metals and energy commodities. Australia has category one resource potential in many of these non-critical commodities.

Part 2 presents detailed information on the geological occurrence of critical commodities within a holistic mineral systems framework, and importantly also describes Australia's mineral deposits that are known to, or may, contain significant quantities of the critical commodities.

Most of the commodities can be grouped into three families of mineral systems.

Mineral system family (1): Mafic-ultramafic-related nickel, platinum-group elements, chromium and cobalt—The occurrence of these commodities is closely related to mafic-ultramafic igneous rocks, particularly for nickel, platinum-group elements and chromium. Based on known resources in Australia, the continent appears to be under-represented in world-class intrusion-hosted nickel, platinum-group elements and chromium deposits. Australia's geology and in particular the presence of many previously unrecognised large igneous provinces leads us to conclude that Australia is highly prospective for major deposits of nickel, platinum-group elements and chromium.

Mineral system family (2): Felsic igneous-related rare-earth element, tungsten, niobium, tantalum, molybdenum, beryllium, tin and bismuth—All of these metals occur (albeit not exclusively) in association with felsic igneous intrusions, in particular with either highly-fractionated granitic rocks and/or with alkaline igneous rocks. There are regions where deposits of these metals are already known in Australia (brownfields), and in the under-cover extensions of these mineral provinces (brownfields to greenfields).

Mineral system family (3): Heavy mineral sand-hosted zirconium, titanium, rare-earth element and thorium—New discoveries of heavy mineral sand provinces recently in Australia attest to the resource potential of the continent for further delineation of major resources of heavy mineral sands.

In addition to these mineral system families, a group of metals and semi-metals including **antimony**, **indium**, **gallium**, **germanium**, **cadmium**, **tellurium** and **selenium** are primarily the by-products of the refining of the major commodities zinc, copper, lead, gold, aluminium and nickel. Australia's high global ranking in resources of all of these major commodities implies that there is significant resource potential for new or increased production of the minor-element by-products listed above.

Australia has category one resource potential for a range of commodities, however countries consider many of these to have category three criticality. For example, **copper** is rated as category one resource potential, despite its category three criticality, due to its economic importance, predicted growth in demand from industrialised and developing economies, and the resource potential of Australia for new discoveries of copper. Other non-critical commodities for which Australia has category one or category two resource potential include zinc, lead, silver, gold, iron ore, bauxite, uranium, diamonds, phosphate, potash, coal, petroleum and natural gas.

Acknowledgements

This report has benefited from the efforts of many individuals beyond the authors. In particularly we would like to thank Marie Lake, David Arnold, Robin Swindell and Silvio Mezzomo for their assistance in production, and Yanis Miezitis, Stephen Wright, Michael Sexton, Richard Blewett, Leesa Carson, David Champion, Marita Bradshaw, Mark Barley, Peter McGoldrick and other staff of Geoscience Australia and the Department of Resources, Energy and Tourism for editorial and other technical assistance.

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(Available at www.ga.gov.au)

Part one

Critical Commodities and Australian Supply

Roger G. Skirrow, Jane P. Thorne, Anthony B. Senior and David L. Huston

1. Introduction

1.1 Metals and minerals for a high-tech world

1.1.1 Global perspective

The availability of metal, non-metal and mineral raw materials (referred to as commodities herein), particularly those that underpin high-technology sectors, is important for the ongoing development of many industries. Several countries or groups of countries have undertaken review studies to assess which commodities are critical. A wide range of metals, non-metallic elements and minerals that are used in generally smaller quantities are also crucially important, yet have significant risk of supply. Major commodities such as iron ore, coal, aluminium and copper are very important in a wide range of sectors, however there is a diversity of supply and substantial resources.

Definitions of 'critical' are discussed elsewhere in this report, but in essence a commodity is critical if it is both economically important and has high risk of supply disruption. These supply risks originate from four main causes: (1) scarcity of the commodity; (2) diversity and stability of supply; (3) production only as a by-product of other commodities; and (4) level of concentration of commodity production and processing within particular countries or by particular companies. The scarcity of a commodity may be determined by many factors including the geological abundance within the Earth; economics of extraction of the commodity; the extent of substitution of one material by another; and the extent of recycling. Criticality can also change over time.

Current and future demand for the major industrial metallic and mineral commodities as well as the lower volume commodities used in high-tech industries are driven by:

- Manufacturing in industrial economies including US, EU countries and Japan;
- Rapid industrialisation and urbanisation in China, India, Brazil, Russia, Indonesia and a number of other countries, forecast to continue at high rates of growth in many cases;
- Policies and new technologies for reducing emissions of greenhouse gases at both the energy production and energy end-use stages, driven by concerns over environmental issues;
- Development of new technologies for telecommunication and entertainment;
- Concerns over food and water security; and
- Consumer desire for improved fuel efficiency and performance of vehicles.

1.1.2 Australian perspective and potential

Australia is a major exporter but is a relatively small consumer of mineral commodities. Therefore the critical commodities for other countries are not critical at present for Australian industries, with a small number of possible exceptions relating to the agricultural sector (phosphate and potash).

The importance of mineral exports for the Australian economy is underlined by the fact that mineral resources contributed 60.5% of the value of exports of goods and services, and generated 10% of Australia's GDP in 2011–12 (BREE, 2012). The long term sustainability of the Australian mining industry and consequent revenue is underpinned by the discovery of very large mineral deposits that have long mine lives—historically these discoveries generally were made in areas that were considered greenfields or frontier at the time. Critical commodities are a potential additional exploration target for Australian mining and exploration industries.

1.2 Purpose and scope of the report

This report is an initial appraisal of the resource potential for critical commodities in Australia. The report covers 34 individual metals, non-metals and minerals (Appendix) and attempts to prioritise these commodities from an Australian perspective.

The purpose of this report is to:

- Provide an assessment of resource potential for metal, non-metal and mineral commodities in Australia;
- Present technical information on the geological occurrence of critical commodities, and of Australia's resources and potential for discovery of new resources; and
- Guide mineral exploration companies towards the geological settings in Australia where resources of the critical commodities are either known, likely to be present, or have category one resource potential to be discovered.

The report comprises two parts:

Part 1, *Critical Commodities and Australian Supply* presents summary information on the global perspectives on critical commodities and identifies resource potential for critical commodities in Australia. The Appendix contains summaries for each of 34 commodities with information on the physical characteristics, geological occurrence, and supply and demand of the metal, non-metal or mineral.

Part 2, *Geology of Critical Commodities and Australia's Endowment and Potential* is a technical description of the geological occurrence of critical commodities and Australia's known resources and resource potential. It is aimed at the mineral exploration sector, academics studying critical commodities, and the mineral processing industry. A mineral systems approach is used to describe the geological occurrence of critical commodities, providing a holistic perspective within which the commodities have been grouped.

1.3 What are critical commodities?

1.3.1 Definition of critical commodities

The terminology and use of 'critical' in the context of raw materials, chemical elements, and minerals is problematic, in part due to the multiple meanings of the word in the English language and also due to the different methodologies used to assess which materials are critical in various studies. The terms 'critical' and 'strategic' also are used loosely in this context. This report differentiates these terms and focuses only on the critical commodities, although some critical commodities also may be strategic for some countries.

There appears to be a convergence of views, captured in the following quotes from two key studies. The US National Academy of Sciences (2008) report on *Minerals*, *Critical Minerals*, *and the U.S. Economy* proposed that 'a mineral can be regarded as critical only if it performs an essential function for which few or no satisfactory substitutes exist', and 'in addition, a mineral can be regarded as critical only if an assessment also indicates a high probability that its supply may become restricted, leading either to physical unavailability or to significantly higher prices for that mineral in key applications'. In this report the word 'mineral' is used in a very broad sense to include individual chemical elements (metals and non-metals) and minerals sensu stricto (see Break-out 1.3.1).

The European Commission (2010) report on *Critical raw materials for the EU* stated: 'a raw material is labelled critical when the risks of supply shortage and their impacts on the economy are higher than for most of the other raw materials'.

Break-out 1.3.1. Definitions

Metals are chemical elements that 'have a characteristic lustre, are good conductors of heat and electricity, and are opaque, fusible, and generally malleable or ductile' (Neuendorf et al., 2005). Most metals occur in nature as compounds within minerals although some important metals such as gold, copper and platinum also occur naturally in elemental (native) form. Among metals there are several subgroups, including transition metals (such as iron, zinc, copper), noble metals (such as gold, platinum, palladium), alkaline earth metals, etc. Semi-metals have characteristics that are transitional between metals and non-metals, such as semi-conductance of electricity.

A mineral is 'a naturally occurring inorganic element or compound having a periodically repeating arrangement of atoms, and characteristic chemical composition, resulting in distinctive physical properties' (Neuendorf et al., 2005).

A mineral deposit is a 'mass of naturally occurring mineral material, e.g. metal ores or non-metallic minerals, usually of economic value, without regard to mode of origin' (Neuendorf et al., 2005).

A mineral system is 'all geological factors that control the generation and preservation of mineral deposits' (Wyborn et al., 1994).

Both the US and EU studies developed concepts of criticality involving simple 2-dimensional matrices, which express the combination of importance in use and availability or supply risk of the material in question (Figures 1.3.1, 1.3.2). As noted in the introduction, there are many factors contributing to each of these two dimensions—for example, supply risk will be influenced by (1) scarcity of the commodity; (2) geopolitical stability of suppliers; (3) diversity of supply and market scale; (4) method of recovery (e.g., as the main product or as a by-product); and (5) level of concentration of commodity production and processing within particular countries.

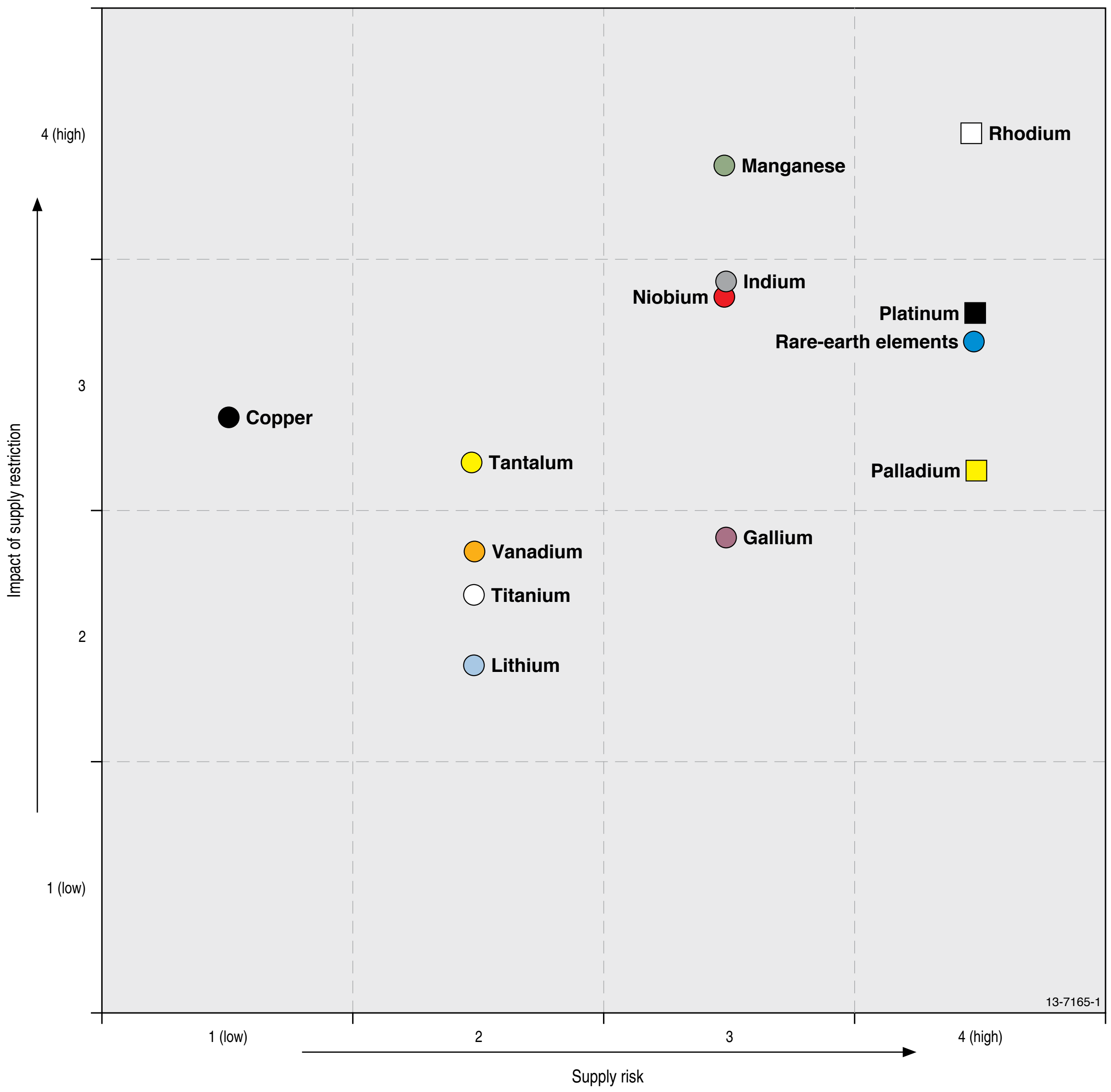


Figure 1.3.1: US National Academy of Sciences (2008) criticality matrix.

This report uses the term 'commodity' to cover the wide range of 34 metals, non-metals and minerals studied. These commodities were selected based on an initial review of previous studies of raw materials criticality by different countries. From this list we have assessed the overall criticality, and made judgements about the resource potential for Australia for each commodity (see Section 1.5).

Most of the critical commodities considered in this report are metals and semi-metals; the remainder are non-metallic elements (such as helium, a noble gas), or minerals (such as graphite, a crystalline form of carbon), or rocks (which are composed of aggregates of one or more minerals, such as bauxite).

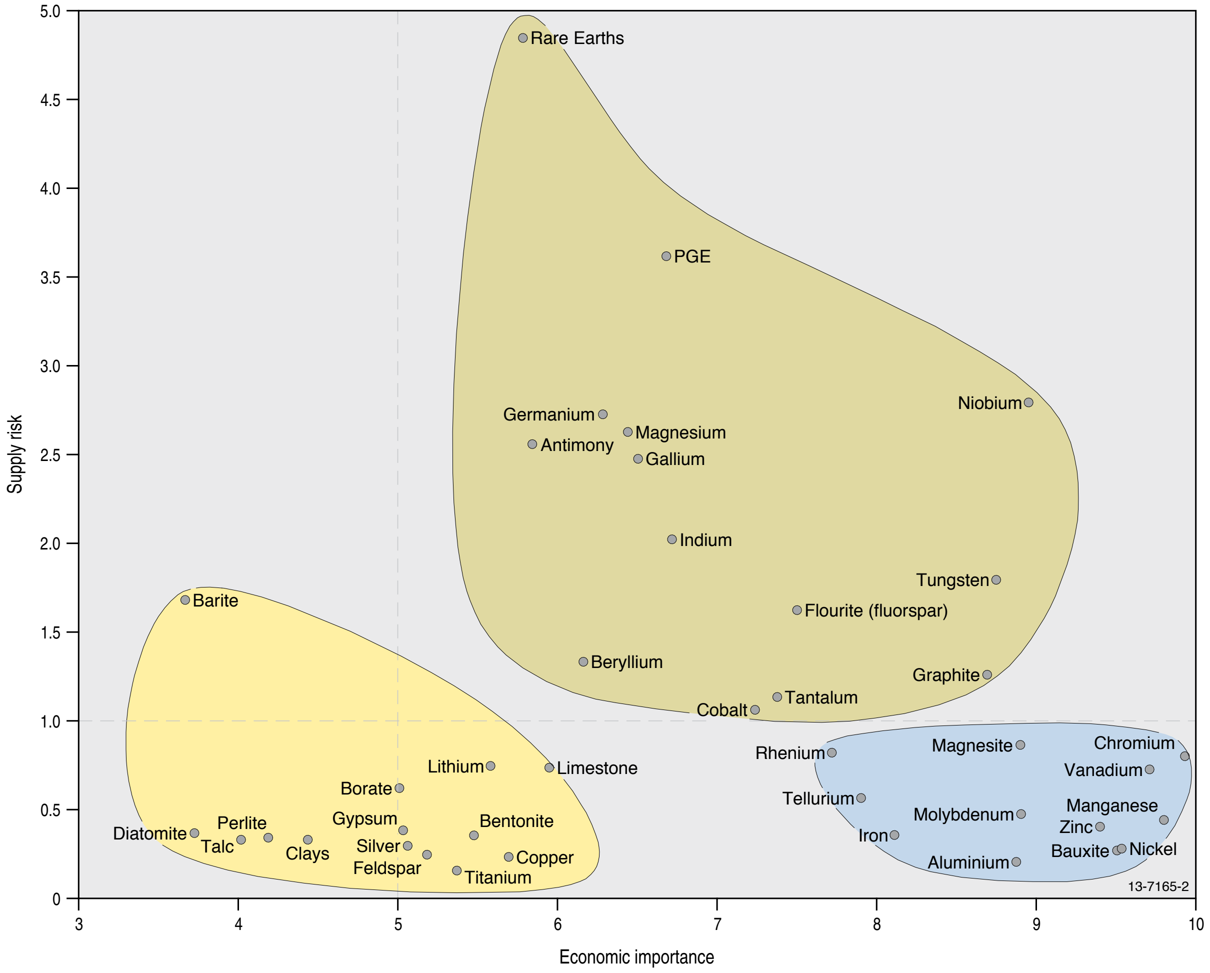


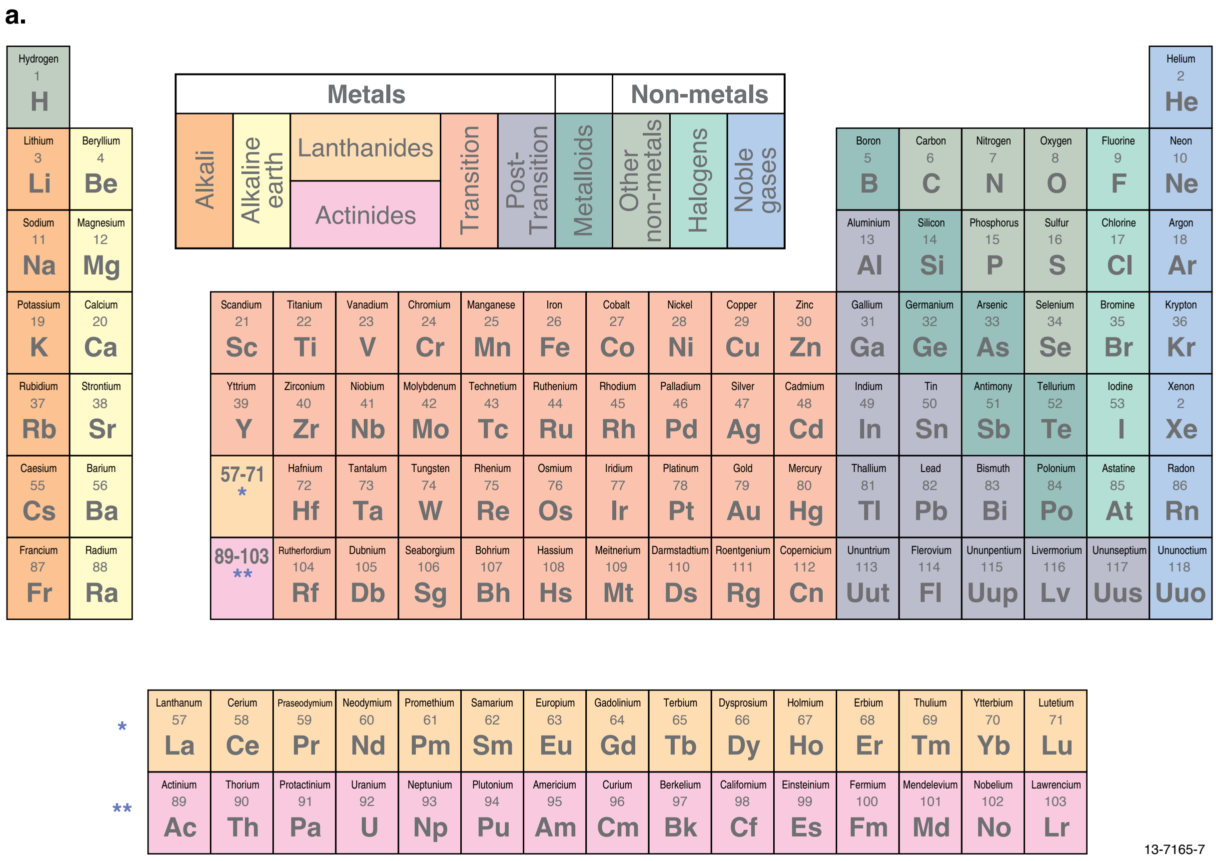
Figure 1.3.2: European Commission (2010) criticality matrix for the European Union.

1.3.2 Uses of critical and other metal and mineral commodities

The periodic table of the elements (Figure 1.3.3) illustrates the groupings of elements with certain shared physical and chemical properties. For example, all metals are good conductors of electricity and are generally malleable and ductile, whereas semi-metals are semi-conductors of electricity, a highly valuable property in electronics and solar energy panels. Some sub-groups have particular shared properties, for example platinum-group elements (including platinum and palladium) and other noble metals such as gold are highly resistant to chemical corrosion.

Other metals are valued for their extremely high melting temperatures and hardness, such as tungsten and rhenium, so that alloys of these metals tend to have greater tensile strength at high temperatures. This property enables rhenium-bearing super-alloys in jet engine turbine blades to operate at higher temperatures than non-rhenium turbines (break-out 1.3.2), reducing aeroplane emissions and fuel costs.

The rare-earth elements, which include the lanthanide series metals as well as scandium and yttrium, have diverse and very useful properties. For example, small percentages of neodymium and dysprosium in some alloys increase permanent magnet strength by orders of magnitude, enabling step changes in miniaturising of telecommunications and other electronic devices, and much more efficient generation of electricity in commercial wind turbines.



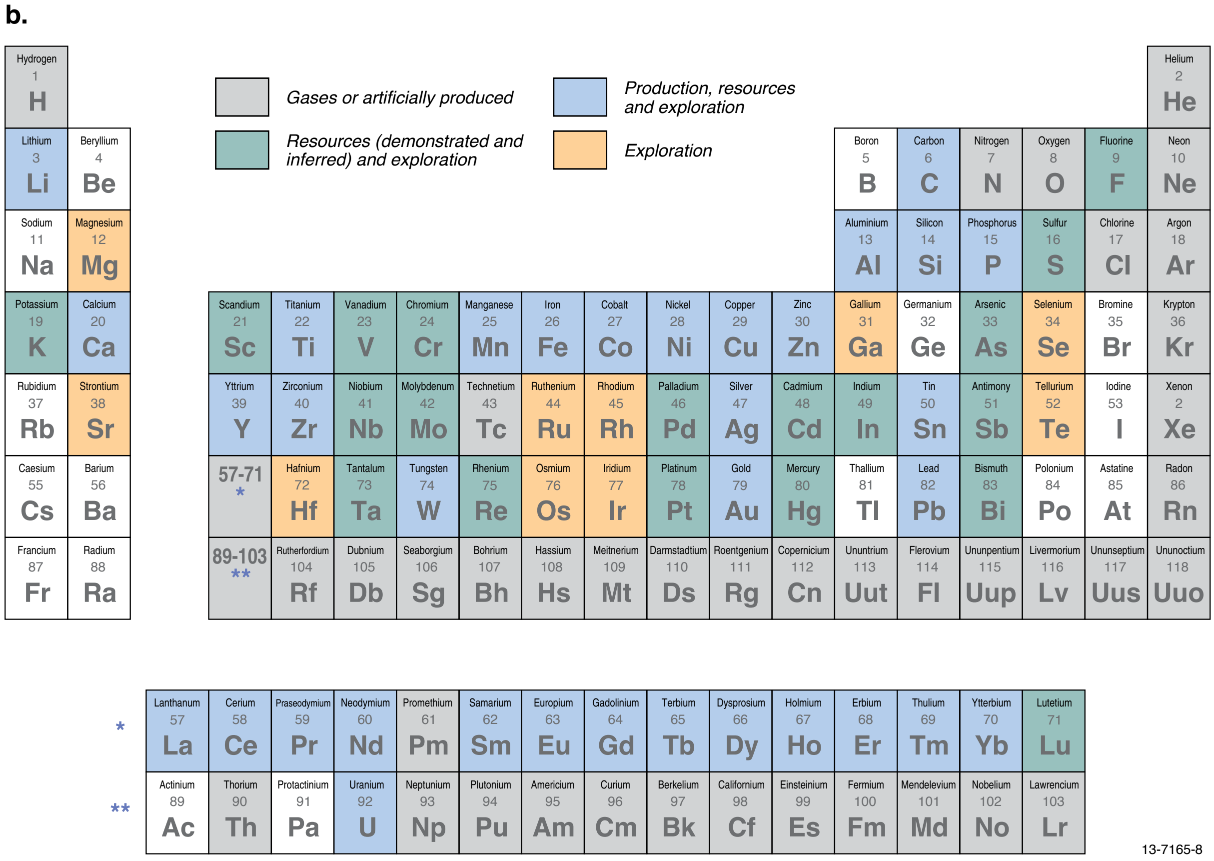


Figure 1.3.3: Periodic tables of the elements showing (a) metals, semi-metals (metalloids) and non-metals with sub-groups, and (b) the status of production, development and exploration in Australia.

Break-out 1.3.2. The use of rhenium in high temperature turbines in the aerospace industry

Operating Property	Non-Rhenium Turbine	Rhenium Turbine
Operating temperature	~2000–2200° F	~3000° F
Power and thrust	X[1]	Approximately 2X
Fuel Efficiency	Y[1]	Y + (40–60%)
Emissions*	Carbon dioxide	64% reduction
	Nitrogen oxide	88% reduction
	Sulphur dioxide	99.9% reduction
	Particulates	Eliminated
Approximate Rhenium contained per turbine	0 kg	~25 kg (3% alloy)

*Source Rio Tinto December 2008 Review. Image: Tony Hisgett, Wikimedia Commons.

[1] The values X and Y refer to nominal power and thrust and efficiency for non-rhenium turbines. The formulae for rhenium turbines indicate improvements in these parameters.

Table 1.3.1 lists some of the key drivers of the technologies in which major as well as minor commodities are used, many of which are considered critical (see Sections 1.4, 1.5). The commodities assessed in this report are shown in bold. Break-out 1.3.3 illustrates the use of mineral commodities in the construction of a typical motor car. Other drivers are the production and use of low-emissions energy, which is likely to see extensive growth in the short, medium and long terms, and the communications and entertainment technology industries.

Table 1.3.1: Common uses of metals, non-metals and minerals in industrial and high-technology applications.

Driver of metal/material usage	Technology/product	Commodities used; bold indicates critical commodities in this study
Industrial production efficiency and infrastructure development	Steel	Fe, **Cr**, **V**, **Mo**, **Ni**, **Co**, **Mn**
	Catalysts	**PGE** (**Pt**, **Pd**)
	Ceramics	**Li**, **Ce**
	Paint	**Ti**, **Cr**
	Moulds	**Zr**
	Flame retardant	**Sb**
	Cryogenics	**He**
Low-emissions energy production	Wind turbines—permanent magnets	**REE** (**Nd**, **Dy**, **Sm**, **Pr**)
	Photo-voltaics (PV)	**In**, **Sb**, **Ga**, **Te**, **Ag**, **Cu**, **Se**
	Nuclear reactors	U, **Th**, **Zr**
Low-emissions energy usage	Electric cars—batteries	**REE** (**La**, **Ce**, **Nd**, **Pr**), **Li**, **Ni**, **Co**, **Mn**, **graphite**
	Electric cars—magnets	**REE** (**Nd**, **Dy**, **Sm**, **Pr**)
	Electric cars—fuel cells	**PGE**, **Sc**
	Cars—light metals	Al, Mg, **Ti**
	Cars—catalytic converters	**PGE**
Communications and entertainment technologies	Wires	**Cu**
	Micro-capacitors—mobile phones etc	**Ta**, **Nb**, **Sb**
	Flat screens—phosphors	**In**, **Y**
	Fibre optics and infra-red	**Ge**
	Semiconductors	**Ga**
Defence / security	Nuclear/radiation detectors	**He**
	Armour and weapons	**Be**, **W**, **Cr**, **V**
	Aerospace—superalloys	**Re**, **Nb**, **Ni**, **Mo**
Transport—fuel efficiency & performance	Light alloys Superalloys (high-temperature performance e.g. in jet engine turbines) High speed trains—magnets	Al, Mg, **Ti**, Sc, **Th** **Re**, **Nb**, **Ni**, **Mo** **Co**, **Sm**
Water & food security	Water desalination	**PGE**, **Cr**, **Ti**
	Agricultural production—fertiliser	Phosphate rock; potash, Mg

Break-out 1.3.3. Metal and other selected element usage in the manufacture of an average car in 2006 (from United States National Academy of Sciences, 2008)

Element/material	Mass (kg)	Property (use)
Iron and steel	963	High strength, durability (frame, engine)
Aluminium	109	Light weight (frame, engine)
Carbon	23	Bond strengthener (tyres and other rubber parts)
Copper	19	Electrical conductivity (wiring)
Silicon	19	Bonding properties (windows)
Lead	11	Conductor (storage batteries)
Zinc	10	Galvaniser, strengthener (galvanised metal and alloy parts)
Manganese	8	Hardness as metal alloy parts
Chromium	7	Corrosion resistance and hardness as metal alloy
Nickel	4	Strength at elevated temperature and corrosion resistance as metal alloy
Magnesium	2	Light weight alloying element with aluminium
Sulfur	0.9	Strengthens rubber tyres
Molybdenum	0.45	Strength and toughness as metal alloy
Vanadium	<0.45	Strength and toughness as metal alloy
Platinum	1.5–3.0 grams	Catalytic properties (catalytic converters)

Note: In addition to the elements listed above, the average car also contains trace amounts of antimony, barium, cadmium, cobalt, fluorspar, gallium, gold, graphite, halite, limestone, mica, niobium, palladium, phosphorus, potash, strontium, tin, titanium and tungsten. Images: (a) http://flickr.com/people/robadob, Wikimedia Commons, (b) Larry D. Moore, Wikimedia Commons, (c) Petter73, Wikimedia Commons.

1.4 Global perspective on critical commodities: country summaries and demand

Recent studies have been undertaken by several countries to identify which commodities are critical for them. The results of these studies, summarised below and in Table 1.4.1, provide a foundation for the assessment of critical commodity resource potential in Australia.

The country studies vary significantly in their objectives, approach and scope, and so their assessments of which commodities are critical differ accordingly. For example the EU and the US studies integrate both supply risk and importance in their assessments, whereas the UK list represents supply risk only. There is nevertheless sufficient commonality in purpose among the studies that a composite list can be compiled which represents a broad (multi-national) perspective on the commodities considered most critical. Table 1.4.1 summarises the critical commodities identified by several countries.

Table 1.4.1 shows that commodities such as iron, aluminium, copper, gold, lead and uranium yield category three overall scores as countries do not consider these commodities to have high risks of supply. Australia's current and potential resources of these non-critical commodities are sufficient to meet forseeable demand. The purpose of Table 1.4.1 is to identify critical commodities to assess Australia's resource potential for these commodities. The commodities included in the assessment are shown with an asterisk in Table 1.4.1, and the assessment of Australia's resource potential for these commodities is summarised in Section 1.5.

Table 1.4.1: Summary of rankings of critical and other commodities from recent studies of materials criticality in the UK, EU, US, South Korea and Japan, and combined rankings as determined in this study (see methodology in note 10, below table). The Willis and Chapman (2012) study also synthesised previous reviews, and is included for comparison. Category one critical elements and minerals are coloured red, those of category two criticality are in orange, and category three criticality are coloured blue.

United Kingdom[1]	EU low C energy[2]	European Union[4]	United States DoE[5]	South Korea[7]	Japan[8]	Willis and Chapman (2012)[9]	This study[10] *ranking	Score[10]
REE	REE	Antimony	Heavy REE	Gallium	Manganese	Beryllium	*REE	29
Tungsten	Tellurium	Beryllium	Tellurium	Indium	Chromium	Gallium	*Gallium	29
Antimony	Gallium	Cobalt	Indium	Lithium	Nickel	Indium	*Indium	26
Bismuth	Indium	Fluorspar	Lithium	Magnesium	Molybdenum	Magnesium	*Tungsten	23
Molybdenum	Niobium	Gallium	Cobalt	Nickel	Cobalt	PGE	*PGE	22
Strontium	Vanadium	Germanium	Gallium	PGE	Vanadium	REE	*Cobalt	21
Mercury	Tin	Graphite	Manganese	REE	Tungsten	Tin	*Niobium	20
Barium	Selenium	Indium	Nickel	Silicon	Indium	Tungsten	Magnesium	17
Graphite	Silver	Magnesium	Light REE	Titanium	Gallium	Antimony	*Molybdenum	15
Beryllium	Molybdenum	Niobium	Magnesium	Tungsten	PGE	Cobalt	*Antimony	14
Germanium	Hafnium	PGE	Vanadium	Zirconium	REE	Germanium	*Lithium	14
Niobium	Nickel	REE		Antimony	Niobium	Manganese	*Vanadium	13
PGE	Cadmium	Tantalum	**US DoD[6]**	Chromium	Tantalum	Nickel	*Nickel	13
Cobalt		Tungsten	Zinc	Cobalt	Strontium	Niobium	*Tantalum	13
Thorium	**Sustainable tech EU[3]**		Tin	Manganese	Lithium	Rhenium	*Tellurium	13
Indium	Tellurium		Iridium	Molybdenum	Antimony	Tantalum	*Chromium	12
Gallium	Indium		Platinum	Niobium	Titanium	Tellurium	*Manganese	12
Arsenic	Gallium		Germanium	Selenium		Zinc	*Selenium	11
Magnesium	REE		FerroChrome	Thallium		Bismuth	*Titanium	10
Tantalum	Lithium		Tungsten	Vanadium		Chromium	*Strontium	9
Selenium	Tantalum		Tantalum	Copper		Fluorine	*Graphite	8
Cadmium	Palladium		Niobium	Lead		Lead	*Tin	8
Lithium	Platinum		Cobalt	Zinc		Lithium	*Germanium	8
Vanadium	Ruthenium		Ferro-manganese	Aluminium		Silicon	*Beryllium	7

United Kingdom[1]	EU low C energy[2]	European Union[4]	United States DoE[5]	South Korea[7]	Japan[8]	Willis and Chapman (2012)[9]	This study[10] *ranking	Score[10]
Tin	Germanium		Beryllium			Silver	*Zirconium	6
Fluorine	Cobalt		Chromium			Titanium	*Bismuth	6
Silver	Titanium					Zirconium	*Fluorine	6
Chromium	Magnesium						Zinc	5
Nickel							*Mercury	3
Rhenium							*Thorium	3
Lead							*Arsenic	3
Diamond							Lead	3
Manganese							*Barium	3
Gold							Silver	2
Uranium							*Cadmium	2
Zirconium							*Copper	2
Iron							Aluminium	2
Titanium							*Rhenium	1
Aluminium							Gold	1
Zinc							Uranium	1
Copper							Diamond	1
							Iron	1
							*Helium	

*Commodity included in this study; helium was not ranked in any of the cited studies

1 British Geological Survey (2012).

2 European Commission (2011).

3 Buchert et al. (2010).

4 European Commission (2010).

5 US Department of Energy (2010).

6 US Department of Defence National Defence Stockpile with Sales Suspended or Restricted (2009). (Not ranked in any order of importance, hence assigned category two criticality = orange).

7 Korean Institute of Industrial Technology: Bae (2000).

8 JOGMEC (2010).

9 Willis and Chapman (2012: summary and consolidation of other lists in the table).

10 Overall rankings in this study were calculated by summing the individual scores for each commodity in each of the UK, EU, US, South Korea and Japan studies, as follows: red = 5 points, orange = 3 points, blue = 1 point. The results in this study are coloured red, orange and blue with arbitrary cut-offs between scores of 10 and 12 and between 3 and 5 to indicate category one criticality (red), category two criticality (orange), and category three criticality (blue).

The most critical commodities are (in order of score shown in final column of Table 1.4.1): rare-earth elements, gallium, indium, platinum-group elements (in particular platinum and palladium), tungsten, niobium, cobalt, lithium, vanadium, nickel, molybdenum, tantalum and chromium. It should be noted that among the rare-earth elements there is considerable variation in criticality with the heavy rare-earth elements at the highest level whereas the light rare-earth elements, scandium and yttrium are less critical.

The assessments of criticality are essentially snapshots current at the time of the assessments, and in most cases do not take into account changes in future demand for the particular commodities. This report identifies possible critical commodities of which Australia has current or potential resources. Table 1.4.2 compares demand in 2006 with projected demand in 2030, for selected critical commodities plus copper, in the emerging technologies sector (European Commission, 2010). In 2006 the demand from emerging technologies generally comprised only a small to moderate fraction of global production (up to factor of 0.4; see column, Indicator 2006). Importantly, projected annual demand in 2030 for gallium, indium, germanium, neodymium, platinum and tantalum all exceed current annual production (European Commission, 2010). Projected demand in 2030 is proportionately lower for silver, cobalt, palladium, titanium and copper than for the former elements. Nevertheless this analysis demonstrates that all of the commodities listed in Table 1.4.2 could experience large to very large growth in demand by 2030.

Table 1.4.2: Production 2006 tonnes and demand in 2006, and projected demand in 2030, from emerging technologies for selected commodities (European Commission, 2010).

Raw material	Production 2006 (tonnes)	Demand from emerging technologies 2006 (tonnes)	Demand from emerging technologies 2030 (tonnes)	Indicator[1] 2006	Indicator[1] 2030
Gallium	152	28	603	0.18	3.97
Indium	581	234	1911	0.40	3.29
Germanium	100	28	220	0.28	2.20
Neodymium (REE)	16 800	4000	27 900	0.23	1.66
Platinum (PGE)	255	very small	345	0	1.35
Tantalum	1 384	551	1410	0.40	1.02
Silver	19 051	5 342	15 823	0.28	0.83
Cobalt	62 279	12 820	26 860	0.21	0.43
Palladium (PGE)	267	23	77	0.09	0.29
Titanium	7 211 000[2]	15 397	58 148	0.08	0.29
Copper	15 093 000	1 410 000	3 696 070	0.09	0.24

1 The indicator measures the share of the demand resulting from driving emerging technologies in total demand for each raw material in 2006 and 2030.

2 Ore concentrate.

1.5 Australia’s potential for critical commodities

1.5.1 Assessment of Australia’s potential

This section assesses Australia's resource potential for selected critical commodities.

In Table 1.5.1 the key results of this review are summarised in two groups of commodities: those with category one resource potential and those with category two resource potential. These are extracted from Table 1.5.2 which presents a more comprehensive assessment, including those rated with category three resource potential (see below). These tables are the result of a synthesis and analysis of Parts 1 and 2 of this report.

Within each of the category one and category two resource potential categories the commodities are listed in order of criticality.

The assessments of resource potential in Table 1.5.1 are subjective judgements based on:

- Level of criticality;
- Australia's resources and potential for new discoveries;
- Market size; and
- Growth outlook.

It is notable that most of the commodities that have a category one resource potential are also regarded as critical by some countries that have undertaken studies of material criticality. There are several commodities that Australia has category one potential for resources, however they are considered to have category three criticality. One example of such commodities is copper, which has category one resource potential despite its category three criticality score as: (a) the growth outlook for copper is strong; (b) Australia's geology and resource potential are considered very favourable for discoveries of new copper resources; (c) and the market size is very large.

Seven of the commodities rated as having category two resource potential also are considered critical by the world's major economies (antimony, indium, lithium, molybdenum, niobium, tantalum, tungsten). Also in the category two group are six other commodities with a category two criticality ranking (beryllium, bismuth, graphite, manganese, tin, titanium). Only one other commodity, thorium, was assigned category two potential despite its category three criticality rating. This assessment reflects the possible growth in markets if emerging and new technologies using thorium (nuclear power generation) have greater rather than lesser uptakes in the medium to long term. The assessment also takes into account Australia's considerable resources of thorium. Helium was also assigned category two resource potential although it was not considered in criticality rankings.

Among the 12 commodities rated as having category three resource potential (Table 1.5.2), two are considered to be of category one criticality by countries (gallium and vanadium) and three of medium criticality (germanium, selenium and strontium). Many of these commodities are of small market size and/or have limited growth outlooks, and/or have low known and potential endowment in Australia. These judgements are a snapshot of the present situation which will change over time.

1.5.2 A mineral systems perspective on Australia's resource potential

An important conclusion of this report is that most of the commodities assessed as having category one and category two resource potential are geologically associated with three mineral system groups. In addition, a fourth opportunity exists for critical commodities that can be produced as by-products from existing operations.

Olympic Dam is a multi-mineral ore body that is mined for uranium, copper, gold and silver, but also contains significant amounts of rare-earth elements and other critical commodities. Image: BHP Billiton.

Mafic-ultramafic igneous-related mineral systems (Ni, PGE, Cr, Cu, Co, Ti)

The nickel and platinum-group element industries globally are very large yet known resources and production are concentrated in relatively few countries, for example platinum-group element industries in South Africa and Russia. Economic platinum-group element deposits are extremely rare and highly valuable. Australia's resource potential is high for discovery of major mafic-ultramafic intrusion-hosted nickel, platinum-group element and chromium deposits. Areas of known and inferred resource potential for these commodities are shown in Figure 1.5.1. A key issue is that many of the prospective terranes for sulfide nickel and platinum-group element deposits are concealed by layers of cover rocks that may be metres to hundreds of metres thick.

Australia also has major known resources of lateritic nickel, some of which are currently being exploited. There are potential opportunities to develop technologies for more efficient extraction of nickel and other associated elements such as scandium from these lateritic deposits.

Intermediate to felsic igneous-related mineral systems (Cu, REE, Be, Li, Mo, Nb, Ta, Sn, W, Bi, Sb)

Commodities associated with intermediate to felsic igneous-related mineral systems are varied. In detail the composition of magmas with which these systems are associated are also varied and include intermediate, evolved felsic and alkaline magmas. Unlike the mafic-ultramafic igneous-related systems, resources and production of commodities associated with intermediate to felsic magmatism are much more widespread, with Australia possessing significant resources of many of the associated critical commodities. At present, Australia is a major producer of copper and lithium, and in the past it has been a major producer of antimony, tantalum, tin and tungsten. Regions of current and historic production (some of which have significant identified resources) must be considered regions with significant potential for additional discovery (Figure 1.5.2).

In addition to commodities with historic or current production, Australia is emerging as a potential producer for commodities such as rare-earth elements and molybdenum.

Surface-related mineral systems, particularly heavy mineral sand deposits (Zr, Ti, REE, Th)

The third mineral system offering category one resource potential for Australia is heavy mineral sands. Government supported work in South Australia was crucial in the identification and discovery of a major new mineral sands province, resulting in several currently operating mines. These mineral systems not only host major industrial commodities such as titanium and zirconium but also contain significant resources of rare-earth elements and thorium. Figure 1.5.3 shows the distribution of major historic and existing mineral sand operations in Australia.

Light rare-earth elements in mineral sand deposits represent very large resources that may be exploited in the future. The rare-earth elements and thorium in these deposits are mainly locked up in monazite and are not currently extracted. Monazite is returned to the pit in a dispersed form, as required by mining regulations. Extraction of rare-earth elements may be more viable where low-thorium monazite is present in mineral sand deposits.

Use of critical commodities: (a) Magnets in wind generators. (b) Photovoltaics. Images: (a) Wongm, Wikimedia Commons. (b) Christoffer Riemer, Wikimedia Commons.

Recovery of by-products from existing ores and concentrates

Several commodities are produced as co-products or by-products of major metal mining; platinum-group element recovery from some nickel ores is an example of co-production. Among those commodities assessed as having medium resource potential, antimony, bismuth and indium are by-products of base metal and/or gold mining, and lower resource potential by-products include cadmium, gallium, germanium, mercury, rhenium, selenium, tellurium and vanadium. The Olympic Dam deposit is one of the largest rare-earth element resources in the world, but at present rare-earth elements are not recovered. Where recovery is currently uneconomic, there may be improvements in mineral processing for ores containing significant concentrations of co-product and by-product elements.

For many Australian mines the minor-element compositions of ores and concentrates are not well known or not published. However, preliminary calculations in this study for several of Australia's base and precious metal ore bodies indicate the potential for substantial resources of elements such as antimony, indium cadmium, gallium, germanium, mercury, rhenium, selenium, and tellurium (see Part 2). In addition, it is known that gallium, germanium and rare-earth elements are enriched in some coal deposits (Dai et al., 2006; Qi et al., 2007; Seredin, 2005). Finally, phosphate deposits are a potentially important source of rare-earth elements as well as other metals such as uranium; Australia is relatively well endowed with phosphate deposits such as those in the Georgina Basin (Northern Territory and Queensland), but the minor-metal compositions of these deposits are not well understood.

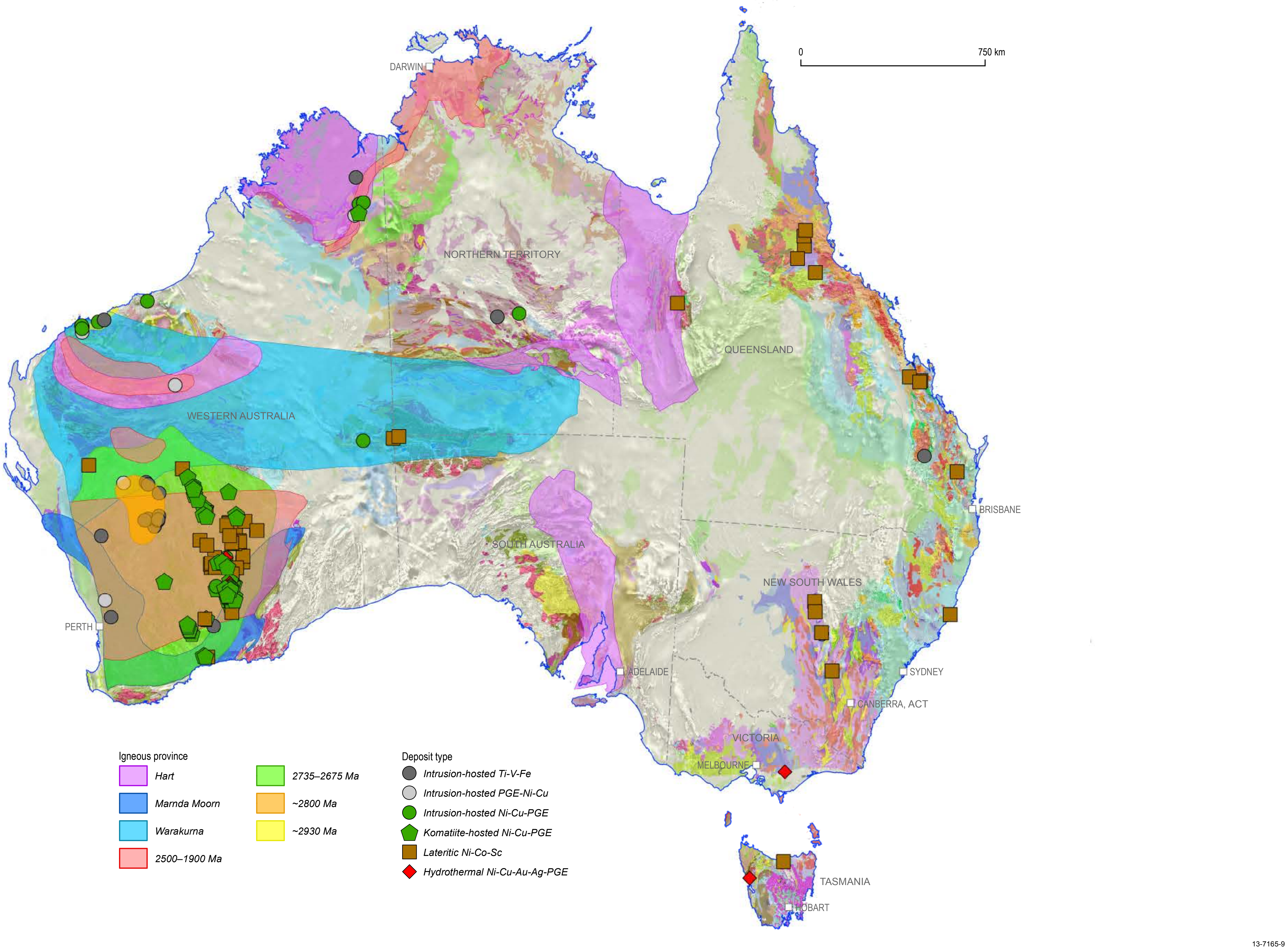


Figure 1.5.1: Distribution of mineral deposits associated with mafic-ultramafic magmatism (locations from OZMIN) and the extents of mineralised igneous provinces (from Hoatson et al., 2008, 2009; Claoue-Long et al., 2009). The background is transparent surface geology draped over reduced-to-pole aeromagnetic data. The legend for the surface geology is presented in Figure 1.5.5.

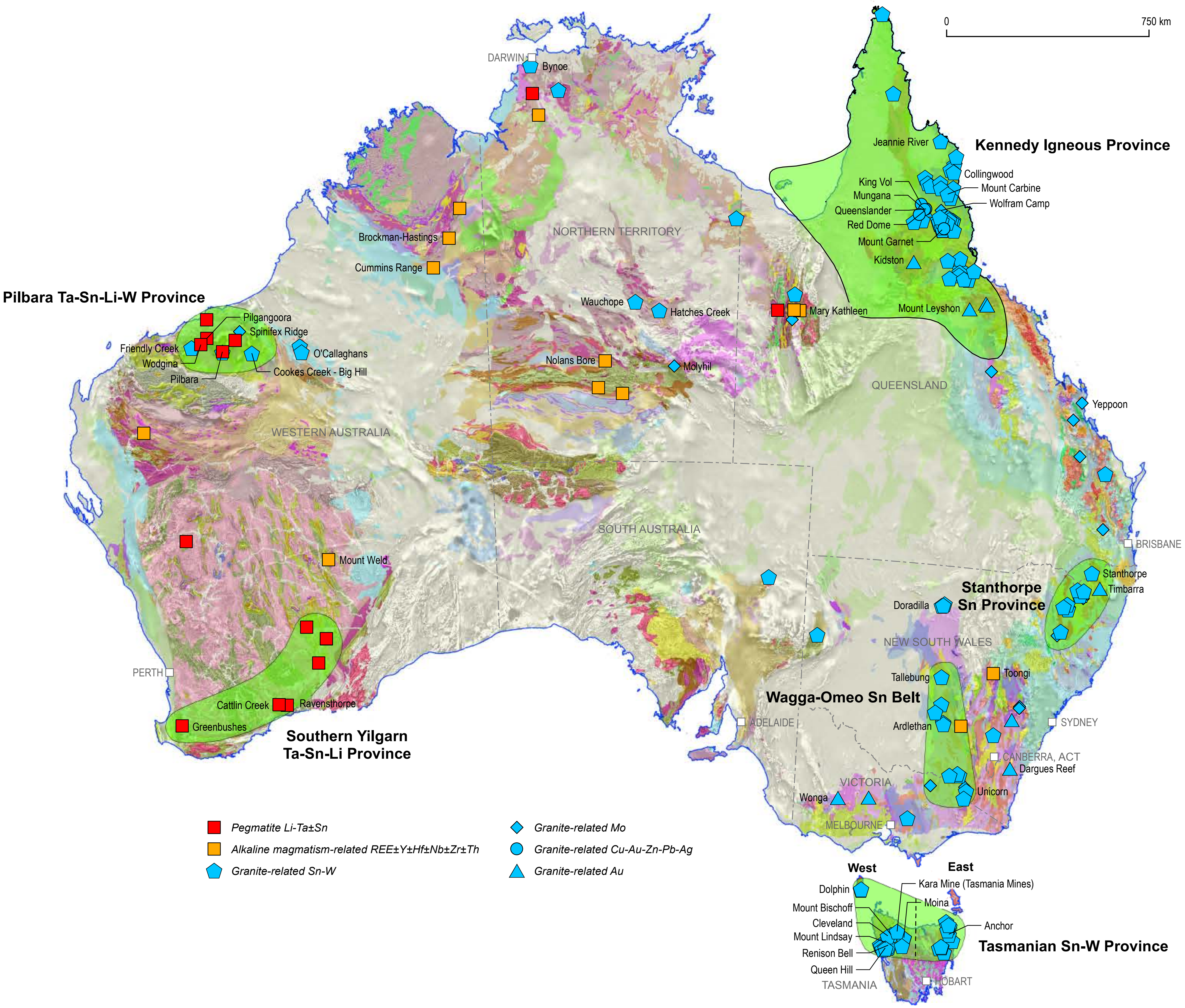
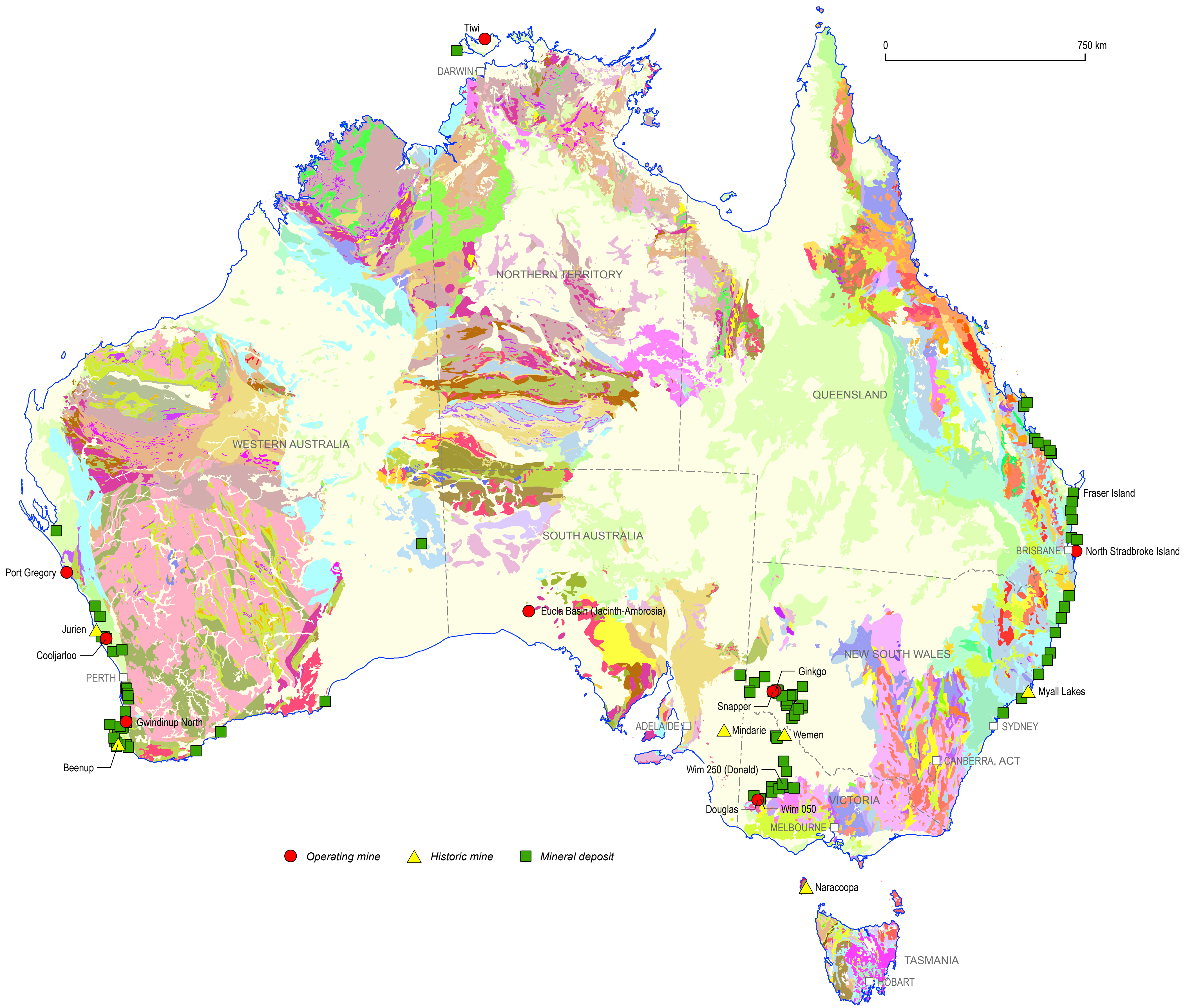
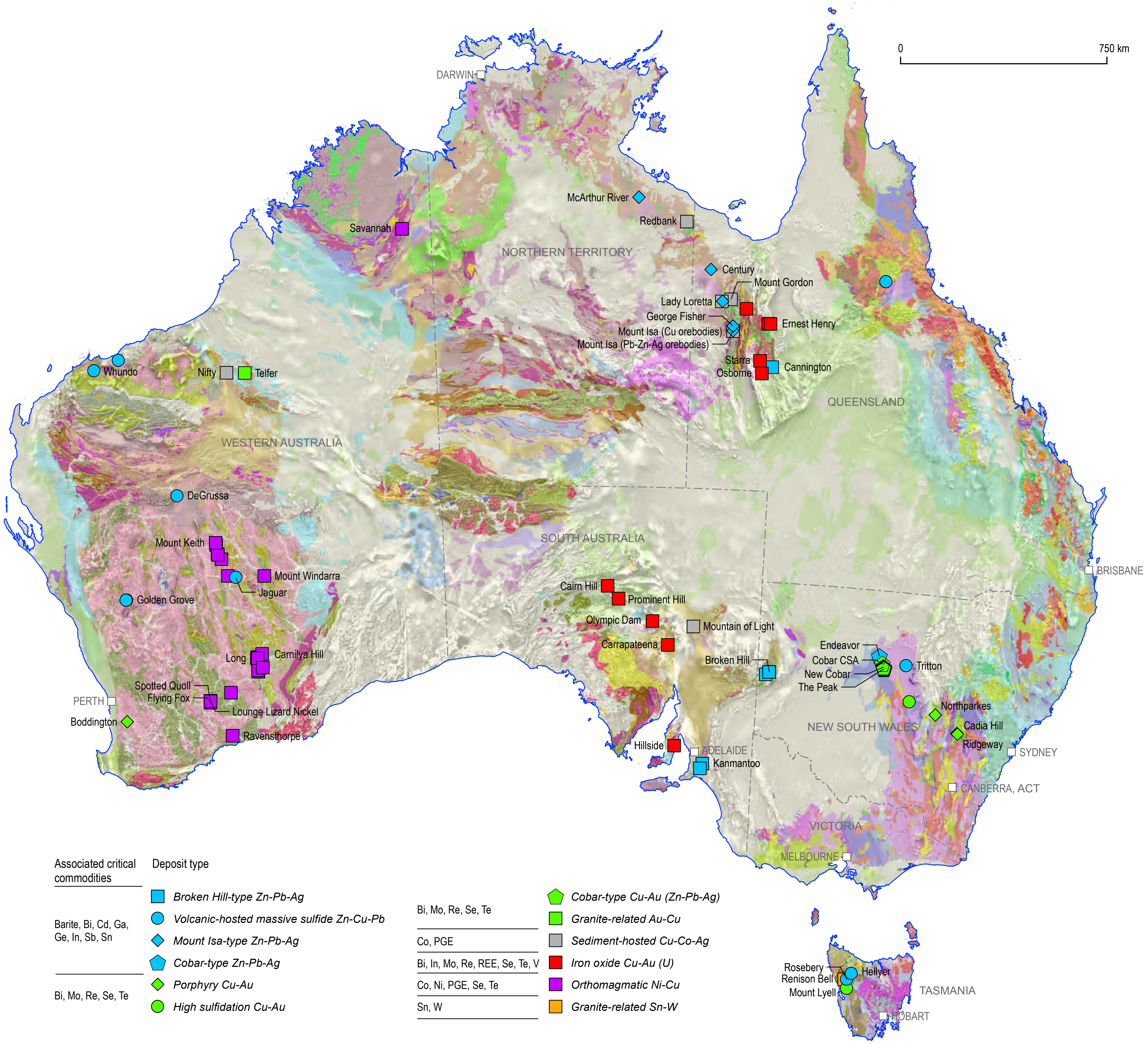


Figure 1.5.2: Distribution of mineral deposits associated with granitic and alkaline magmatism (locations from OZMIN). The location of the Kennedy Igneous Province is from Champion and Bultitude (2013) and D Champion (pers. comm., 2013). The background is transparent surface geology draped over reduced-to-pole aeromagnetic data. The legend for the surface geology is presented in Figure 1.5.5.



13-7165-11

Figure 1.5.3: Distribution of mineral deposits associated with heavy mineral sand placer deposits (from OZMIN). The background is surface geology. The legend for the surface geology is presented in Figure 1.5.5.



13-7165-12

Figure 1.5.4: Distribution of operating of recently closed mines illustrating the existing and potential recovery of critical commodities as by-products. The background is transparent surface geology draped over reduced-to-pole aeromagnetic data. The legend for the surface geology is presented in Figure 1.5.5.

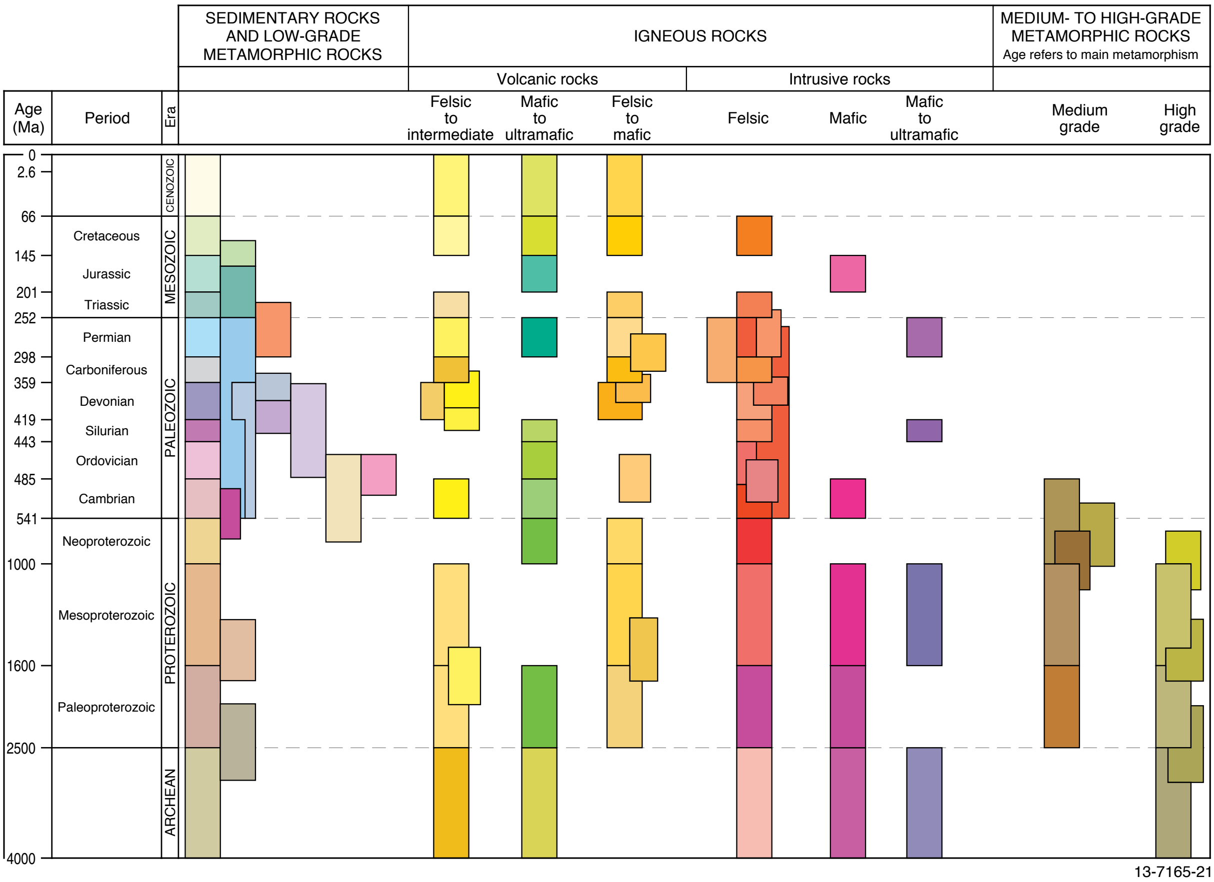


Figure 1.5.5: Legend for surface geology drape in Figures 1.5.1 to 1.5.4 and Figure 2.2.1.

Table 1.5.1: Summary of key results of assessment: category one and category two resource potential.

Category one resource potential	Criticality
Rare-earth elements (including scandium and yttrium)	29
Platinum-group elements	22
Cobalt	21
Nickel	13
Chromium	12
Zirconium	6
Copper	2

Category two resource potential	Criticality
Indium	26
Tungsten	23
Niobium	20
Molybdenum	15
Antimony	14
Lithium	14
Tantalum	13
Manganese	12
Titanium	10
Graphite	8
Tin	8
Beryllium	7
Bismuth	6
Thorium	3
Helium	N/A

Table 1.5.2: Summary of results: assessment of Australian potential to supply critical commodities.

Commodity (Ordered by potential)	[1]**Criticality ranking (score)**	[2]**Australian production (2011) as % of global**	[3]**Economic resources World; Australia**	[4]**Scale of market; import value for largest importer ($US)**	**Context**
Rare-earth elements, including scandium and yttrium 🟥	Category one (29) 🟥	0%	114 000 kt[5] REO & Y_2O_3; 2070 kt REO & Y_2O_3	REE: Although Japan is the largest importer, value of imports is not available; the value of imports into the US was $615 million in 2012. Sc: very small Y: very small	China dominates production and resources of REE; current and medium term demand for light REE probably will be met with new global production but a shortfall in heavy REE production is projected; Australia has major REE resources in mineral sand, iron-oxide copper-gold and igneous-related mineral systems, and has emerging new heavy REE provinces. Australia has Sc resources in lateritic Ni deposits but the Sc market is very small currently.
Platinum-group elements (including Pt and Pd) 🟥	Category one (22) 🟥	0.1%	66 000 t[6]; 4.7 t	$5960m, large	Supply of PGE is dominated by South Africa and Russia; Australia has category one potential for discoveries of new resources due to favourable geology; widespread demand expected to grow due to uses in vehicles, clean energy technologies and desalination.
Cobalt 🟥	Category one (21) 🟥	4%	7334 kt; 1204 kt	$850m, large	Democratic Republic of Congo dominates Co production and resources but China is leading importer; Co is a key element in emerging technologies on a foundation of industrial uses, hence good growth outlook; Australia has substantial resources and category one potential for basin-related Co (with Cu).
Nickel 🟥	Category one (13) 🟥	12%	76 000 kt; 20 400 kt	$4905m, large	Nickel is a major industrial commodity with China dominating demand; Australia has the world's largest resources (mostly in lateritic Ni deposits), but the metallurgy of these deposits has limited the development; Australia has category one potential for discovery of major new Ni sulfide deposits.
Chromium 🟥	Category one (12) 🟥	0.3%	>480 000 kt; n.a.	$2663m, very large	Chromium is a key industrial commodity with production and resources dominated by South Africa and Kazakhstan but demand from mainly China; Australia has significant potential for large Cr resources although known deposits and production are small.
Zirconium 🟥	Category two (6) 🟧	53%	62 320 kt ZrO_2; 31 320 kt ZrO_2	$1174m, large	Australia holds 50% of world resources of Zr (as zircon, $ZrSiO_4$) within heavy mineral sand deposits); major new provinces have been discovered in Australia; its industrial use in ceramics and demand from China should ensure a strong medium-long term position for Australian supply.
Copper 🟥	Category three (2) ▬	6%	690 000 kt; 86 700 kt	$15 339m, very large	Copper is a foundation industrial commodity, but has category three criticality; due to size of industry and expected growth in demand it is crucial for Australia's mining and exploration industries and with significant potential for new discoveries (basin-related; IOCG; etc).
Indium 🟧	Category one (26) 🟥	n.a.	n.a.	$420m for Ga, Hf, In, Nb, Re; small for In	Indium is a by-product of Zn production; Australia has world's largest Zn resources (mainly basin-related mineral systems) hence potential to recover In; however, the market is currently small with global production of just 0.64 kt.

Category one 🟥 Category two 🟧 Category three ▬

Small <$100m Medium $100–1000m Large >$1000m Very large >$10 000m (m denotes million)

Commodity (Ordered by potential)	[1]Criticality ranking (score)	[2]Australian production (2011) as % of global	[3]Economic resources World; Australia	[4]Scale of market; import value for largest importer ($US)	Context
Tungsten	Category one (23)	0.02%	3300 kt; 376 kt	$159m, medium	Resources and production of W are dominated by China; Australia's resources and potential are considerable, in mainly granite-related mineral systems; demand mainly from China, the US and the EU. Australia has several deposits at feasibility study stage.
Niobium	Category one (20)	n.a.	3000 kt; 205 kt	$420m for Ga, Hf, In, Nb, Re; small or medium for Nb	Brazil dominates production and resources of Nb; Australia holds significant resources in pegmatites and also in some REE deposits.
Molybdenum	Category one (15)	0%	10 100 kt; 167 kt	$815m, medium	Molybdenum is a major industrial commodity; production and resources dominated by China, the US and Chile where most Mo occurs in porphyry Cu and Mo deposits; molybdenite is the main host for the commodity Re; Australia is less endowed with Mo-rich porphyry deposits but has high grade Mo-Re resources in Queensland.
Antimony	Category one (14)	1%	1800 kt; 106 kt	$206m, medium	China dominates production, resources and demand; Hillgrove Sb-Au (NSW) has largest identified Sb resource outside China; significant Sb resources are also contained in known Zn-Pb-Ag deposits in Australia but recovery may not be economic at present. Several Australian deposits are expected to come online.
Lithium	Category one (14)	34%	13 000 kt; 1 006 kt	$108m, medium	Australia is currently the second largest Li producer after Chile but delineation of major resources globally may meet Li demand in short-medium term; development of emerging energy technologies may change the demand outlook; extraction of Australia's hard-rock Li resources is relatively high-cost; Australia's salt lakes and saline groundwaters have unknown potential.
Tantalum	Category one (13)	10%	131 kt; 62 kt	Not available	Australia holds second largest resources (in pegmatites) but produces only 10% of world's Ta; Ta is an important element in high-tech industries although market is small.
Manganese	Category one (12)	17%	1646 Mt[7] Mn ore; 197 Mt Mn ore	$199m; medium	Major industrial commodity; Australia is a major producer (mainly from one deposit) with substantial resources; potential for undiscovered deposits unclear.
Titanium	Category two (10)	15% ilmenite 62% rutile	Ilmenite: 1235 Mt; 189 Mt Rutile: 51.3 Mt; 27.2 Mt	$549m, medium	Ilmenite and rutile are major industrial minerals; Australia has strong resource position with discoveries being made of new mineral sand provinces.
Graphite	Category two (8)	0%	77 000 kt[5]; n.a.	$134m, medium	Development of large scale fuel-cell applications could drive strong future demand for graphite; China and India dominate production and resources; only small deposits are known in Australia although potential in high-grade metamorphic terranes could be significant.
Tin	Category two (8)	2%	4 863 kt; 243 kt	$434m, medium	The uses of Sn in high-tech industries may sustain demand; Australia has considerable Sn resources and good potential for discovery of additional granite-related deposits.

Category one 🟥   Category two ▬   Category three ▬

Small <$100m   Medium $100–1000m   Large >$1000m   Very large >$10 000m (m denotes million)

Commodity (Ordered by potential)	[1]Criticality ranking (score)	[2]Australian production (2011) as % of global	[3]Economic resources World; Australia	[4]Scale of market; import value for largest importer ($US)	Context
Beryllium	Category two (7)	0%	n.a.	$4259m, large	Beryllium minerals are relatively rare so recycling is significant (19%); the US dominates production and is the leading importer; Be is a strategic element, used in military and electronic applications; pegmatites are the main source of Be; Australia has some world-class pegmatite (Li, Nb, Ta) deposits but resources of Be are unknown.
Bismuth	Category two (6)	0%	320 kt; n.a.	$41m, small	China dominates production and resources; no Australian EDR but past production was significant from Tennant Creek; there is potential for new Bi resources with granite-related W and Sn deposits and in some volcanic-related Cu-Pb-Zn deposits.
Thorium	Category three (3)	0%	1400 kt ThO_2; n.a.	$21m, small	Australia has 29% of global resources, second to the US, in mainly heavy mineral sand deposits; currently there is no market for Th. Development of new-generation nuclear reactors could provide major potential for Australian suppliers.
Helium	Not assessed	very small	n.a.	$86m, small	Based on limited data US dominates production and resources, and EU and Japan are the largest importers; as an emerging major global player in conventional and unconventional gas resources, Australia may have very considerable He resources but they are currently undefined.
Gallium	Category one (29)	0%	n.a.	$420m for Ga, Hf, In, Nb, Re; small for Ga	Gallium is a by-product of treating bauxite (Al ore) and Zn; although reserve and resource data are unavailable; Australia's high global rankings in resources of bauxite and Zn mean there is category one potential for significant Ga resources; however, current market is very small (216 kg global primary production), limiting the potential.
Tellurium	Category one (13)	0%	n.a.	$109m (with boron), medium	Some Australian volcanic-hosted massive sulphide deposits have significant Te but Australian resources and potential are unclear; there may be potential to recover Te from copper concentrates.
Vanadium	Category one (13)	0%	15 000 kt; 1519 kt	$16m, small	The European Union, Japan, Russia and China are main importers of V, which is used primarily in steel making; Australia resources are considerable but market and growth are limited.
Selenium	Category two (11)	0%	93 kt	$186m, medium	China is the main importer of Se; growth in solar cell use may result in increased demand for Se, which is a by-product of mainly Cu and Ni refining; Australia has no resources in EDR category but recovery from Cu and other ores may represent a potential source.
Germanium	Category two (8)	0%	n.a.	$0.1, small	Very small market and recycling mean Ge offers limited potential; nevertheless, as Ge is a by-product of Zn smelting, Australia could be well-placed as a potential supplier.
Strontium	Category two (8)	0%	6800 kt; n.a.	$24m, small	Strontium is an industrial element of small market size; limited potential exists in Australia.

Category one 🟥 Category two 🟧 Category three ▬

Small <$100m Medium $100–1000m Large >$1000m Very large >$10 000m (m denotes million)

Commodity (Ordered by potential)	[1]Criticality ranking (score)	[2]Australian production (2011) as % of global	[3]Economic resources World; Australia	[4]Scale of market; import value for largest importer ($US)	Context
Fluorite	Category two (6)	0%	240 000 kt fluorite; n.a.	$78m, small	Fluorite is an industrial commodity; Australia's resources and potential are limited.
Arsenic	Category three (3)	0%	n.a. but very large	$5518m, large	Due to toxicity of As, substitution in wood treatment may reduce demand although semiconductor uses may grow; China is main producer; Australian resources are unknown but potential exists to recover as by-product from pyrite-rich deposits (common).
Barium	Category three (3)	0%	7800 kt barite ($BaSO_4$); n.a.	$148m, medium	China dominates production and resources; minor historic Australian production and no EDR; barite is associated with some volcanic-hosted massive sulphide deposits but limited potential for new deposits; hence little potential for Australia to have impact on global supply.
Mercury	Category three (3)	0%	93 kt; n.a.	$28m, small	Asian economies dominate demand whereas Mexico and China hold largest resources; substitution and recycling may impact demand outlook; some Australian Zn-Pb-Ag deposits may contain significant Hg (1 kt) but its potential for recovery as a by-product is unknown.
Cadmium	Category three (2)	2%	640 kt; 61 kt	$27m, small	Recycling and substitution of NiCd batteries may impact growth outlook; as Cd is a by-product of Zn production, Australia is well placed to increase its production, due to its world-leading Zn resource position; however market is currently very small.
Rhenium	Category three (1)	0%	2.5 kt; n.a.	$420m for Ga, Hf, In, Nb, Re; small or medium for Re	Rhenium production is mostly as a by-product of Mo refining from porphyry Mo and Cu deposits, hence Chile and US are major producers and resource holders; Australia has a high grade resource in Qlueensland.
Category one 🟥	Category two 🟧	Category three —		Small <$100m Medium $100–1000m Large >$1000m Very large >$10 000m (m denotes million)	

1 *Criticality ranking* is from Table 1.4.1 (see column 'This study'), which is based on synthesis of non-Australian country's assessments of criticality for their nation.

2 *Australian production as percent of world production* is based on Geoscience Australia (2013) and United States Geological Survey (2012) data for 2011.

3 *Economic resources, world and Australia* data are from Geoscience Australia (2013) where available and USGS data for 2011.

4 *Scale of market - import value for largest importer* data are from UN comtrade database (www.comtrade.un.org).

5 *Kilotonnes (kt), 1000 tonnes*

6 *Tonnes (t)*

7 *Megatonnes (Mt), 1 000 000 tonnes*

Part two

Geology of Critical Commodities, and Australia's Endowment and Potential

David Huston, Terry Mernagh, Helen Dulfer, Roger Skirrow

2. Introduction

2.1 A mineral systems framework for critical commodities

The critical commodities discussed in this report differ from more broadly traded commodities such as Cu, Zn, iron ore and Au in that they are either traded, at present, to a very limited extent, or have a restricted resource and/or production base. Many critical commodities are produced as by-products and are recovered late during the metallurgical recovery process. In many cases, grades of these commodities are poorly constrained or unknown, resulting in highly uncertain resource estimates for Australia and the world. Reserve and resource data (both JORC-compliant or pre-JORC) are not available for many critical commodities (e.g., Te, Hg, As, Ga, In, Ge, Cd, fluorite and Se), and many critical commodities (e.g., As, Sb, Bi, Cd, Hg, Se and Te) attract penalties during the smelting of concentrates the major economic metal such as Ni or Cu etc.

Although mineral deposits have diverse characteristics in Australia and globally, these deposits can be related using temporal and genetic relationships, the tectonic setting in which they formed and the chemical characteristics of their host (and, hence, ore fluid) into a small number of mineral systems. Following the concept of a petroleum system (Magoon and Dow, 1994), Wyborn et al., (1994) defined a mineral system as 'all geological factors that control the generation and preservation of mineral deposits'.

Table 2.1.1 groups mineral deposits into nine broad mineral systems, including porphyry-epithermal, granite-related, iron oxide-copper-gold, subaqueous volcanic-related, mafic-ultramafic orthomagmatic, orogenic, basin-related, alkaline, and surficial. For each of these mineral systems, we summarise their characteristics and constituent deposit types, briefly describe important Australian examples and discuss potential to contain critical commodities. The locations of these deposits are shown in Figure 2.1.1.

A nickel mine in Western Australia. Image courtesy of Thiess Pty Ltd.

Table 2.1.1. Characteristics of major mineral systems.

Mineral system (included deposit-types)	Tectonic/geodynamic setting	Geological setting	Redox state of metal-bearing fluids	Geodynamic driver	Fluid driver
Porphyry-epithermal (porphyry Cu-Au-Mo, low sulfidation epithermal, high sulfidation epithermal, skarn)	Convergent–magmatic arc	Volcanic-plutonic igneous province	Weakly oxidised to weakly reduced ($\Sigma H_2S \sim \Sigma SO_4$ to $\Sigma H_2S > \Sigma SO_4$); strongly oxidised ($\Sigma SO_4 > \Sigma H_2S$) fluids in high sulfidation epithermal deposits	Change in subduction (direction, speed or dip angle)	Magmatism (magmatic fluids and/or convection of ambient fluids)
Granite-related (intrusion-related gold, intrusion-related Sn-W, porphyry Mo, pegmatitie rare metal, Rossing-type U?)	Convergent, generally inboard from arcs generally with post-collisional timing	Volcanic basin	Moderately to strongly reduced ($\Sigma H_2S > \Sigma SO_4$ to $\Sigma H_2S >> \Sigma SO_4$)	Collision and accretion, change in subduction (direction, speed or dip angle)	Felsic magmatism (magmatic fluids and/or convection of ambient fluids)
Iron-oxide copper-gold (Olympic Dam-type IOCG, Andean-type IOCG, Cloncurry-type IOCG; Tennant-type IOCG)	Convergent, distal back-arc to within-plate; near craton margins	Pre-existing back-arc or continental rift basin host settings; volcanic-plutonic provinces	Both highly oxidised ($\Sigma SO_4 > \Sigma H_2S$) and weakly to moderately reduced ($\Sigma H_2S \sim \Sigma SO_4$ to $\Sigma H_2S > \Sigma SO_4$)	Shift from contraction to extension	Mafic and felsic magmatism (convection of ambient fluids and magmatic fluids)
Mafic-ultramafic orthomagmatic (komatiite-associated Ni-Cu, mafic-ultramafic intrusion-hosted Ni-Cu, PGE and Fe-V-Ti)	Convergent–back-arc, divergent	All types of basin and basement	Not applicable	Change in subduction (direction, speed or dip angle), plate reorganisation, meteorite impact	Mafic-ultramafic magmatism
Subaqueous volcanic-related (volcanic-hosted massive sulfide, Broken Hill-type Zn-Pb-Ag)	Convergent–back-arc, divergent	Back-arc basin, transpressional basin, ensialic rift	Weakly to strongly reduced ($\Sigma H_2S \sim \Sigma SO_4$ to $\Sigma H_2S >> \Sigma SO_4$)	Change in subduction (direction, speed or dip angle), plate re-organisation	Magmatism (magmatic fluids and/or convection of ambient fluids–seawater)
Orogenic (lode gold, Cobar-type Cu-Au-Zn-Pb-Ag, Couer d'Alene Ag-Zn-Pb)	Convergent–collision and post-collision	Volcanic, back-arc, for-arc, platform/passive margin, rift, sag	Mostly reduced ($\Sigma H_2S > \Sigma SO_4$)	Collision and accretion, change in subduction (direction, speed or dip angle)	Magmatism (magmatic fluids and/or convection of ambient fluids), topography; deformation, metamorphic devolatilisation
Basin-hosted (Mt Isa-type Zn-Pb-Ag, Mississippi Valley-type Zn-Pb, sediment-hosted Cu-Co-Ag, unconformity-related U, sandstone-hosted U, calcrete-hosted U, iron ore, phosphate, graphite)	Late convergent–back-arc, divergent, early basin inversion	(Rifted) passive margin, platform, ensialic basins	Mostly oxidised ($\Sigma SO_4 > \Sigma H_2S$) fluids, although sedimentary precursors (banded iron formation, carbonaceous shale) form under mixed conditions prior to upgrading by later processes	Extension, plate reorganisation, basin inversion	Plate reconfiguration and shift in stress (extension to contraction or visa-versa); basin dewatering, convection, topography, tectonic pumping, post-orogenic magmatism
Alkaline intrusion-related (diamonds, REE deposits, peralkaline granite-related U-Th-REE)	Commonly within plate	All types of basin and basement		Unknown	Unknown
Surficial (placers [Au, Sn, heavy minerals, diamond, paleoplacer Au-U], supergene upgrading [secondary Cu, non-sulfide Zn and Pb, bauxite, channel iron, lateritic Ni-Co], salt lake Li-K-B)	All	Regolith, all types of basins	Both oxidised ($\Sigma SO_4 > \Sigma H_2S$) and reduced ($\Sigma H_2S > \Sigma SO_4$)	Uplift, climate change	Topography (for placers), meteoric (for supergene upgrading)

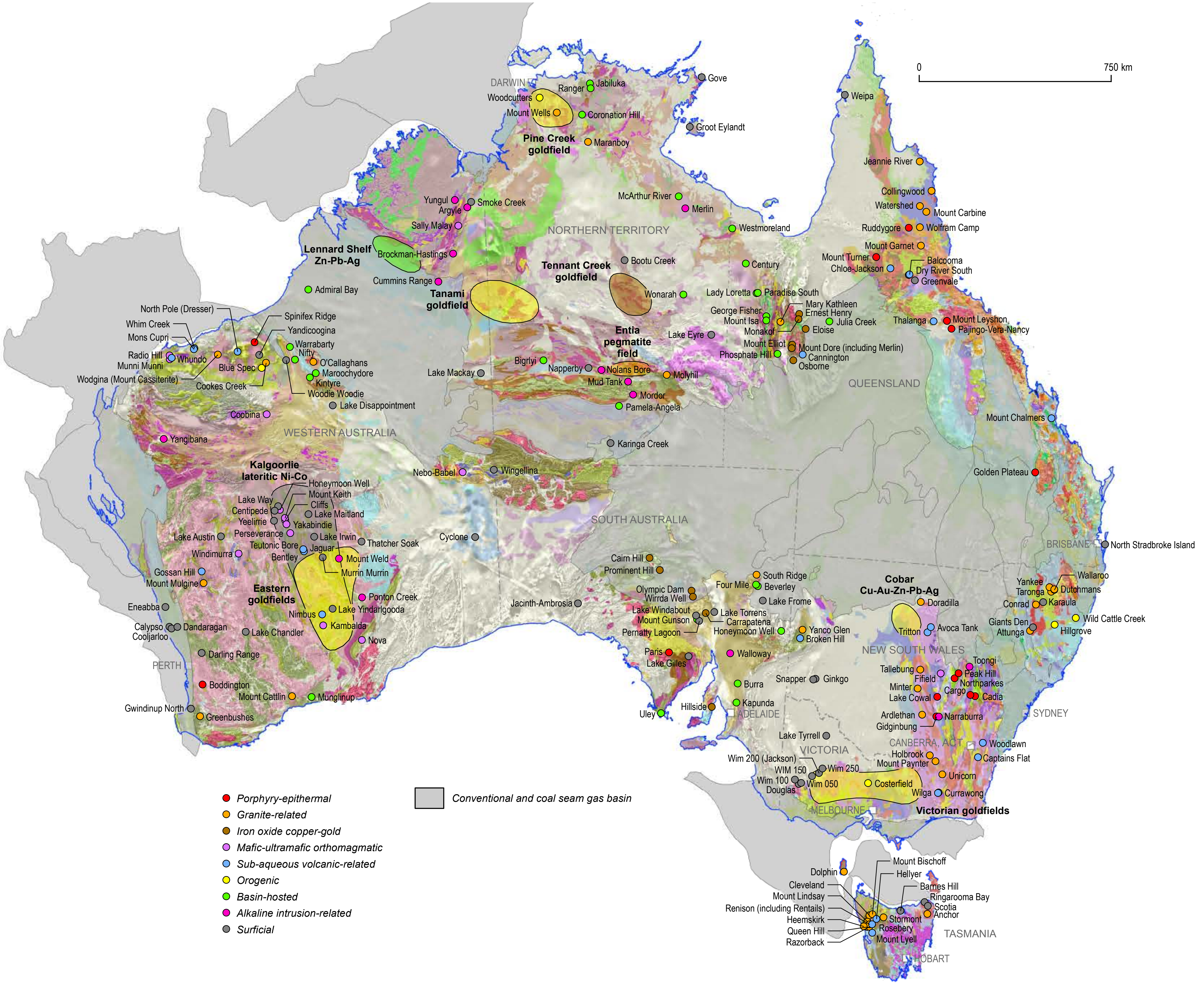


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Figure 2.1.1: Location of individual mineral deposits and mineral provinces mentioned in text. The background is transparent surface geology draped over reduced-to-pole aeromagnetic data. The legend for the surface geology is presented in Figure 1.5.5.

2.2 Porphyry-epithermal mineral system

Mineral deposits of the porphyry-epithermal mineral system are associated with magmatism that generally, although not exclusively, is associated with magmatic arcs within convergent geodynamic settings. This mineral system involves mainly magmatic-hydrothermal and meteoric fluids that form porphyry Cu-Au-Mo deposits[1], epithermal Au-Ag, Ag-Zn-Pb and Au-Cu deposits, and Cu-Au and Zn-Pb-Ag skarn deposits. More detailed descriptions of aspects of the porphyry-epithermal mineral system can be found in Buchanon (1981), White and Hedenquist (1995), Seedorff et al. (2005), Simmons et al. (2005) and Berger et al. (2008).

2.2.1 Geological setting

Mineral deposits that form in the porphyry-epithermal mineral system generally have a spatial and temporal association with intermediate to felsic sub-aerial volcanic rocks and related sub-volcanic intrusions. Although, geologically recent porphyry-epithermal mineral systems are mostly thought to form in magmatic arcs (both continental and oceanic) associated with convergent plate margins (Seedorff et al., 2005; Simmons et al., 2005), the geological setting of older examples is less clear, and some workers have suggested alternative settings that do not involve arcs (e.g., Hou et al., 2003). In all cases, deposits are thought to have formed at shallow crustal levels (<1.5 km for epithermal and <6 km for porphyry deposits: Seedorff et al., 2005; Simmons et al., 2005). This very shallow depth of emplacement and consequent low preservation potential account for the fact that geologically old (Paleozoic or older) deposits are uncommon (Seedorff et al., 2005; Simmons et al., 2005).

Figure 2.2.1 shows schematically the relationship of different deposits to geological features within the porphyry-epithermal mineral system. This diagram also distinguishes three types of epithermal deposits. Adularia-sericite Au-Ag (or low sulfidation[2]) and Ag-Zn-Pb (intermediate sulfidation) epithermal deposits are located schematically in the low temperature, periphery of the mineral system, with porphyry Cu-Au-Mo and pyrophyllite-kaolinite (high sulfidation or acid-sulfate) Au-Cu epithermal systems more proximal to intrusive bodies. Skarn deposits are also zoned in this mineral system, with Cu-rich skarns generally very close to the causative intrusion, but Zn-Pb-rich skarns more distal. An important feature of the porphyry-epithermal mineral system is the telescoping of different deposit types, for instance porphyry Cu-Au-Mo deposits and epithermal deposits of various types.

2.2.2 Sources of fluid, metals and energy

Although most workers concur that magmas were probably the energy source in the porphyry-epithermal mineral system, the evidence is not definitive as to the role of magmatic-hydrothermal fluids as sources of fluid, sulfur and metals. For deposit types more proximal to intrusive complexes, such as porphyry Cu-Au-Mo, pyrophyllite kaolinite Au-Cu epithermal and Cu-rich skarns, a direct magmatic-hydrothermal source for the fluids, metal and sulfur is likely (Arribas, 1995; Bodnar, 1995), but for the more distal adularia-sericite epithermal and Zn-rich skarn deposits, the evidence is less clear. Although Simmons et al. (2005) suggest a significant magmatic hydrothermal component for some adularia-sericite epithermal deposits, they also recognise that definitive evidence for such a component is not present in many deposits. In all cases, however, a significant meteoric fluid component is present (Simmons et al., 2005). In any case, the likely driver of fluid flow, whether magmatic-hydrothermal of heated meteoric, is probably magma emplacement.

2.2.3 Fluid pathways

In the porphyry-epithermal mineral system, pathways for fluids and their contained metals, ligands and sulfur include faults, stratigraphic aquifers and crystallising intrusive bodies. Crystallising intrusions are particularly important pathways for high-temperature, proximal deposits such as porphyry Cu-Au-Mo deposits and Cu-rich skarns. These deposits are commonly associated with phallic intrusions and apical zones of larger intrusions (Figure 2.2.1). The fluid pathways for epithermal and Zn-rich skarns include faults and stratigraphic aquifers. The volcanic-intrusive complexes generate geothermal systems which are focussed along these fluid pathways. Regional zones of propylitic alteration are indicative of convective fluid flow systems (Masterman et al., 2005).

2.2.4 Depositional processes

Mechanisms for ore deposition in the porphyry-epithermal mineral system are many and varied, with the main mechanisms being depressurisation and associated processes such as boiling, fluid mixing,

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[1] Porphyry Mo deposits have been included as part of the granite-hosted mineral system.

[2] We have adopted names for deposit types based on observable features (e.g., characteristic alteration assemblages) as opposed more abstract features such as sulfidation state.

cooling, and wall rock interaction. Mechanisms that form porphyry Cu-Au-Mo deposits include exsolution of a magmatic-hydrothermal fluid from the causative magma followed by cooling and mixing with meteoric fluids (Seedorff et al., 2005). Highly acidic ore fluids produced by disproportionation of magmatic SO_2 are neutralised by wall rock reaction or fluid mixing to produce pyrophyllite-kaolinite Au-Cu epithermal deposits (Simmons et al., 2005). In adularia sericite Au-Ag and Ag-Zn-Pb deposits, ore deposition is caused by boiling of the ore fluid as it approaches the paleosurface and/or by fluid mixing and cooling (Simmons et al., 2005). In skarn deposits, ore deposition is caused by acid neutralisation as the ore fluid interacts with carbonate rocks to form the skarn.

2.2.5 Australian examples

Because of the lack of major, geologically young, felsic to intermediate (i.e., Mesozoic and younger) magmatic belts, deposits of the porphyry-epithermal mineral system are not common in Australia. The most important Australian porphyry-epithermal mineral provinces are the Paleo- to Mesoarchean North Pilbara Terrane (Marshall, 1999), the Neoarchean Southwest Terrane (McCuaig et al., 2001), the Siluro-Ordovician Macquarie Arc and the Middle Carboniferous Drummond Basin (Champion et al., 2009). In addition, there are a number of smaller and/or emerging porphyry-epithermal mineral provinces elsewhere in Australia.

Cadia Hill open cut mine, an example of porphyry copper–gold deposits. Image: Alan Whitaker.

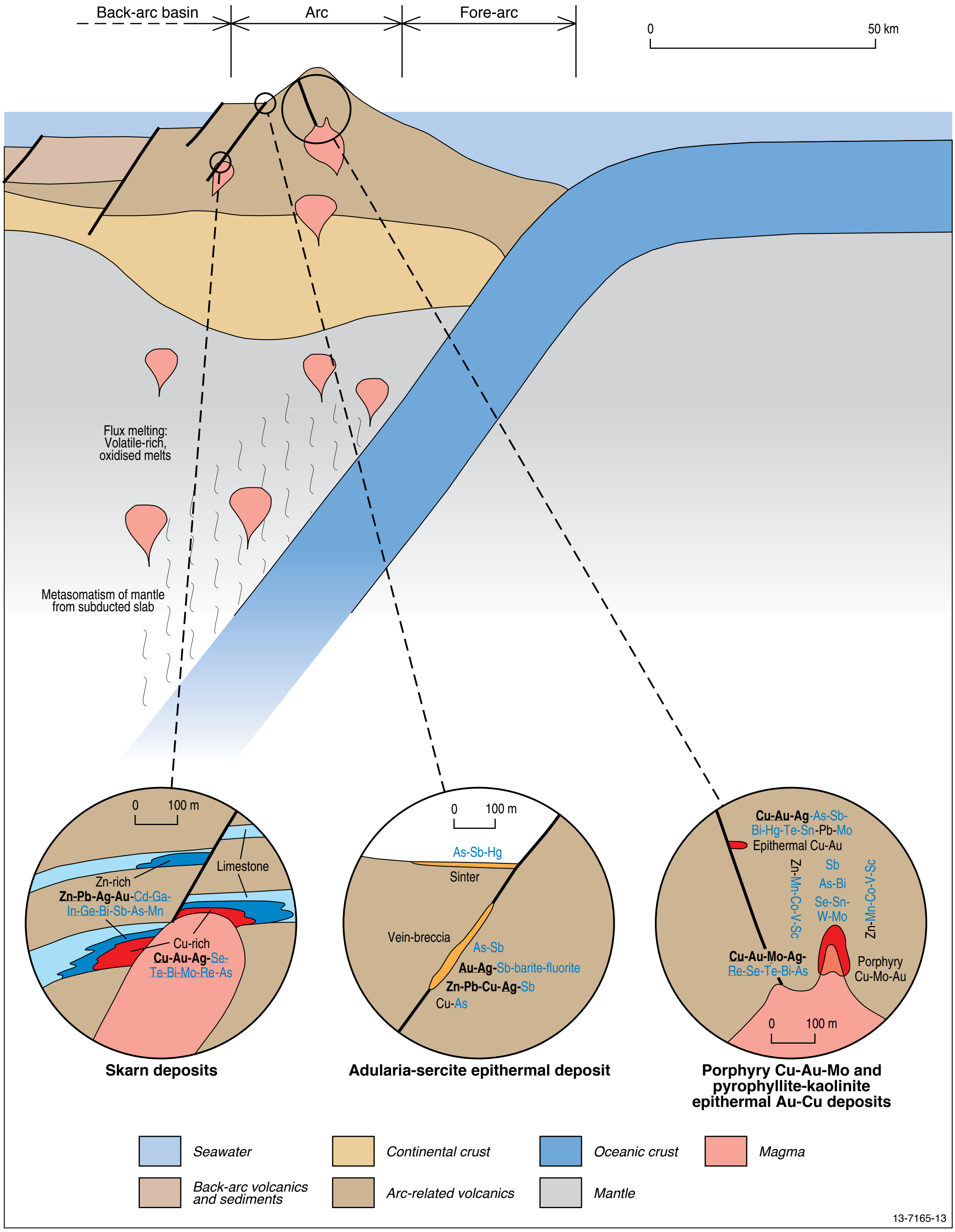

Figure 2.2.1: Diagrammatic sketch of the porphyry-related mineral system illustrating the relative location of deposits types within the overall setting and the likely distribution of critical and other commodities within and around these deposit types. In the commodity lists, blue indicates critical commodities, underlined bold indicates major products, bold indicates commonly recovered by-products, underlined normal font indicates commodities with limited recovery as a by-product (usually during downstream processing), and normal text indicates commodities that are geochemically anomalous, but not recovered.

Table 2.2.1: JORC- and NI43-101-compliant resources for undeveloped deposits with critical commodities in Australia.

Molybdenum deposits	State	Size (Mt)	Mo (%)	Cu (%)	WO_3 (%)	Re (ppm)	Ag (ppm)	Comments
Spinifex Ridge	WA	652	0.05	0.08			1.3	
Unicorn	VIC	203	0.036	0.048				
Molyhil	WA	1.64	0.13		0.42			
Merlin	QLD	6.9	1.4			23		Includes Little Wizard

Tin deposits	State	Size (Mt)	Sn (%)	W (%)	F (%)	Cu (%)	Zn (%)	Pb (%)	Ag (ppm)	In (ppm)	Comments
Rentails	TAS	19.331	0.44								Tailings of Renison mine
Mt Linday	TAS	43	0.2	0.1							At 0.2% Sn-equivalent cut-off grade
Heemskirk	TAS	4.4	1.1								Includes Queen Hill, Montana and Severn
Mt Garnet (Sn)	QLD	7.38	0.6								
Mt Garnet (F)	QLD	5.27			15.25						
Jeannie River	QLD	2.24	0.6								
Conrad	NSW	2.254	0.23			0.22	0.46	1.26	106.2	6.7	
Doradilla	NSW	7.81	0.28								
Ardlethan	NSW	3.025	0.42								

Lithium deposits	State	Size (Mt)	Li_2O (%)	Ta_2O_5 (ppm)	Comments
Mt Cattlin	WA	18.188	1.08	156	

Tungsten deposits	State	Size (Mt)	WO_3 (%)	Cu (%)	Zn (%)	Pb (%)	Mo (%)	Comments
Big Hill	WA	47.43	0.10					At 0.05% WO_3 cut-off grade
Mt Mulgine	WA	8.18	0.21					
O'Callaghans	WA	78	0.33	0.29	0.50	0.25		
King Island (Dolphin)	TAS	10.593	0.93				0.12	Excludes 2.7 Mt of tailings grading 0.17%WO_3.
Wolfram Camp	QLD	1.42	0.60					
Watershed	QLD	20.66	0.25					
Mt Carbine	QLD	59.4	0.12					Includes 12 Mt low grade stockpile
Attunga	NSW	1.29	0.61				0.05	

Bismuth deposits	State	Size (Mt)	Bi (%)	Au (ppm)	Ag (ppm)	Comments
Stormont	TAS	0.1508	0.17	2.89	3.82	At 0.5 g/t cut-off grade

Nickel-platinum group element deposits	State	Size (Mt)	Ni (%)	Cu (%)	PGE (ppm)	Au (ppm)	Co (%)	Comments
Munni Munni	WA	23.6	0.09	0.15	2.7	0.2		PGE distribution: 1.5 ppm Pd, 1.1 ppm Pd and 0.1 ppm Rh
Panton	WA	14.3	0.27	0.07	4.58	0.31		PGE distribution: 2.19 ppm Pt and 2.39 ppm Pd
Nebo-Babel	WA	392	0.3	0.3	0.18			
Nova	WA	10.2	2.4	1.0			0.08	

Antimony deposits	State	Size (Mt)	Sb (%)	Au (ppm)	WO_3 (%)	Comments
Hillgrove	NSW	6.349	1.6	4.3	0.02	
Wild Cattle Creek	NSW	1.59	1.29	0.16	0.0454	At 0.2% Sb cut-off
Blue Spec	WA	0.646	1.2	15.8		

Graphite deposits	State	Size (Mt)	Graphite (%)	Comments
Uley	SA	6.6	8.7	

Rare-earth element deposits	State	Size (Mt)	ZrO_2 (%)	HfO_2 (%)	Nb_2O_5 (%)	Ta_2O_5 (%)	Y_2O_3 (%)	TREO (%)	HREO (%)	ThO_2 (%)	Ga_2O_5 (%)	Comments
Toongi	NSW	73.2	1.96	0.04	0.46	0.03	0.14	0.75				
Narraburra	NSW	55	0.1	0.004	0.008		0.006	0.03				
Hastings-Brockman	WA	36.2	0.8913	0.0318	0.3546	0.0182		0.2102	0.1802		0.011	
Cummins Range	WA	4.17						1.72		0.0047		Also 11% P_2O_5 and 187 ppm U_3O_8

The North Pilbara Terrane contains a number of quartz veins with textures and mineralogies consistent with adularia-sericite deposits (Marshall, 1999), a significant porphyry Cu-Mo deposit and several pyrophyllite- and kaolinite-bearing alteration zones (Van Kranendonk and Pirajno, 2004). These porphyry-epithermal deposits range in age from ~3490 Ma to ~2760 Ma (Huston et al., 2002), with the Spinifex Ridge porphyry Cu-Mo deposit (Table 2.2.1) having an age of ~3300 Ma (Stein et al., 2007). The world-class Boddington deposit (total resources at 31 December 2010 of 1.53 Gt grading 0.102% Cu and 0.579 g/t Au), in the Saddleback Greenstone Belt of the Southwest Terrain of the Yilgarn Craton, is interpreted as a ~2707 Ma porphyry Cu-Au deposit that has been overprinted by a ~2629 Ma lode gold event (McCuaig et al., 2001: Stein et al., 2001).

The main porphyry-epithermal province in Australia is the Siluro-Ordovician Macquarie Arc in New South Wales, which contains major porphyry Cu-Au deposits at Cadia (global resource of 1.31 Gt at 0.31% Cu and 0.74 g/t Au: Cooke et al., 2007) and Northparkes (global resource of 153 Mt at 1.03% Cu and 0.46 g/t Au: Cooke et al., 2007). This province has many features of a magmatic arc and is interpreted as such by many workers (e.g., Crawford et al., 2007; Meffre et al., 2007). In addition to the major porphyry Cu-Au deposits, the Macquarie Arc also contains adularia-sericite Au-Ag and pyrophyllite-kaolinite Au-Cu epithermal deposits at Lake Cowal and Cargo, and at Peak Hill and Gidginbung, respectively (Cooke et al., 2007; Champion et al., 2009).

The fourth major Australian porphyry-epithermal province is the Drummond Basin in northeast Queensland, which contains several adularia-sericite Au-Ag deposits, the most important of which is Pajingo-Vera-Nancy (global resources of 43.5 t Au and 69.8 t Ag: Richards et al., 1998). Apart from these major provinces, the Golden Plateau adularia-sericite Au-Ag epithermal deposits are hosted by Lower Permian volcanic rocks along the western side of the Connors-Auburn Province near Cracow in south-eastern Queensland, and are related to the extensional event that formed the Bowen Basin. As of 31 December 2011, the economically demonstrated resources (EDR)[3] for epithermal gold deposits in Queensland is 37.56 t gold (Geoscience Australia, 2013).

Smaller, sub-economic and emerging porphyry-epithermal provinces elsewhere in Australia include the Permo-Carboniferous Kennedy magmatic province of northermal Queensland, and the Mesoproterozoic (?) Peterlumbo Ag-Pb province (Paris deposit) in South Australia. In the Kennedy Magmatic Province, porphyry Cu-Au deposits are associated with the intermediate Almaden Supersuite (Champion et al., 2009), and include the Mount Turner, Ruddygore and, most importantly, the ~289 Ma (Mugalov et al., 2008) Mount Leyshon deposit (global resource 70 Mt grading 1.43 g/t Au: Morrison and Blevin, 2001).

One of the more significant greenfields Australian discoveries in 2011 was the Paris Ag prospect in the southern Gawler Province of South Australia. Subsequent exploration has identified several other similar prospects in the region, which has been termed the Peterlumbo mineral field (www.investigatorresources.com.au). The Paris prospect consists mainly of sheet-like zones and sub-vertical veins in dolomite just below the unconformity with Gawler Range Volcanics. The deposit is interpreted to be epithermal in origin and has some similarities to chimney- and manto-type deposits in Mexico and South America.

2.2.6 Associated critical commodities

Porphyry Cu-Au-Mo and epithermal deposits are geochemically zoned, both at the district and deposit scales (Buchanon, 1981; Berger et al., 2008). For example, at the Ann-Mason porphyry Cu-Mo deposit in Nevada (US), Cohen (2011) document a vertical zonation of Cu → Mo → W → Sn → As-Bi → Sb → Li → Tl from the ore zone over a distance of 3 km. Selenium enrichment extended throughout this vertical zonation, but Zn, Mn, Co, V and Sc were enriched 1–3 km laterally from the ore zone. Berger et al. (2008) found similar patterns more generally about porphyry Cu-Au-Mo deposits, although noting that Ag, Ba, Pb, Sb and Te can also be enriched lateral to ore. In some cases, Ag is also enriched also within ore zones. Of the elements enriched in and around porphyry Cu-Au-Mo deposits, only Cu, Mo, Au, Ag, Re and Se are recovered (see below); the other elements, including critical commodities, are not of sufficient grade or value to warrant recovery. Cu-rich and Zn-rich skarns have broadly similar geochemical associations to the proximal and lateral parts of the porphryry Cu-Au-Mo systems, respectively.

Buchanon (1981) documented a generalised vertical geochemical/mineralogical zonation in adularia-sericite Au-Ag epithermal deposits, as follows: Cu-As → Zn-Pb-Cu-Ag → Au-Ag-Sb-Ba-F → As-Sb → Hg, with Au and Ag enrichment beginning at the base of boiling zones. Adularia-sericite Ag-Zn-Pb epithermal deposits have a broadly similar pattern, albeit with enhanced Ag and base metal grades. Pyrophyllite-kaolinite epithermal deposits are not as well zoned, but are characterised by a metal assemblage of Cu-Au-Ag-As-Sb-Bi-Hg-Te-Sn-Pb-Mo (White and Hedenquist, 1995).

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[3] Economically demonstrated resources are resources that are presentaly though to be economically viable, and include JORC-compliant ore reserves and measured and indicated mineral resources.

Of the critical commodities considered in this review, Mo is economically the most significant in the porphyry-epithermal mineral system and is a common by-product of porphyry Cu-Au-Mo deposits globally. Although Mo is not recovered (or reported) from porphyry Cu-Au deposits of the Macquarie arc, the Spinifex Ridge deposit contains a JORC-compliant ore reserve totalling 0.295 Mt Mo (and 0.520 Mt Cu: Table 2.2.1), the largest Mo resource in Australia.

Rhenium is recovered as a by-product during roasting of molybdenite concentrates, which in turn are by-products from porphyry Cu-Mo deposits (Magyar, 2003). Although molybdenite from porphyry Cu-Mo deposits can contain up to 0.4% Re, typical analyses are in the range 0.01-0.10% (McCandless et al., 1993). Based on a molybenite Re content of 33 ppm (average of two molybdenite separates), as determined during Re-Os age dating (Stein et al., 2007; Barley et al., 2008; M Barley, pers.comm., 2013), the Spinifex Ridge deposit contains on the order of 16 t Re[4].

In addition to Mo, some porphyry Cu-Au-Mo deposits produce by-product Ag and Se (e.g., Erdenet (Mongolia): Maksimyuk et al., 2008). Selenium, Te and precious metals are commonly extracted from anode slimes produced during copper refining. Approximately 90% of Se is produced in this manner from copper concentrates in the United States (Butterman and Brown, 2004), presumably sourced mainly from porphyry Cu ores.

Although limited critical commodities are produced as by-products from the porphryry-epithermal mineral system, a number of critial commodities (e.g., Sb, Bi, Ga, In, Ge, Mn and Cd) potentially could be recovered from concentrates produced by mines of porphyry and epithermal deposits. Recovery of these commodities would depend upon recovery methods and critical commodity prices. Some critical commodities (e.g., As, Sb, Mn and Cd) currently can attract smelter penalties.

2.3 Granite-related mineral system

Deposits of the granite-related mineral system typically are associated with orogenic to post-orogenic, (generally) relatively reduced felsic magmatism that typically forms well inboard of convergent margins. These features differentiate this mineral system from the porphyry-epithermal mineral system, which is closely associated with intermediate, relatively oxidised magmatism (Blevin, 2004). Deposits that form part of the granite-related mineral system include granite-related Sn-W-F (including a variety of skarn deposits), pegmatite-hosted Ta-Nb-Li-Be, porphyry Mo and intrusion-related gold deposits. Aspects of the granite-related mineral system are presented by Černý et al. (2005), Ludington and Plumlee (2009) and Hart (2005).

2.3.1 Geological setting

Most deposits that form in the granite-related mineral system (Figure 2.3.1) are associated with felsic magmatic rocks in orogenic belts well inboard of plate margins during mineralisation (Thompson and Newberry, 2000). Granite emplacement typically has an orogenic to post-orogenic timing, with pegmatite belts emplaced during tectonic reactivation of shields and platforms. In many cases the granites and pegmatites are localised along deep fault systems that can coincide with major metamorphic and tectonic boundaries (Hart, 2007).

The broad compositional character (I-, S- or A-type; metaluminous, peraluminous or peralkaline) of granites serves as an important guide to the abundance of elements and volatiles in the granites, and their behaviour during fractionation processes (Blevin, 2004). Tin, W, and F tend to be associated with reduced, fractionated I-type or S-type granites, whereas peralkaline granites tend to be strongly compositionally evolved and high in Ta, Nb, Li, Be and related elements. The cooling and crystallisation of these peralkaline granites may also result in the formation of pegmatites which are valued for the suite of rare elements (e.g. in Ta, Nb, Li, and Be) that tend to be concentrated in the residual magmas. Černý (1993) classified rare element pegmatites into two groups, LCT (Li-, Cs- and Ta-rich) and, NYF (Nb-, Y- and F-rich) types. Martin and de Vito (2005) suggested that LCT-type pegmatites form during crustal shortening, subduction and collision, whereas NYF-type pegmatites form during crustal attenuation.

Porphyry Mo deposits are associated with high level rhyolitic stocks (Luddington and Plumlee, 2009) in contrast to the more intermediate and oxidised compositions of stocks associated with porphyry Cu-Au-Mo deposits. Intrusion-related gold deposits are associated with deeper level, reduced and felsic magmatic bodies (Hart, 2005). Both deposit types are located inboard of subduction-related magmatic arcs, with porphyry Mo deposits associated with extension following cessation of subduction (Luddington and Plumlee, 2009).

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[4] Rhenium potential reported herein is indicative only and based upon very limited data

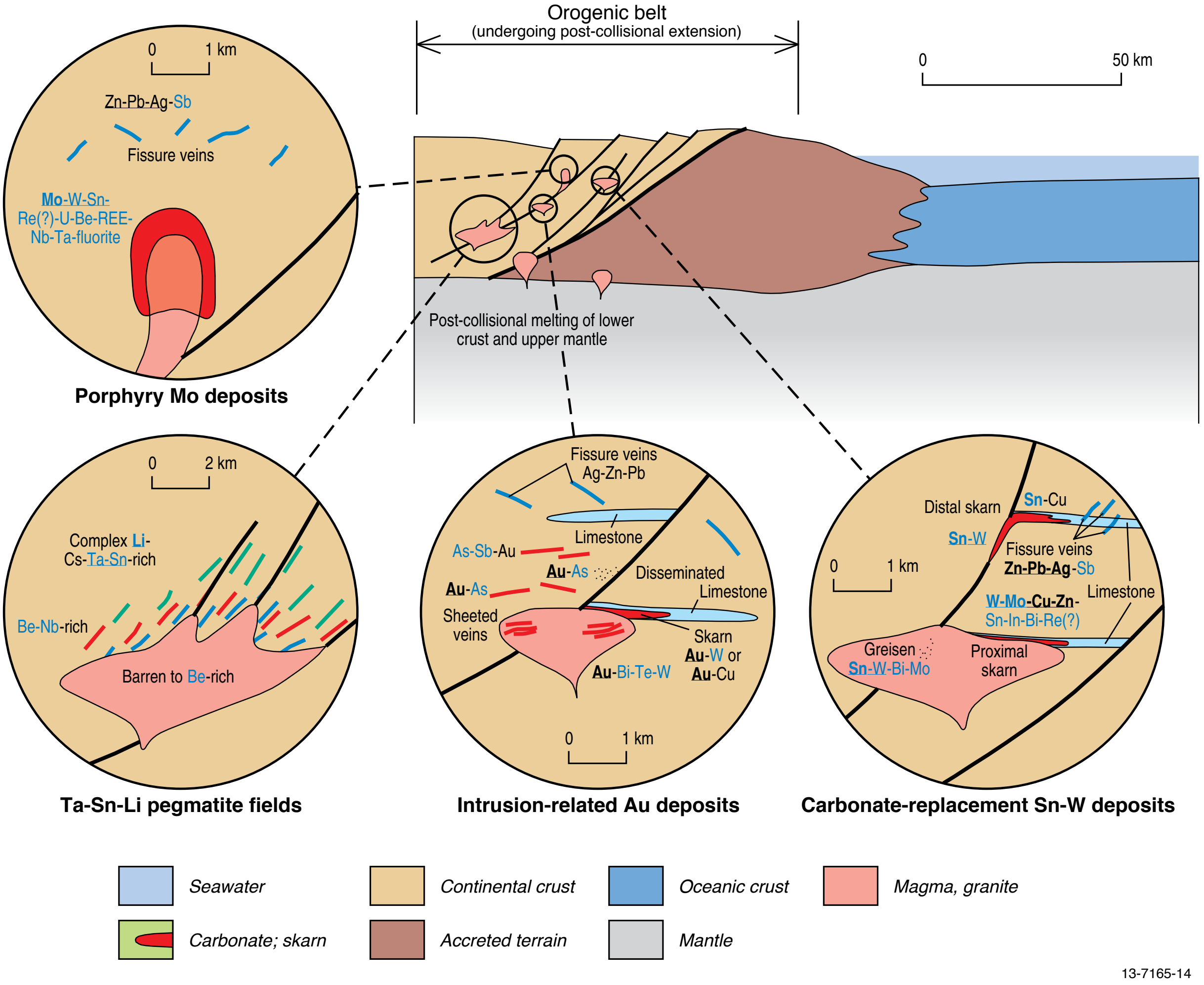

Figure 2.3.1: Diagrammatic sketch of the granite-related mineral system illustrating the relative location of deposits types within the overall setting and the likely distribution of critical and other commodities within and around these deposit types. In the commodity lists, blue indicates critical commodities, underlined bold indicates major products, bold indicates commonly recovered by-products, underlined normal font indicates commodities with limited recovery as a by-product (usually during downstream processing), and normal text indicates commodities that are geochemically anomalous, but not recovered.

2.3.2 Sources of fluid, metals and energy

Although some controversy exists about intrusion-related gold deposits (see Hart, 2005 for discussion), there is a general consensus that magmas are the source of fluid, metals and energy in the granite-related mineral system (Černý et al., 2005). Tungsten is typically associated with granites with intermediate compositional ranges while Sn±W±F is associated with felsic, fractionated granites. The oxidation state of granites is also critical: Sn is associated with reduced granites whereas W can be associated with both reduced and oxidised granites but is best developed in intermediate to relatively reduced granite suites (Blevin, 2004). Intrusion-related gold deposits are spatially associated with moderately reduced granites of felsic to intermediate composition (Hart, 2005).

Three models have been put forward concerning the formation of pegmatites. The magmatic model (London, 2008) proposes that pegmatites represent pneumatolitic, exsolved granitic fluids that crystallise in the country rocks. The metamorphosis model (Simmons et al., 1996) infers that pegmatite fluids are created by dewatering of metamorphic rocks in the thermal aureoles of granite. As a consequence, the pegmatite fluids have a granitic character and most of the time they match the character of nearby granites. The final model, the metasomatic model, infers that in rare situations, the interaction of heated fluids with rock can result in major changes in rock textures and composition, resulting in pegmatite formation (Schaller et al., 1925). Of these, the most probable model is the magmatic model.

Like the porphyry-epithermal mineral system, the emplacement of granitic magmas also causes convection of ambient basinal, metamorphic and/or meteroric fluids, which can produce coeval vein or carbonate replacement Zn-Pb-Ag deposits. In many cases, individual granite-related mineral systems are strongly zoned, grading outward from Sn-, W- and/or Mo-dominant deposits closely associated with granite emplacement to peripheral Zn-Pb-Ag deposits.

2.3.3 Fluid pathways

Like the porphyry-epithermal mineral system, fluid pathways in the granite-related mineral system include faults and shear zones, stratigraphic aquifers and the mineralising magmas themselves. The most important ore controls are faults and shear zones, which not only control the flow of hydrothermal fluids, but also the emplacement of magmas. In many cases, mineralisation is localised in or above the apices of granitic cusps and ridges as these features concentrate magmatic-hydrothermal fluids evolving as the magmas crystallise. In some cases, structures associated with the formation of granite cusps or ridges allow fluid movement hundreds of metres to kilometres from the causitive granite, producing distal skarn or carbonate replacement bodies well removed from the granite (e.g., Renison: Kitto, 1998). Pre-existing structures and structures associated with granite emplacement can also control the distribution of the outer Zn-Pb-Ag deposits.

Localised controls on fluid flow and ore deposition include variations in vein structure, lithologic (e.g., presence of carbonate units) and structural changes, vein intersections, and cross-faults. Many pegmatite bodies are controlled by shear zones and may be syn-metamorphic and syn-kinematic.

2.3.4 Depositional processes

Depositional processes in the granite-related mineral system are similar to those in the porphyry-epithermal mineral system, and involve magmatic-hydrothermal fluid evolution from crystallising magmas, depressurisation (including second boiling), mixing with ambient fluids, cooling and water-rock interaction, the last process is particularly important in forming skarn deposits hosted by carbonate rocks.

Crystal growth rates in pegmatite must be incredibly fast to allow gigantic crystals to grow within the confines and pressures of the Earth's crust. For this reason, the consensus on pegmatitic growth mechanisms involves a combination of the following processes (London, 2008):

- Low rates of nucleation of crystals coupled with high diffusivity to force growth of a few large crystals instead of many smaller crystals;
- High vapour and water pressure, to assist in the enhancement of conditions of diffusivity;
- High concentrations of fluxing elements such as boron and lithium which lower the temperature of solidification within the magma or vapour; and
- Low thermal gradients coupled with a high wall rock temperature, explaining the preponderance for pegmatite to occur only within greenschist metamorphic terranes.

2.3.5 Australian examples

Mineral provinces of the granite-related mineral system are present through much of Australia, ranging from Neoarchean Ta-Sn pegmatite fields in the Pilbara and Yilgarn Cratons in Western Australia to Paleozoic granite-related hydrothermal Sn-W deposits in the Tasmanides of eastern Australia.

There are five major Sn and W provinces in the Tasmanides of eastern Australia (Figure 1.5.2). The western Tasmanian province, which includes King Island (Table 2.2.1), has produced over 142 kt of Sn and more than 63 kt of WO_3 (Solomon and Groves, 1994). There are a wide variety of deposit types including distal skarn tin deposits (e.g. Renison, Mount Bischoff, Cleveland, Queen Hill and Razorback), proximal Sn skarns (Mount Lindsay), greisens (e.g. Heemskirk), and quartz-cassiterite-wolframite systems (e.g. Shepherd and Murphy, Balfour, Oakleigh Creek and Interview River, not shown in Figure 2.2.1), with ages between 365 and 350 Ma (Champion et al., 2009). The east Tasmania province, which, at 380-375 Ma (Champion et al., 2009), is slightly older than the west Tasmania province, has yielded about 90 kt of Sn and about 14 kt of WO_3 (Solomon and Groves, 1994). Major deposits include Aberfoyle, Storey's Creek, Scamander, Rex Hill and Anchor.

The Wagga-Omeo Sn province (Figure 1.5.2, which ranges in age from 410 Ma to 430 Ma (Champion et al., 2009), extends from Victoria into central New South Wales and contains the Tallebung, Minter, Ardlethan-Gibsonvale (non-JORC-compliant resources of 3.025 Mt gading 0.42% Sn) and Mount Paynter deposits. In 2008, Dart Mining discovered the Unicorn porphyry Cu-Mo-Ag deposit (Table 2.2.1) in northeastern Victoria, which was interpreted as a Climax-type porphyry Mo deposit (Hochwimmer, 2012). This deposit is located south of the Holbrook disseminated Mo-Sn-Cu deposit, which has an age of ~421 Ma (Norman et al., 2004). These two deposits are at the southern end of the Wagga tin province. Although the Doradilla Sn deposit (Table 2.2.1) is geographically just north of this province, it is significantly younger (~231 Ma: Burton et al., 2007) and probably related to a younger mineralising event associated with the evolution of the New England Orogen.

The Stanthorpe Sn province (Figure 1.5.2) occurs in north-eastern New South Wales, within the New England Orogen. The most important granite in this region is the Mole Granite, which is associated with over 150 individual tin deposits, including the Yankee, Wallaroo, and Dutchman's deposits. Deposits associated with the nearby Ruby Creek Granite have ages of ~242 Ma (Norman et al., 2004). A polymetallic resource, including In, has been established for the Conrad project and a W-Mo resource has been established for the Attunga deposit (Table 2.2.1). A pre-JORC resource of 37.589 Mt grading 0.153% Sn was defined for the Taronga deposit in 1981.

The Sn and W fields of northeastern Queensland (in Kennedy Igneous Province: Figure 1.5.2), which include the Herberton, Collingwood, Mt Carbine and Kangaroo Hills Sn provinces of Solomon and Groves (1994), have yielded over 150 kt of Sn and over 4 kt of wolframite from about 2000 mines and prospects. Major deposits in this region include Baal Gammon, Collingwood, Mount Carbine, Wolfram Camp (W-Bi-Mo), Mount Garnet (Figure 2.1.1), Great Southern, Morning Cloud, Smiths Creek, Pinnacles, Windermere and Watershed (not shown in Figure 2.1.1), and Mount Garnet. In 2012 mining recommenced at the Baal Gammon deposit west of Herberton based on a total resource of 2.679 Mt grading 1.0% Cu, 40g/t Ag, 0.2% Sn and 38 g/t In (at the time of writing the Sn was not recovered). Undeveloped resource estimates have recently been released for the Mount Garnet project (Table 2.2.1), including both Sn and fluorite resources. These Sn fields are spatially and temporally associated with the 315-260 Ma Kennedy Igneous Province (Champion et al., 2009).

Other hydrothermal Sn-W-F deposits with identified resources include the South Ridge Sn deposit in South Australia (pre-JORC resource of 0.173 Mt grading 1.15% Sn), the Molyhil W-Mo deposit in the Northern Territory, and the Yanco Glen deposit in New South Wales (Table 2.2.1). Western Australia contains the O'Callaghans W-Cu-Zn-Pb skarn, and the Big Hill (Cookes Creek) and Mount Mulgine W deposits (Table 2.2.1). Tin-tungsten prospects without identified resources include the Maranboy/Yeuralba Sn-W and the Mount Wells Sn prospects in the Northern Territory (Geoscience Australia, 2013).

Rare-metal pegmatites and alkaline igneous rocks are the dominant source of Ta, Nb, Li, and Be in Australia. Alkaline igneous rocks are discussed later in this chapter. The Archean North Pilbara Craton contains at least 120 pegmatite deposits in over 27 pegmatite groups and fields (Pilbara Ta-Sn-Li-W province: Figure 1.5.2), including the giant Mount Cassiterite Ta orebody (ore reserves not reported) in the Wodgina pegmatite district. A number of pegmatites are also known to occur in the Archean Yilgarn Craton (Southern Yilgarn Ta-Sn-Li province: Figure 1.5.2) and the most significant of these are the producing Greenbushes (total resources of 120.5 Mt grading 2.4% Li_2O as of 30 September 2012; Ta-Sn resources not reported) and Mount Cattlin (18.188 Mt grading 1.08% Li_2O and 156 ppm Ta_2O_5) deposits. Proterozoic pegmatite swarms also occur in the Arunta Region in the Northern Territory. Pegmatites in the Harts Range region, informally named the Entia pegmatite field, appear to be analogous to the NYF-type pegmatite and associated granitic suite of Černý (1991).

An unusual deposit that may be part of the granite-related mineral system is the Mary Kathleen deposit in northwest Queensland, which was mined for U until the 1970s. This deposit, which produced over 10 kt U_3O_8, is a garnet-pyroxene skarn most likely associated with emplacement of the ~1740 Ma Burstall Granite (Maas et al., 1987; Schofield and Huston, 2010).

2.3.6 Associated critical commodities

Granite-related mineral systems are strongly zoned, particularly at the district scale, where the metals are zoned relative to genetically-related granites. Typically, this zonation begins with the ore metal assemblage adjacent or within the granite and then grades to distal, low-temperature metal assemblage characterised by Zn, Pb and Ag. As examples, around carbonate-replacement Sn deposits (e.g., Renison, Tasmania), the zonation is Sn-W → As → Cu → Pb-Zn-Ag → Sb (Kitto 1998), and for intrusion-related gold deposits, the zonation is Au-Bi-Te±W → As-Au → As-Sb-Au → Ag-Pb-Zn (Hart, 2005).

In most of the hydrothermal deposits that form in the granite-related mineral system, critical commodities such as Sn, W and Mo are the primary product. The only exceptions are intrusion-related gold deposits, where, by and large, Au is the only recovered commodity. Figure 2.3.1 shows the distribution of other critical commodities in these systems, some of which may also be recoverable.

Like the porphyry-epithermal mineral system, Re may be recoverable in Mo-bearing deposits from granite-related mineral systems. As an example, a single analysis of Re in molybdenite in the Molyhil W-Mo skarn deposit (Table 2.2.1) yielded 13 ppm (D Huston, unpublished data). Taken at face value, this analysis suggests that the Molyhil deposit could contain around 0.14 t Re. The Unicorn porphry Mo-Cu-Ag deposit in northeastern Victoria could also contain a substantial Re resource. Cassiterite, wolframite and monazite has been recovered from the Climax porphyry Mo deposit, and commodities such as U, Be, REE, Nb and Ta potentially could be recovered from Climax-type deposits (Luddington and Plumlee, 2009).

Other critical commodities that possibly could be recovered in the granite-proximal part of the granite related mineral system include As, Bi and In. Arsenopyrite is a major component of many carbonate-replacement Sn deposits (Kitto, 1998), locally constituting over 10% of the ores. At the Stormont skarn in the west Tasmania Sn province, Bi and Au are the main commodities of interest (Table 2.2.1). This small deposit, which has a metal assemblage more akin to intrusion-related gold deposits, suggests potential for Bi in the west Tasmania and other hydrothermal Sn provinces around Australia. The Baal Gammon and Conrad resources include 38 ppm and 6.7 ppm In, respectively. In addition, fluorite is a common mineral present in many intrusion-related deposits, although generally as an accessory or minor mineral.

A common feature of all granite related mineral systems is the presence of (generally vein-type) distal Zn-Pb-Ag deposits. These deposits have supported historic mining districts such as Zeehan or Dundas in western Tasmania, but, at present, their limited tonnages (at most a few Mt) cannot support independent milling operations, although they have been mined recently when they can supplement the ore feed to a nearby mill (e.g., Rosebery in western Tasmania). These fissure vein deposits, like other Zn-bearing deposits (see below), are potential sources of Ga, In, Ge, Mn and Cd, although the tenor is not known.

Although the main products of magmatic-hydrothermal Sn-W deposits can overlap with LCT-type pegmatites, the associated metal assemblages are quite different. Pegmatite fields containing LCT-type pegmatites are commonly zoned around source granites from barren to Be-Nb-rich to LCT pegmatites (London and Kontak, 2012). In addition, individual pegmatites are commonly mineralogically zoned, although not in systematic patterns. Hence, at Greenbushes, Ta-rich zones are distinct from Li-rich zones (Partington et al., 1995). Critical commodities mined from LCT-bearing pegmatite-fields include Be, Nb, Ta, Sn and Li. In 2011, Australia produced 421 kt of spodumene concentrate. The Mount Cassiterite deposit is currently on care and maintenance, so no tantalite concentrate is currently being produced in Australia. At 31 December 2011, the EDR for Li and Ta were 1006 kt and 62 kt, respectively (Geoscience Australia, 2013).

2.4 Iron oxide copper-gold mineral system

Iron oxide copper-gold (IOCG) deposits (Hitzman et al., 1992) are a diverse family of mineral deposits characterised by the following features: (1) Cu with or without Au, as economic metals, (2) hydrothermal ore styles and strong structural controls, (3) abundant magnetite and/or hematite, (4) Fe oxides with Fe/Ti greater than those in most igneous rocks, and (5) no clear spatial associations with igneous intrusions as, for example, displayed by porphyry and skarn ore deposits (Williams et al., 2005). In addition, most IOCG deposits display a broad space-time association with batholithic granitoids, occur in crustal settings with very extensive and commonly pervasive alkali metasomatism, and many are enriched in a distinctive, geochemically diverse suite of minor elements including various combinations of U, REE, F, P, Mo, Ag, Ba, Co, Ni and As (Williams et al., 2005). Many of these minor elements are also critical commodities in the context of the present study.

Uranium-rich IOCG deposits in which U is an economic metal are an important yet uncommon subset of the IOCG family (Hitzman and Valenta, 2005). Currently the Olympic Dam deposit is the only IOCG deposit in which U is extracted as a major economic commodity. This deposit is the world's largest single resource of U (BHP Billiton, 2010 Annual Report, www.bhpb.com). In a global context, most of the other IOCG deposits containing higher grades of U are found in the Gawler Craton and Curnamona Province of southern Australia (Hitzman and Valenta, 2005; Skirrow, 2011). Based on current knowledge of IOCG deposits globally, it would appear that the IOCG deposits with the highest grades of REE are also confined to southern Australia.

2.4.1 Geological setting

Figure 2.4.1 shows a generalised model for IOCG mineral systems. The geodynamic settings of IOCG deposits have been widely debated (Williams et al., 2005). Hayward and Skirrow (2010) briefly reviewed tectonic and geodynamic models, in particular for the Gawler Craton, and proposed a distal continental retro-arc environment where earlier subduction-related processes (possibly at ~1850 Ma) led to metasomatism of the upper mantle. Melts derived from this enriched mantle, driven by a mantle plume or perhaps by removal of lithospheric mantle, resulted in extensive crustal melting and production of high-temperature A- and I-type magmas associated with K-rich mafic melts between ~1595 Ma and ~1575 Ma. In the Gawler Craton the felsic melts are represented by the Hiltaba Suite and Gawler Range Volcanics, which are temporally and spatially linked to IOCG deposits in the Olympic IOCG Province. In the Curnamona Province to the east of the Gawler Craton the Benagerie Volcanics and A-type granites on the northern Benagerie Ridge are probably the igneous equivalents of the Gawler Range Volcanics and Hiltaba Suite, respectively (Schofield, 2010).

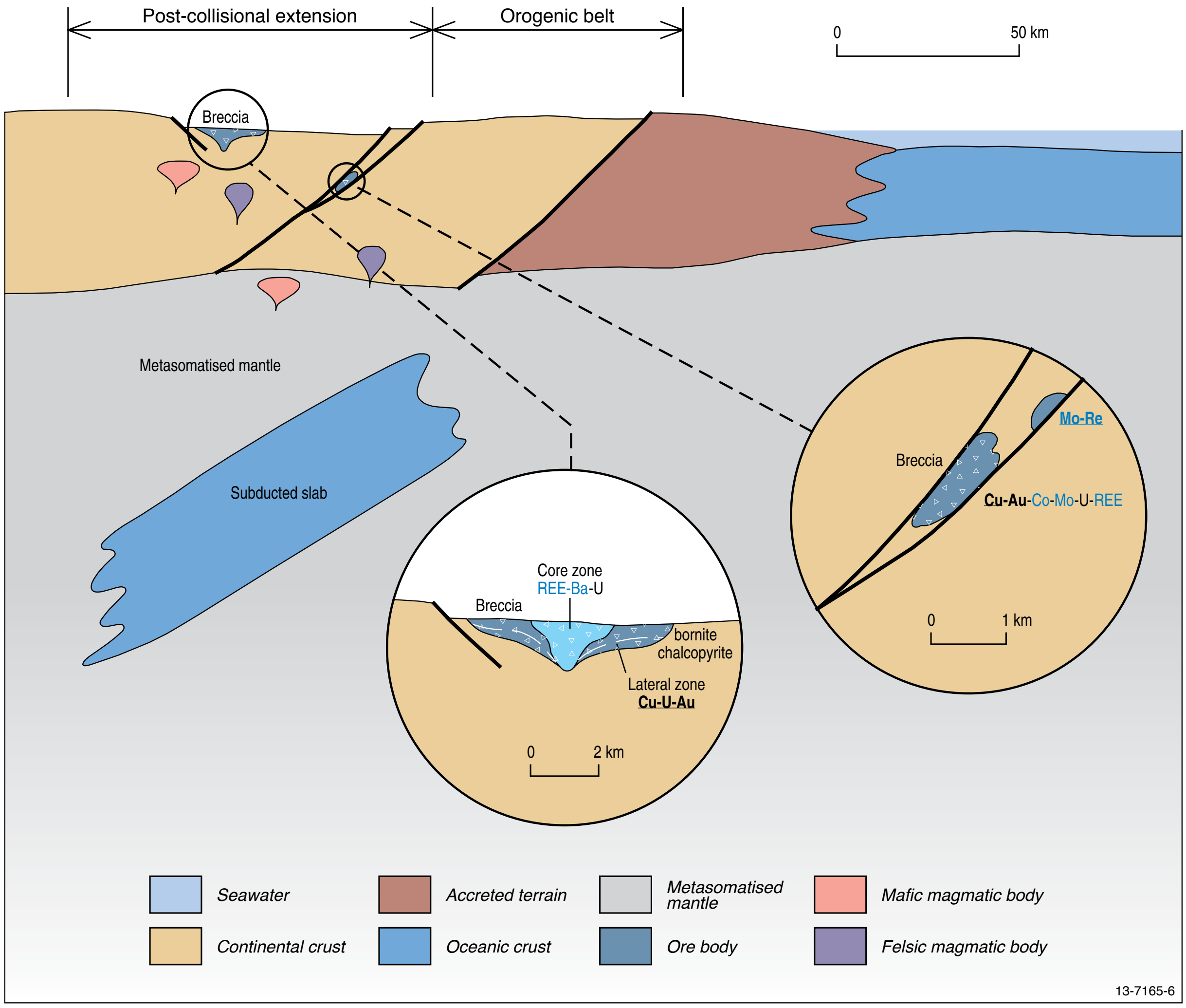

Figure 2.4.1: Diagrammatic sketch of the iron oxide-copper-gold mineral system illustrating the relative location of deposits types within the overall setting and the likely distribution of critical and other commodities within and around these deposit types. In the commodity lists, blue indicates critical commodities, underlined bold indicates major products, bold indicates commonly recovered by-products, underlined normal font indicates commodities with limited recovery as a by-product (usually during downstream processing), and normal text indicates commodities that are geochemically anomalous, but not recovered.

2.4.2 Sources of fluids, metals and energy

High to extreme paleogeothermal gradients are considered to be a key driver (energy source) of regional-scale upper crustal fluid flow in major IOCG systems. Regional to crustal scale (hydro)thermal systems are necessary to explain the huge scale of the alteration systems and the masses of hydrothermal precipitates (e.g., 10^7 to 10^{10} tonnes of ore rich in hydrothermal Fe oxides, sulfides and silicates) in individual IOCG deposits. In the Gawler Craton and possibly in other major IOCG provinces bimodal magmatism was roughly coeval with IOCG formation. The mafic igneous rocks may mark the foci of crustal-scale thermal anomalies, as well as providing a source of ore metals and/or sulfur in IOCG systems (Johnson and McCulloch, 1995; Skirrow et al., 2002, 2007). Additionally, high-temperature A- or I-type crustal (felsic) melts, emplaced at high levels in the crust or at surface, are considered to have augmented the thermal flux provided by mantle magmatism, and so their presence is considered important as an indicator of a favourable driver or energy source in the IOCG systems. These igneous associations and their tectonic context are shown schematically in Figure 2.4.1.

A distinctive feature of IOCG deposits is the presence of two distinct fluids during deposit formation: (1) a highly oxidised fluid (e.g., meteoric/ground waters), and (2) deep-sourced high-temperature brines (magmatic-hydrothermal fluids and/or fluids reacted with metamorphic rocks). In many IOCG systems there is also evidence of volatile-rich fluids during ore formation (e.g., CO_2-bearing; see review by Williams et al., 2005, and references therein). The sources of Cu, Au, S, Cl and CO_2 may be either coeval magmas (felsic and/or mafic) or sedimentary and igneous rocks that were leached by the ore fluids, as marked by the presence of Na-Ca regional alteration zones (Oreskes and Einaudi, 1992; Johnson and McCulloch, 1995; Haynes et al., 1995; Williams et al., 2005; Oliver et al., 2004; Skirrow et al., 2007). Uranium and REE were most likely leached from granitoid or felsic volcanic rocks. Alternatively, direct magmatic-hydrothermal sources of U and REE are possible in IOCG systems; there is currently insufficient evidence available to distinguish between these possible scenarios for the sources of U and REE.

Pre-IOCG basins hosting major IOCG provinces tend to lack major reduced sucessions (Haynes, 2000) and commonly show evidence for the (former) presence of evaporite minerals; rift basin sequences may supply some of the Fe, Cl, and S to IOCG deposits, particularly those of overall oxidised character with subaerial to shallow marine depositional settings. These include continental back-arc basins and foreland basins. Low metamorphic grade of these basins prior to IOCG formation is favourable because of potentially higher permeability and fluid content than basins metamorphosed to medium or high grade. In models involving non-magmatic fluids, exposure near/at the paleosurface of U- and REE-rich source rocks is favourable for sourcing highly oxidised surface-derived waters capable of transporting U and REE. Topographic depressions (e.g., calderas, grabens, maar complexes, etc) are conducive to mixing of shallow-crustal and deep-sourced fluids.

2.4.3 Fluid pathways

Terrane boundary zones initiated during earlier orogenic belt formation are believed to form part of the crustal-scale magma and fluid pathways for major IOCG systems. Such boundaries have been documented beneath the Olympic Dam deposit in the Gawler Craton (Lyons and Goleby, 2005; Heinson et al., 2006; Direen et al., 2007; Hayward and Skirrow, 2010). Groves et al. (2010) extended this concept to other major IOCG deposits globally. Major IOCG systems may preferentially occur in the hangingwall of boundary zones between crustal blocks, above zones of partial crustal melting and mafic underplating (Figure 2.4.1). Fluid flow is enhanced by juxtaposition of earlier rift basins with this high-temperature melt province. Pre-existing basinal structures and second-order cross structures (e.g., conjugate fault sets) localise dilational deformation, brecciation (at high crustal levels), and fluid flow. The intersections of second-order faults with crustal-scale terrane boundaries are favoured locations for IOCG systems.

Hydrothermal alteration zones mark the passage of fluids and hence map fluid flow pathways. In IOCG systems regional Na-Ca alteration zones may represent fluid flow paths in deeper and/or more distal parts of the systems, where some of the ore constituents were leached (e.g., Barton and Johnson, 1996; Oliver et al., 2004). On the other hand, magnetite-biotite, magnetite-K-feldspar, and hematite-rich alteration zones represent more proximal IOCG settings, and thus not only mark fluid flow paths but also represent the sites of physico-chemical gradients proximal to the sites of ore deposition (see below).

2.4.4 Depositional processes

Although it is widely accepted that two fluids were involved in the formation of most if not all of the major IOCG deposits, it remains unclear which of the two fluids carried the bulk of the copper, gold, uranium, REE and other metals. In the Olympic Dam district, the high temperature brines carried at least 300 ppm Cu in places but data for the oxidised lower temperature fluid are inconclusive (Bastrakov et al., 2007). Similar hypersaline brines in other IOCG provinces globally also carry elevated levels of Cu and other transition metals (e.g., Carajás province, Brazil: Xavier et al., 2010, and references therein). For IOCG systems of the eastern Gawler Craton a key Cu-Au-U depositional process appears to have been mixing of large volumes of oxidised groundwaters (or shallow basinal waters) with deep-sourced Fe-rich brines of intermediate redox state (Haynes et al., 1995). This process would have resulted in reduction and cooling of the oxidised fluids as well as possible changes in pH and ligand activity of both fluids, causing metal deposition. Additionally, reaction of the oxidised fluids with rocks rich in Fe^{2+}-rich minerals such as magnetite, siderite and chlorite, or with reduced sulfur in sulfide minerals, or with reduced carbon, also may have resulted in Cu-Au-U deposition. Chemical modelling by Bastrakov et al. (2007) showed that higher grade Cu and Au mineralisation is expected in zones where hematite has replaced earlier magnetite.

The implication of these findings is that hematite-rich alteration zones in IOCG systems are more favourable for higher grade Cu-Au-U mineralisation in comparison to magnetite-rich zones. The hematite may occur above the magnetite (e.g., Olympic Dam) or laterally adjacent to the magnetite (e.g., Prominent Hill, Belperio et al., 2007). The U mineralisation may occur in overlapping and/or separate zones relative to Cu-Au mineralisation. The occurrence of the REE in IOCG systems is less clear but in the Olympic Dam deposit the barren hematite core is in fact significantly enriched in the light REEs (Reeve et al., 1990; Ehrig et al., 2013). Elevated light REE concentrations also occur throughout the Cu-Au mineralised zones.

2.4.5 Australian examples

There are two major IOCG provinces in Australia of global significance: the Olympic IOCG Province along the eastern margin of the Gawler Craton in South Australia, and the Cloncurry district in the eastern Mount Isa Inlier of northwest Queensland. In addition there are several other metallogenic provinces that contain or may contain medium sized or small IOCG deposits, including the Tennant Creek district (Northern Territory), Curnamona Province (South Australia and New South Wales), and the Aileron province, Northern Territory (Schofield, 2012).

The Olympic IOCG Province is defined by the distribution of known early Mesoproterozoic IOCG±U mineralisation and alteration, and encompasses three known districts (from north to south): Mt Woods Inlier which hosts the Prominent Hill deposit; Olympic Dam district hosting the Olympic Dam, Carrapateena and Wirrda Well deposits; and the historic Moonta-Wallaroo Cu-Au mining district with the recently discovered Hillside deposit. The Olympic IOCG Province is a metallogenic entity superimposed on older geological domains. The Olympic Dam deposit is currently the world's fourth largest Cu resource, fifth largest Au resource and the world's largest U resource by far, with all resources contained in a single deposit with an areal extent of less than 25 km^2 (BHP Billiton Annual Report 2012). The resource in 2012 stood at 9576 Mt at 0.82% Cu, 0.26 kg/t U_3O_8, 0.31 g/t Au and 1.39 g/t Ag (www.bhpbilliton.com).

The only other currently producing IOCG mine in the province is the Prominent Hill deposit, where production commenced in 2009, although Cu production also came from several small open pits and underground mines in the Moonta-Wallaroo IOCG district on the Yorke Peninsula. The Hillside deposit in this district has a resource of 330 Mt at 0.6% Cu and 0.15 g/t Au (February 2013), and is currently undergoing feasibility studies (www.rexminerals.com). The small Cairn Hill deposit in the Mt Woods Inlier produces iron ore (magnetite) with by-product copper. Carrapateena and Wirrda Well are significant deposits buried under relatively deep cover (>450 m). A resource was announced in 2011 by OzMinerals for the Carrapateena deposit: 203 Mt at 1.31% Cu (cutoff 0.7%), 0.56 g/t Au, and 270 ppm U (www.ozminerals.com).

The Olympic Dam deposit is hosted by the Olympic Dam Breccia Complex (ODBC) in the Roxby Downs Granite, a member of the Hiltaba Suite. The geology of the deposit is described in detail by Reeve et al. (1990), Oreskes and Einaudi (1992), Haynes et al. (1995), Reynolds (2000) and Ehrig et al. (2013). The zoned funnel-shaped ODBC comprises multi-phase heterolithic breccias ranging from granite-rich to hematite-rich. The core hematite-quartz breccias lacks major Cu mineralisation but have elevated concentrations of REE, Ba and locally U. The margins of the core zone contain native Au and Cu mineralisation with low temperature illite and local silicification, and grade outwards and downwards into hematite-granite breccias hosting the bulk of the Cu-U-Au mineralisation. The distribution of individual hematitic breccia bodies partly controls Cu grades. However grades are also controlled by an important deposit-wide sharp interface between bornite and chalcopyrite that is broadly funnel shaped and in detail highly convoluted. Bornite-chalcocite mineralisation above the interface commonly attains grades of 4–6% Cu, whereas chalcopyrite mineralisation below the interface rarely exceeds 3% Cu (Reeve et al., 1990).

The deeper and peripheral zones of the ODBC contain greater proportions of magnetite and chlorite relative to hematite and sericite, and siderite is locally abundant. Uranium mineralisation is present throughout the hematite-rich breccias broadly in association with Cu mineralisation, but higher grade zones occur at the upper margin of the bornite-chalcocite zone. Uraninite (as pitchblende) is the dominant U mineral, whereas minor coffinite and brannerite occur in upper/shallower and deeper/peripheral zones, respectively (Reynolds, 2000). Olympic Dam ores have average grades of 0.17% La and 0.25% Ce with the light REEs present mainly within basnasite and florencite; REEs are not extracted currently (Ehrig et al., 2013).

The Cloncurry district in the eastern Mt Isa Inlier hosts the large Ernest Henry IOCG deposit as well as several medium sized and small IOCG and affiliated deposits. IOCG mineralisation developed in the Mesoproterozoic, during two periods, around 1590 Ma and 1500–1530 Ma (see Williams et al., 2005 and references therein). The breccia-hosted Ernest Henry deposit differs from the generally hematite-rich IOCG deposits in the Olympic IOCG Province in that the major iron oxide is magnetite, with associated hydrothermal K-feldspar, biotite and carbonate (Williams et al., 2005). Unlike the Olympic Dam, Prominent Hill and Carrapateena deposits in which bornite and chalcocite are important ore minerals, Cu mineralisation at Ernest Henry is primarily as chalcopyrite. Uranium and REE concentrations at Ernest Henry, while highly anomalous, are much lower than in the major deposits of the Olympic IOCG Province. Molybdenite is rare at Olympic Dam (0.0015 weight percent, Ehrig et al., 2013) but is widespread as a minor phase in the Ernest Henry deposit (Williams et al., 2005). Notwithstanding these and other differences in mineralogy and geochemistry, the magnetite-rich Ernest Henry deposit and hematite-rich IOCG deposits of the Olympic IOCG Province constitute a spectrum of deposit styles within the IOCG family. From a mineral systems perspective they share features of geological setting, sources of fluids-metals-energy, fluid pathways, and ore depositional processes, as summarised above.

Other Cu-Au deposits in the Cloncurry district include Osborne, Eloise, Mt Elliot, Mt Dore, Monakoff, and many other small deposits and prospects. Among these deposits there is considerable variation in deposit geology, style, mineralogy and geochemistry (Williams and Skirrow, 2000). The abundances of minor elements are highly variable; for example some of the Cu-Au deposits are notable for their Co (Mt Elliot; Williams and Skirrow, 2000).

2.4.6 Associated critical commodities

IOCG deposits are characteristically diverse in their minor element compositions, and contain elevated concentrations of many critical commodities. Recently published data for the Olympic Dam deposit have revealed the presence of an extremely broad range of minerals and corresponding geochemical variation. More than 90 minerals have been identified, and in addition to Cu, U, Au and light REEs the deposit is enriched to strongly enriched in As, Ba, Bi, C, Cd, Co, Cr, F, Fe, In, Mo, Nb, Ni, P, Pb, S, Sb, Se, Sn, Sr, Te, V, W, Y, and Zn (Ehrig et al., 2013). It is interesting to note that almost all of these elements are included in the current study of critical commodities.

Alteration, mineralisation and elemental abundances are zoned within the Olympic Dam deposit. Ehrig et al. (2013) describe the zones from the periphery inward and upward from depth towards the deposit centre, as follows: (1) reduced Fe-oxide alteration (magnetite-apatite-siderite-chlorite-quartz) → oxidised Fe-oxide alteration (hematite-sericite-fluorite) → hematite-quartz-barite alteration, (2) siderite → fluorite → barite, (3) sphalerite → galena → pyrite → chalcopyrite → bornite → chalcocite → non-sulfide, and (4) distal or paragenetically early (?) base-metal poor (Mo-W-Sn-As-Sb) → base-metal rich (Cu-Pb-Zn) minerals → sulfide-barren hematite-quartz-barite breccia in the deposit centre.

As noted above, some IOCG deposits and affiliated(?) deposits in the Cloncurry district are enriched or highly enriched in combinations of Ba, Co, Ni, As, Mo, Re and other elements (Williams et al., 2005). The Merlin deposit is a high-grade Mo-Re resource (6.7 Mt at 1.4% Mo with 0.3% Mo cutoff, and 23 ppm Re, as of 2012) with minor Cu-Au mineralisation and insignificant iron oxides that occurs adjacent to the Mt Dore IOCG deposit, and with which Merlin mineralisation may be affiliated (www.ivanhoeaustralia.com)

The Tennant Creek historic mining district in the central Northern Territory is best known for its high grade Proterozoic Au deposits associated with magnetite-hematite-rich ironstones (Wedekind et al., 1989; Huston et al., 1993; Skirrow and Walshe, 2002). It has produced 5.5 million ounces of Au at an average grade of 19.3 g/t Au, but also has produced significant Cu (488 000 t Cu at average grade of 2.9%) and 5000 t of Bi. The wide variety of Bi minerals includes sulfosalts with Se (Wedekind et al., 1985).

2.5 Mafic-ultramafic orthomagmatic mineral systems

Mineral deposits hosted in orthomagmatic mafic-ultramafic rocks are associated with mantle-derived magmas that have undergone a high degree of partial melting. They have been identified in various tectonic settings including continental rifts, continental rifted margins, continental large igneous provinces, mid-ocean ridges and mid-continent anorogenic provinces. The mineral system can form Ni-Cu, Ni-Cu-Co and Ni-Cu-PGE sulfide deposits, as well as chromitite and Fe-Ti-V oxide deposits found in association with magnetite (Figure 2.5.1).

2.5.1 Geological setting

Layered mafic-ultramafic tholeiitic or komatiitic intrusions are present in Australian Archean cratons or Proterozoic orogens and host some of the largest deposits in Australia. Continental rifts are an ideal setting for emplacement because the mantle-derived magma can reach the crust easily (Barnes and Lightfoot, 2005). Most intrusions are differentiated into a lower ultramafic zone where Ni-Cu sulfide and chromitite deposits form, and an overlying mafic zone where Fe-Ti-oxides crystallise, with PGE deposits located close to the mafic-ultramafic boundary.

Iron-Ni-Cu±PGE sulfide deposits can occur within komatiitic volcanics found within Archean greenstone belts. The ore deposits are usually located at the base of flows, controlled by structural traps such as faults and folds or found within associated dykes and sills.

Chromitite can also be found as podiform deposits within complexes of oceanic crust and upper mantle that were emplaced at convergent plate boundaries. More specifically, chromitites form where melts react with sections of subducted old lithospheric mantle at the plate boundary (Zhou and Robinson, 1997; Cawthorn et al., 2005). These are not as large as those found within mafic-ultramafic intrusions. All major ophiolite-related chromitite deposits are Phanerozoic in age ranging from 500 Ma (Thetford, Canada) to 10 Ma (New Caledonia) (Stowe, 1994).

Mafic-ultramafic mineral systems can also involve laterites, as well as hydrothermal and placer deposits. These are discussed in other sections of this report.

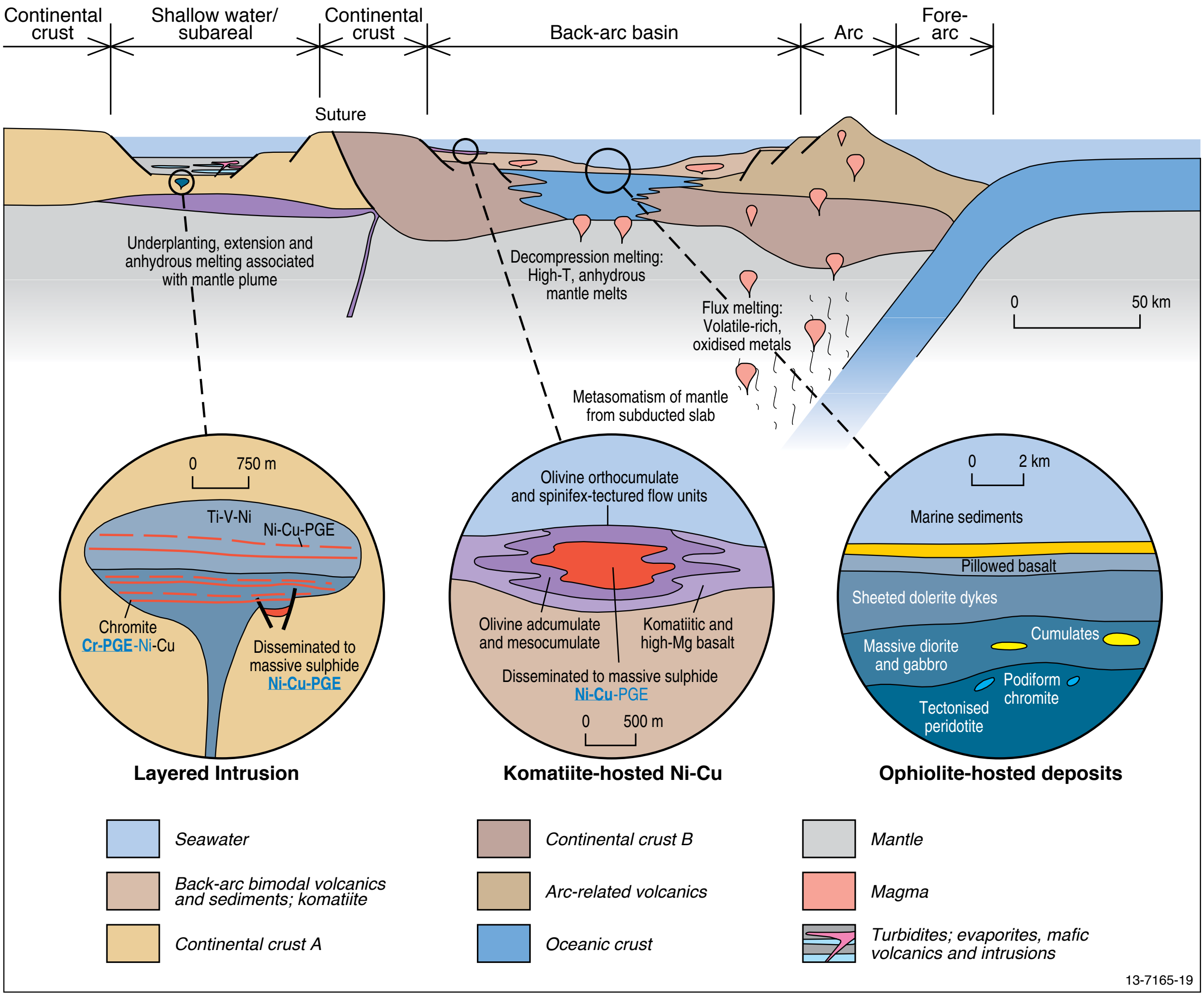

Figure 2.5.1: Diagrammatic sketch of the mafic-ultramafic orthomagmatic mineral system illustrating the relative location of deposits types within the overall setting and the likely distribution of critical and other commodities within and around these deposit types. In the commodity lists, blue indicates critical commodities, underlined bold indicates major products, bold indicates commonly recovered by-products, underlined normal font indicates commodities with limited recovery as a by-product (usually during downstream processing), and normal text indicates commodities that are geochemically anomalous, but not recovered.

2.5.2 Sources of fluid (magma), metals, sulfur and energy

Magmas are the source of fluid, metals and energy in orthomagmatic mafic-ultramafic volcanic deposits. The generation of mafic and ultramafic magmas usually takes place in the asthenospheric or lithospheric mantle. A high degree of partial melting and large volumes of magma are required to produce a silicate liquid that is rich in base metals (Barnes and Lightfoot, 2005).

The most mineralised komatiite volcanic sequences dominantly have Al-undepleted (Al_2O_3/TiO_2 = 15–25) chemical affinities (Hoatson et al., 2006). There are few restrictions on the composition of the parent magma for intrusions. Parent magmas are generally evolved basaltic parentage with compositions ranging from high-Mg basalt (15% MgO), magnesian basalts (12% MgO), tholeiitic basalt (7% MgO) to more silica-rich variants such as boninite and siliceous Mg-rich basalts (Hoatson et al., 2006). However, high-Mg (>10% MgO) and high Cl basaltic magmas with Pt and Pd concentrations > ~0.01–0.03 g/t have the highest potential for significant platinum group elements deposits to form (Hoatson, 1998).

As the amount of S in the mantle and derived melts is very low (10–400 ppm), the addition of S to the magma is critical for mineralisation. Moreover, the timing of S addition is also very important. Although Ni partitions into sulfide liquid in preference to silicate magma and crystallising minerals, in the absence of immiscible sulfide liquid, Ni preferentially partitions into olivine, which controls its abundance until sulfide melt saturation (Barnes and Lightfoot, 2005). Possible mechanisms for rapid S saturation include crustal contamination, assimilation of crustal metals that are rich in S, crystal fractionation or magma mixing (Hoatson, 1998). However, early S saturation could also deplete the magma of Ni and other base metals, and the resulting base metal sulfide liquid could settle out of the magma before emplacement (Barnes and Lightfoot, 2005).

The amount of Cr, PGE and V within the magma is also minor. Enrichment factors, relative to the magma, of about 1000, 1000 and 400 respectively are required to produce an economic deposit (Cawthorn et al., 2005). Many different process may operate to produce enrichment, including assimilation of chalcophile metals such as PGE, Au, Ag, Ni and Cu by sulfide droplets (Barnes and Lightfoot, 2005).

2.5.3 Fluid (magma) pathways

In many mafic-ultramafic volcanic or intrusive systems the magma rises to the lithosphere as a plume. As Ni has a moderate partition factor with olivine the Ni-Cu sulfide magma needs to reach the crust with minimum olivine fractionation and sulfide segregation (Barnes and Lightfoot, 2005). Faults and other associated structures are, therefore, important pathways for the magma to be emplaced or extruded rapidly (Hoatson, 1998). If the plume does not rise at a plate boundary, Begg et al. (2010) suggest that the plume will rise beneath the thick lithosphere and then be channelled by the lower boundary of the lithosphere to areas of thinner lithosphere adjacent to a cratonic margin where it will be extruded or emplaced.

2.5.4 Depositional processes

Layered mafic-ultramafic intrusions usually have a well defined and predictable structure that can contain multiple ore bearing horizons. The base of the intrusion has an ultramafic composition ranging from dunite, lherzolite, harzburgite, websterite, clinopyroxenite and orthopyroxenite (Hoatson, 1998). Nickel-Cu sulfides can settle out at the base of the intrusion as the velocity of the magma decreases when it enters the magma chamber (Barnes and Lightfoot, 2005). Chromium also drops out of the melt early and, therefore, layers rich in chromitite can also be found at the base of the intrusion and are associated with olivine and orthopyroxene (Hoatson, 1998). Sulfide bodies containing Ni, Cu and PGE are commonly found in pyroxenitic layers near the stratigraphic level that plagioclase first becomes a cumulus mineral (150 m below to 500 m above the mafic-ultramafic boundary) or mineralisation may also occur at the base of cyclic units (Hoatson, 1998). The top half of the intrusion is mafic and here the host rocks are typically norite, gabbronorite and troctolite (Pirajno and Hoatson, 2012). Near the top of the fractionated mafic stratigraphy Ti-V oxides can be found and consist of layers and lenses of massive disseminated titanomagnetite or vanadium-magnetite (Pirajno and Hoatson, 2012). Mafic-ultramafic pipes may be associated with intrusions and these can also contain mineral deposits. The depositional processes involved in these layered intrusions are thought to involve multiple injections of magma and in some cases contamination to obtain sulfur saturation (Hoatson et al., 2006).

Nickel-Cu sulfide deposits are also found within flow-dominated volcanic environments. They occur when komatiitic magmas reached the surface and attained sulfur saturation through melting or assimilation of sulfur-rich footwall rocks. For example, mineralisation can occur if the lava is extruded onto a sulfur-rich deep marine facies (Houle et al., 2008). Massive sulfide deposits then form in restricted channels at the base of flows or disseminated nickel mineralisation can occur within sill or dyke intrusions (Markwitz et al., 2010). Mineralisation is restricted to two facies: compound sheet flows with internal pathways or dunitic compound sheet flows (Hoatson et al., 2006).

Podiform chromitite deposits are usually comprised of small, irregularly folded, and dislocated pods that are lenticular in shape. Within ophiolite complexes mineralisation is confined to the dunites in either the lower mantle-derived peridotites or the transitional zone between the depleted upper mantle peridotite and the layered gabbro cumulate rocks (Figure 2.5.1). For enrichment of chromite to occurs olivine and chromite must be physically separated in the melt, however, the mechanism for enrichment remains unknown (Matveev and Ballhaus, 2002). Crustal contamination and magma mixing are unlikely scenarios for their formation. Contamination is unlikely as no silica-rich material is readily available and magma mixing requires magma volumes unlikely to occur in these settings (Irvine, 1975; 1977; Lago et al., 1982; Paktunic, 1990; Cawthorn et al., 2005).

2.5.5 Australian examples

In 2012, Australia was the largest holder of economic Ni resources with 26.8% of the world's resources (Geoscience Australia, 2013). Australia's Ni production is dominated by komatiite deposits (82%) that are associated with Archean greenstone sequences, whereas, the majority of Australia's Ni resources are located in laterite deposits (69%) (Hoatson et al., 2006). This is in contrast to the world situation where komatiite deposits (18%) provide the fourth largest contribution after flood basalts (30%), astrobleme (20%) and basal sulfide associations (20%) (Hoatson et al., 2006).

Australian Archean komatiite-hosted and layered mafic-ultramafic intrusion Ni deposits are largely confined to the older crustal components of Western Australia and South Australia (Hoatson et al., 2009). The most significant Archaen deposits are located in the Eastern Goldfields Superterrane of the Yilgarn Craton, and with smaller deposits and prospects known in the Pilbara Craton (e.g., Radio Hill) and the Gawler Craton (e.g., Harris Greenstone Belt). The Proterozoic orogenic deposits are located in the Halls Creek Orogen, the Litchfield Province and the Albany-Fraser Orogen. In 2013, most of Australia's nickel was produced from the Leinster, Mount Keith and Cliffs mines located north of Kalgoorlie (Geoscience Australia, 2013).

The mafic-ultramafic rocks in the Yilgarn Craton are related to magmatic events dated at 2800 Ma in the Windimurra intrusion (Sm-Nd age: Ahmat and Ruddock, 1990) and 2705 Ma for komatiitic flows in the Eastern Goldfields Superterrane (Kent and Cassidy, 1996). The Mount Keith Ni deposit, in the Eastern Goldfields Superterrane, contains one of the largest komatiite-associated Ni resources in the world with a total resource of 335 Mt at 0.52% Ni (Hoatson et al., 2006; BHP Billiton Limited, 2013). Other large komatiitic-hosted magmatic Ni sulfide deposits located in the Yilgarn Craton include the Perseverance, Kambalda, Yakabindie and Honeymoon deposits (Markwitz et al., 2010).

The Pilbara Craton has one of the oldest known mineralised layered intrusions in the world (Hoatson, 1998). The Munni Munni Complex is dated at 2927±13 Ma (Sm-Nd mineral isochron age: Sun and Hoatson, 1992), and the same magmatic event has produced a wide range of mineralisation including PGE, Cr, V and Ti. For example, the Radio Hill intrusion is a small mafic-ultramafic body that contains the most significant known Ni-Cu-Co sulfide resources in the Pilbara Craton (Hoatson et al., 2006). The mothballed Radio Hill mine has a Ni resource of approximately 27 400 tonnes (4.22 Mt at 0.65% Ni and 0.76% Cu) and a Pd resource of 1.275 Mt at 0.493 g/t (Geoscience Australia, 2013). Most of the mineralisation occurs in structural depressions along the basal contact and in a feeder conduit (Hoatson et al., 2006). In contrast the Munni Munni intrusion, located in the Pilbara Craton, contains the one of the largest PGE resources in Australia (Table 2.2.1: Hoatson et al., 2006; Geoscience Australia, 2013).

Palaeoproterozoic mafic-ultramafic intrusions were emplaced between 1960-1840 Ma (SHRIMP II U-Pb zircon ages: Page et al., 1995) in the Halls Creek Orogen located in the East Kimberly. These intrusions contain a range of magmatic and hydrothermal deposits of PGE, Cr, Ni, Cu, Co, Ti, V, Fe and Au (Hoatson, 2000). Intrusions that host these deposits include the Black Hills Yard, Sally Malay, Norton, Panton (Table 2.2.1), Springvale, McIntosh and Toby intrusions. The most significant of these deposits are Sally Malay and Panton. Some of these deposits (e.g., Panton) contain significant PGE.

Other examples of mineralised Proterozoic mafic-ultramafic intrusion are the intrusions hosting the Nebo and Babel deposits within the Musgrave Province in Western Australia. The combined Nebo-Babel Ni-Cu-PGE deposit (Table 2.2.1) consists of both disseminated and massive sulfides that are hosted within a grabbronorite magma conduit emplaced into a sulfide-free orthogenisis at 1068 Ma and off-set by a fault (Seat et al., 2009; Godel et al., 2011). In this case, S saturation is thought to have originated in the mantle and crystallisation involved multiple magma pulses. The entrained sulfide accumulated in physical traps on the way to the conduit and was later emplaced along the footwall contact (Seat et al., 2009).

More recently, the Nova Ni-Cu deposit (Table 2.2.1) was discovered undercover by a drill hole that intersected 4 m of mineralisation at 4.02% Ni and 1.41% Cu on 21 July 2012. The drill hole was testing a large electromagnetic anomaly that is the first of four anomalies to be tested (Sirius Resources, 2012). From initial drilling the style of mineralisation appears more similar to large Proterozoic magmatic sulfide deposits located in Canada rather than the typical Western Australian ultramafic-associated deposits (Sirius Resources, 2012).

2.5.6 Associated critical commodities

Major critical commodities found within mafic-ultramafic orthomagmatic mineral systems include PGE, chromitite and V and Ti oxides. However, other crictical commodities, such as Mo, Se, Te, Co, and Sc, can also be associated with mineralisation in mafic-ultramafic ore bodies (Barnes and Lightfoot, 2005).

Platinum-group elements include Pt, Pd, Ir, Os, Rh and Ru. Within layered mineral intrusions Cu-rich zones can be enriched in Au, Pd and Pt and Cu-poor zones can be enriched in Os, Ir, Ru and Rh. Western Australia and the Northern Territory currently have all of Australia's PGE EDR, with the EDR for Western Australia associated with orthomagmatic deposits. However, the concentrations of PGE in orthomagmatic deposits are commonly not recorded (Geoscience Australia, 2013), and several other magmatic-related PGE prospects (e.g., Fifield in NSW) are known elsewhere in Australia. Although 60% of Australia's total PGE resource is located in deposits that have PGEs as the major commodity, in 2012, all of Australia's production was as a by-product from PGE resources associated with Ni sulfide deposits in Western Australia (Geoscience Australia, 2013).

Chromite deposits in Australia are either found within layered mafic-ultramafic intrusions in Western and central Australia or within Phanerozoic aged serpentinised ultramafic-mafic complexes within the Tasmanides. The only mine that is currently producing chromitite in Australia is located in the Coobina ultramafic intrusion in the Pilbara Craton (Consolidated Minerals Limited, 2012). It is a 10 km long dyke-like body that contains numerous pods and lenses of chromitite interlayered with serpentinite (Bye, 1975; Tyler, 1991).

Titanium- and V-bearing magnetite mineralisation can occur in the upper parts of mafic-ultramafic igneous complexes. The Windimurra, Lady Alma, Barrambi and Youanmi igneous complexes, which are all part of the ~2810 Meeline Suite located in the Yilgarn Craton, host this style of mineralisation (Ivanic et al., 2010). In 2012, Windimurra was the only producing V mine in Australia and had a total resource of 242.6 Mt at 0.48% V_2O_5 representing 654 000 tonnes of contained V.

2.6 Sub-aqueous, volcanic-related mineral system

In 1965, the existence of a major hydrothermal vent was confirmed in the Atlantis II Deeps in the Red Sea (Miller et al., 1966). This kicked off a period of deep sea exploration the resulted in discovery of the first black smoker on the East Pacific Rise in 1977. A black smoker is a hydrothermal vent on the seafloor. The name refers to the venting fluids, which appear as black smoke due to the precipitation and entrainment of fine sulfide particulates in buoyant, venting hydrothermal plumes. Hundreds of black smoker deposits have been discovered over the last four decades, initially in the axial valleys of mid-oceanic ridges, but more recently in a large range of tectonic environments, including seamounts, back-arc basins and rifted arcs (Hannington et al., 2005). The discovery of these deposits has validated the volcanic-hosted massive sulfide (VHMS) ore deposit model that has been developing since the 1840s (Stanton, 1990). Analyses of black smoker material indicate that in addition to the base metals, Cu, Zn and Pb, and precious metals, Ag and Ag, these modern VHMS deposits contain a large variety of commodities, including many critical commodities. Analyses of ancient VHMS deposits indicate a similar range in commodities, and some critical commodities (e.g., Sn and In) have been recovered from these deposits.

The original deposits discovered in the Atlantis II Deeps, however, differ in many ways from the more common black smokers. The Atlantis II deposits are presently forming in an ensialic rift, the Red Sea, and involve dense, bottom-hugging brines (Zierenberg and Shanks, 1983), not the chimneys and black smoke plumes characteristic of black smoker deposits. The Atlantis II Deeps deposit is most likely an analogue of Broken Hill-type deposits. Like black smoker and VHMS deposits, Broken Hill-type deposits also contain significant concentrations of critical commodities.

2.6.1 Geological setting

Direct observation of modern systems and interpretations of ancient systems suggest that, by and large, deposits of the sub-aqueous, volcanic-related mineral system occur in extensional and, to a much lesser extent, transtensional tectonic settings (Figure 2.6.1). These include both divergent and convergent geodynamic environments. Although most modern black smokers occur in divergent mid-oceanic ridges, these deposits are unlikely to be preserved owing to seafloor weathering and subduction. Rather, most ancient VHMS deposits are hosted by extensional back-arc basins and rifted arcs in an overall convergent geodynamic system (Franklin et al., 2005). Broken Hill-type deposits, by contrast, form in divergent ensialic rifts and in back-arc basins (Leach et al., 2010), both of which have a higher chance of preservation than mid-oceanic ridges.

There is some evidence that the style of deposit can vary depending upon the geographic position within the mineral system. Mercier-Langevin et al. (2007) and Huston et al. (2011a) suggested that Zn-rich VHMS deposits associated with chlorite±sericite-dominant alteration assemblages occur within back-arc basins, whereas Cu-rich VHMS deposits associated with pyrophyllite±kaolinite-bearing alteration assemblages occur closer to the (rifted) magmatic arc.

As implied by their name, volcanic-hosted massive sulfide deposits are hosted by or closely associated with volcanic rocks. In contrast, an association with volcanic rocks is not as clear cut with Broken Hill-type deposits. Although some of these deposits are associated with (felsic) volcanic rocks (e.g., association of Broken Hill with the metavolcanic Hores Gneiss: Page and Laing, 1992), in most cases the succession in the footwall to these deposits contains abundant mafic volcanic and high level intrusive rocks (Huston et al., 2006).

2.6.2 Sources of fluid, metals and energy

In the sub-aqueous, volcanic-related mineral system, the dominant ore fluid is evolved seawater and the main source of metals is rock leaching. Stable isotope data, particularly oxygen isotope data (Huston et al., 2011a), point to the dominance of evolved seawater in VHMS deposits, and the presence of extensive zones leached in Zn, Pb, Cu and related elements in both VHMS (Brauhart et al., 2001) and BHT districts (Huston et al., 2006) can account for the metals present in the deposits. The main role that the coeval magmatism plays is as a heat source to drive circulation of evolved seawater, although magmatic-hydrothermal fluids may be involved in Cu-rich deposits with pyrophyllite-kaolinite alteration assemblages or in very uncommon, extremely Sn-rich (e.g., Neves Corvo, Portugal) deposits (e.g., Huston et al., 2011a). An important difference between VHMS and BHT systems is the potential roll of evaporites as a source of chloride in the latter.

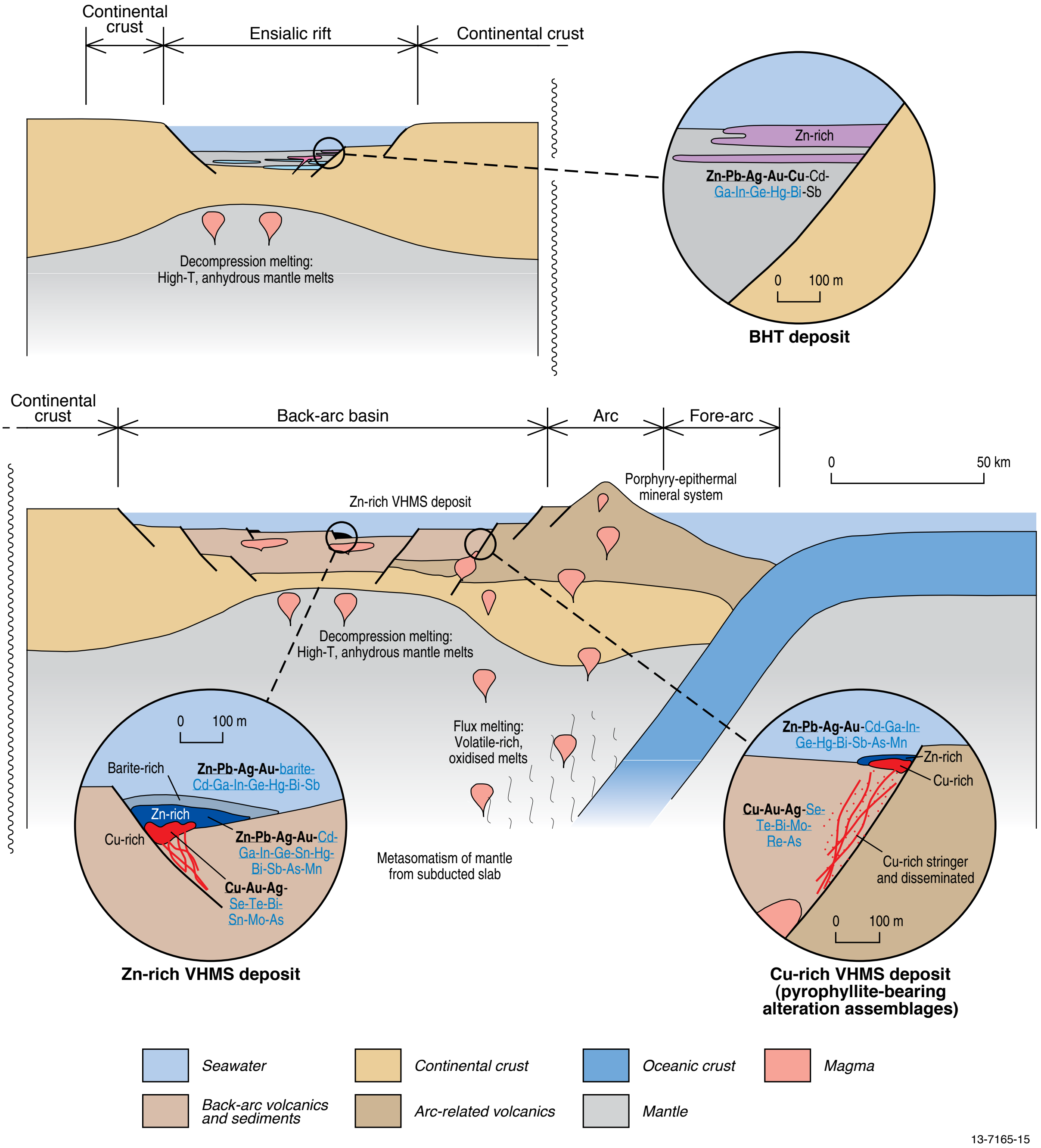

Figure 2.6.1: Diagrammatic sketch of the sub-aqueous, volcanic-related mineral system illustrating the relative location of deposits types within the overall setting and the likely distribution of critical and other commodities within and around these deposit types. In the commodity lists, blue indicates critical commodities, underlined bold indicates major products, bold indicates commonly recovered by-products, underlined normal font indicates commodities with limited recovery as a by-product (usually during downstream processing), and normal text indicates commodities that are geochemically anomalous, but not recovered.

2.6.3 Fluid pathways

In many well studied VHMS systems, district-scale alteration zones include semi-conformable alteration zones 1–3 km below the seafloor from which transgressive zone extend upwards to the seafloor and VHMS deposits (e.g., Franklin et al., 1981; Brauhart et al., 1998). The semi-conformable zones involve high temperature chlorite-rich, albite-rich and/or epidote-rich alteration assemblages that commonly have been leached of metals (Galley, 1993; Huston et al., 2006). These zones are most likely zones of lateral fluid flow at the base of convective cells driven by subvolcanic intrusions. In addition, these zones have acted as chemical reactors where the convecting fluids are heated, reduced (so that $\Sigma H_2S > \Sigma SO_4$) and charged with metals, including some strategic commodities (Brauhart et al., 2001).

The crosscutting zones are interpreted as upwelling zones, commonly controlled by synvolcanic faults, that focus fluid flow into the depositional environment (Franklin et al., 1981; Brauhart et al., 1998). Semi-conformable albitic alteration zones present in BHT districts (Huston et al., 2006), by analogy, may have also been fluid pathways.

2.6.4 Depositional processes

The main depositional process in the sub-aqueous volcanic-related mineral system is mixing between upwelling ore fluids and ambient seawater at or near the seafloor. This results in cooling, which leads to rapid precipitation of Cu, Zn, Pb and Ag as metal sulfides (Ohmoto et al., 1983). This mechanism also results in deposition of a large range of strategic commodities, including Bi, As, Ga, In and Cd. Sulfide precipitation and dilution by seawater also rapidly decreases the amount of H_2S in the fluid, which can cause deposition of Au, and possibly Sb. If the ambient seawater is sulfate-rich, mixing can also cause deposition of barium in the ore fluid as barite (Ohmoto et al., 1983). Both VHMS and BHT deposits are commonly well zoned (Cu → Zn-Pb-Ag → barite, from base: Eldridge et al., 1983), and contain a large range of strategic commodities (Sb, Te, Hg, As, Ga, In, Ge, Mn, Cd, Sn, Mo, Bi and Se) in addition to the main commodities (Zn, Pb, Cu, Au and Ag), attesting to the efficiency of seawater mixing as a depositional mechanism.

2.6.5 Australian examples

After the basin-hosted mineral system, the sub-aqueous volcanic-related mineral systems are the largest source of Zn, Pb and Ag in Australia as well as a major source of Cu and Au. The ~1690 Ma (Page and Laing, 1992) Broken Hill (New South Wales) deposit was, before mining, the world's largest single Zn-Pb-Ag accumulation, and the similarly-aged Cannington deposit in Queensland is currently the world's largest Ag producer. Minor BHT deposits include ~1700 Ma (Kositcin et al., 2010) sub-economic deposits (e.g., Chloe) near Einasleigh in Queensland. Although BHT deposits are known as major Zn, Pb and Ag producers, they have also produced significant Au.

Major Australian VHMS districts include the ~500 Ma (Mortensen et al., in press) Mt Read province in western Tasmania (Rosebery, Hellyer, Mount Lyell), the ~2950 Ma (Barley, 1992) Golden Grove district in Western Australia (Scuddles, Golden Grove), and the ~420 Ma (Champion et al., 2009) Woodlawn province of eastern New South Wales (e.g., Woodlawn, Captains Flat, etc) and northeastern Victoria (e.g., Currawong and Wilga). There are a large number of smaller VHMS deposits and prospects throughout Australia that range in age from ~3480 Ma (North Pole barite: Van Kranendonk et al., 2008) to ~277 Ma (Mount Chalmers: Crouch, 1999), with significant production from the North Pilbara Granite Greenstone Terrane in Western Australia (e.g., Whim Creek, Mons Cupri, Wundo), the Eastern Goldfields Superterrane in Western Australia (e.g., Teutonic Bore, Jaguar, Bentley, Nimbus; ~2695 Ma: Pidgeon and Wilde, 1990), the ~480 Ma (M Fanning in Rae, 2000; Hutton et al., 1997) Balcooma and Mt Windsor (e.g., Thalanga) districts in Queensland, the ~480 Ma (D Huston, unpub. data) Girilambone district (e.g., Tritton and Avoca Tank) in New South Wales and the New England Province in eastern New South Wales and Queensland (e.g., Mount Chalmers). In Australia, VHMS deposits are not only major producers of Zn, Pb and Ag, but also produce significant Cu and Au.

2.6.6 Associated critical commodities

As discussed above, the efficiency of seawater mixing as a depositional mechanism means that BHT and VHMS deposits contain anomalous to very high concentrations of a number of critical commodities. Table 2.6.1 provides indicative concentrations[5] for a number of critical commodities in Australian BHT and VHMS deposits. The most important of these include those that occur in solid solution in sphalerite (Cook et al., 2009) and, hence, have a strong geochemical affiliation with Zn: Cd, Ga, Hg, In, Ge and Mn. Of these, the best established correlation with Zn is Cd, followed by Ga. At the Rosebery (Mount Read province, Tasmania) deposit, a strong correlation ($r^2 = 0.947$, $n = 75$) suggests the Cd/Zn ratio (by mass) of the ores is 2.7×10^{-3}, whereas at the Dry River South (Balcooma Province, Queensland) deposit this ratio is 1.9×10^{-3} ($r^2 = 0.986$, $n = 20$). Using these ratios and EDR data as of 31 December 2011, Rosebery and Dry River South grade 273 ppm for 6.4 kt and 131 ppm for 0.1 kt Cd, respectively (Table 2.6.1). Zinc smelters (e.g., Nyrstar's Hobart Zinc Works) commonly produce Cd as a by-product although Cd can attract a smelter penalty.

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[5] The concentrations presented in Table 2.6.1 are based on limited publicly available data and must be regarded as indicative values only.

Table 2.6.1: Estimated concentrations and content of Cd, Ga, Hg and Sb for selected Zn-Pb deposits in Australia.

Area	Size (Mt)	Zn (%)	Pb (%)	Cu (%)	Ag (ppm)	Au (ppm)	Cd (ppm)	Cd (kt)	Ga (ppm)	Ga (kt)	Hg (ppm)	Hg (kt)	Sb (ppm)	Sb (kt)
Rosebery	23.5	10.1	3.5	0.4	118	1.6	273	6.4			44	1.0	271	6.4
Dry River South	0.73	6.9	2.5	0.9	62.1	0.64	131	0.10	60	44				
Nimbus	4.065	1.20	0.158	0.018	83.9	0.24					66	0.27		
Mt Isa	351.8	3.8	3.0		65.7		65	23			8.3	2.9	68	23.8

The estimates of concentrations and contained metal for critical elements are based upon reported ore reserves/mineral resources and geochemical relationships obtained from publically available sources (at 31 December 2011). **The estimates are indicative only and do not consider the technical viability or economics of extraction**. Data sources for the geochemical data are McGoldrick (1986), Carr et al. (1984) and Huston (1988).

Analytical data for Ga are also available for the Dry River South deposit. Although not as strong as that of Cd and Zn, the correlation between Zn and Ga ($r^2 = 0.679$; $n = 20$) is statistically significant at 99% confidence level, and a Ga/Zn ratio (by mass) is 8.7×10^{-4}, suggests a very approximate grade at Dry River South of 60 ppm for 44 t Ga (Table 2.6.1).

The Hg concentrations of the Broken Hill deposit and a number of VHMS deposits are reasonably well known. Carr et al. (1986) report ranges and geometric means for a large number of Australian Zn-Pb-Ag deposits. The Broken Hill deposit has geometric mean of 8.2 ppm and a range of 1–37 ppm (n = 35). VHMS deposits are even more variable, with Carr et al. (1986) reporting a total range in geometric means of 0.1-18 ppm (seven deposits) and Smith and Huston (1992) reporting an arithmetic mean of 43 ppm for the Rosebery deposit, which suggests an indicative resource of 1.0 kt Hg based on the current EDR (Table 2.6.1), although the economic and technical viability of this resource is uncertain. MacPhersons Resources has published a JORC-compliant *in situ* total resource at the Nimbus deposit citing a grade of 66 ppm Hg for 267 t Hg (Table 2.6.1: macphersonsresources.com.au).

Although public-domain assay data for In, Ge and Mn in VHMS and BHT deposits are not available for Australian deposits, Schwarz-Schampera and Herzig (2002) indicate that In is a significant minor to trace metal in many VHMS ores, and Ge and Mn is present in VHMS sphalerite (Cook et al., 2009). Although data for BHT deposits are not available, it is likely that Cd, Ga, In, Ge and Mn are present at trace levels. Indium is also produced as a by-product from zinc smelters.

Although not present as solid solution in sphalerite, Sb also has a broad association with Zn, Pb and, particularly, Ag. At Rosebery, Sb is moderately correlated with Ag ($r^2 = 0.651$; $n = 75$), with an average Sb/Ag ratio is 2.3. Using this ratio and reported Ag grade for Rosebery, the indicated Sb grade is approximately 270 ppm for 6.4 kt (Table 2.6.1). In the early 1990s, Sb, along with Ag and Au, mostly reported to the copper-precious metals concentrate at Rosebery, with a grade of ~0.47% (Huston et al., 1992). In most cases, such a 'dirty' copper concentrate would attract a penalty to offset smelter costs of treatment and disposal of Sb (e.g., Larouche, 2001). Hence, although an Sb resource may exist at Rosebery, it may not be economically or technically viable to recover. Zinc-rich ore samples from the Dry River South deposit typically contain 20–100 ppm Sb (Huston, 1988), and a dump sample from the Mt Chalmers deposit in Queensland returned <50 ppm Sb (Huston et al., 1992). Although generally anomalous, the Sb content of VHMS ores is highly variable.

Broken Hill-type deposits are even more enriched in Sb, with the 1, 2 and 3 lenses at Broken Hill averaging ~400 ppm (Table 2.6.1: Johnson and Klingner, 1975) and the Broadlands and Nurnham-Nisdale lenses at Cannington averaging 505 ppm and 680 ppm, respectively (Walters and Bailey, 1998). Due to its large size, prior to mining, Broken Hill contained total Sb of similar order to the Hillgrove deposit in New South Wales, currently Australia's largest Sb resource. However, this Sb has not been recovered.

Limited data are also available for elements that geologically are more closely allied with Cu (e.g., Mo, Re, Se and Te), or can be associated with Cu or Zn (e.g., Bi and Sn). As an example, Cu concentrate from the Mount Lyell copper field typically contained 0.1% Mo, 80 ppm Se and 40 ppm Te in the early 1990s (KE Faulkner, written comm., 1991). It is probable that the Se and Te are (have been) recovered during smelting and refining, as discussed in Section 2.2.1, although the Mo is probably not. A single analysis of Mt Lyell molybdenite yielded 147 ppm Re (D Huston, unpub. data), suggesting an indicative Re grade for the Cu concentrate of around 0.2 ppm. Although Se and Te are present in significant levels in most VHMS deposits, molybdenite is not commonly reported in these deposits, suggesting that significant Mo concentrations are not that common. No data are available for these elements in BHT deposits.

Bismuth can be present in both Zn-Pb-rich and Cu-rich ores from VHMS deposits. At Rosebery, Bi is associated with Cu, whereas at Dry River South it is enriched in Zn-Pb-rich ores. In both cases, concentrations run to several hundred ppm, approaching 1000 ppm at Dry River South (Huston, 1988). At the Broken Hill deposit, average Bi contents of individual lodes range up to 50 ppm, and decrease in the stratigraphically upper lodes. Because Bi is commonly a trace to minor solute in galena, it may report to lead concentrates, where is can be recovered. In Cu concentrates, high Bi levels can attract a penalty (Larouche, 2001).

The Kidd Creek deposit in Ontario, Canada has produced significant amounts of Sn through its mining history (Hennigh and Hutchinson, 1999), and the Neves Corvo deposit is a major tin deposit (Relvas et al., 2006). According to Hennigh and Hutchinson (1999), Sn is generally associated with Zn in VHMS deposits, although at Neves Corvo, it occurs towards the stratigraphic base, in association with Cu (Relvas et al., 2006). In Australia, very little information is available about Sn contents of VHMS deposits. At the Dry River South deposit, Sn is associated with Zn, with grades of Zn-rich samples typically between 100 ppm and 500 ppm (Huston, 1988). This Sn is present as cassiterite and Sn sulfide minerals. No data on Sn concentrations in BHT deposits are available.

Other critical commodities that can be anomalous in the sub-aqueous volcanic-related mineral system include As, fluorite and barite. Assays of ore samples from Zn-rich Rosebery and Dry River South deposits indicate As grades of hundreds to thousands of ppm (Huston, 1988), whereas the Cu-rich Mount Lyell and Mount Chalmers deposits have much lower (<50–400 ppm) concentrations (Huston et al., 1992). These data suggest that As concentrations in VHMS deposits are quite variable and relate to the metallogenic characteristics of individual deposits. Although no As data are available for BHT deposits, Johnson and Klingner (1975) report F contents (as fluorite) at Broken Hill up to 1.35% (in the Number 2 lens).

The last critical commodity present in the sub-aqueous volcanic-related mineral system is barite. Barite is widely distributed in Australian VHMS deposits, although relatively uncommon in BHT deposits. Barite is common in VHMS deposits from the North Pilbara Granite Greenstone Terrane, the Mount Read province, and the Woodlawn province. All three of these mineral provinces contain significant barite deposits with minor base metals as well as Zn-Pb-Ag and Cu-Au deposits with barite-rich lenses or zones.

The sub-aqueous volcanic-related mineral system has a diverse suite of trace elements, some of which have been identified as critical. Of these, Cd, Se and Te are probably recovered as by-products from smelting and refining of Zn and Cu concentrates from Australian deposits, and In and Sn have been recovered as by-products from VHMS deposits elsewhere in the world. In addition to these commodities, Ga, Hg and Ge also have potential for recovery from Zn concentrates, whereas Sb, and possibly Mn, although anomalous, can cause metallurgical difficulties and are not recovered. Barite deposits formed in this mineral system have been mined and have potential to be mined, with by- or coproduct precious and base metals. Although these and other commodities (e.g., Bi, Mo and Re) are known to be present in this mineral system (Figure 2.5.1), controls on the distribution, both between and within deposits, are poorly understood.

2.7 Orogenic mineral system

The orogenic mineral system (Figure 2.7.1) unites a diverse group of mineral deposits that form during orogenesis, and include lode gold and Cobar-type Cu-Au-Zn-Pb-Ag deposits. These deposits form in response to major orogenic events caused by accretion or changes in subduction direction or dip. In many cases, the deposit form during short periods of extension during overall contractional tectonostructural events (Blewett et al., 2010).

2.7.1 Geological setting

Both lode gold and Cobar-type Cu-Au-Zn-Pb-Ag deposits, the two main deposit types in the orogenic mineral system, are associated with continental margin accretionary (oceanic-continental) and collisional (continent-continent) orogens. They typically occur in granite-greenstone terranes or in terranes dominated by turbiditic (meta-sedimentary) rocks, and are commonly associated with second- and third-order faults and shear zones (Vearncombe et al., 1989; Lawrie and Hinman, 1998). Temporally, the deposits commonly form during the late stages of orogenesis. Although present in rocks that are characterised by a large range in metamorphic grade (pumpellyite-prehnite to granulite facies), these deposits are most common in low to mid-greenschist facies rocks (Groves et al., 1998). This observation on lode gold deposits led Groves et al. (1998) to propose a crustal continuum model for lode gold deposits, in which metal assemblages change with depth, with Hg and Sb enriched in high level systems (a trend also present in the porphyry-epithermal mineral system). As Cobar-type deposits are much less common and less studied, variations in deposit characteristics with crustal depth have not been documented, although Zn-Pb-rich deposits seem to be slightly younger than Cu-Au-rich deposits in the Cobar district (cf., Champion et al., 2009).

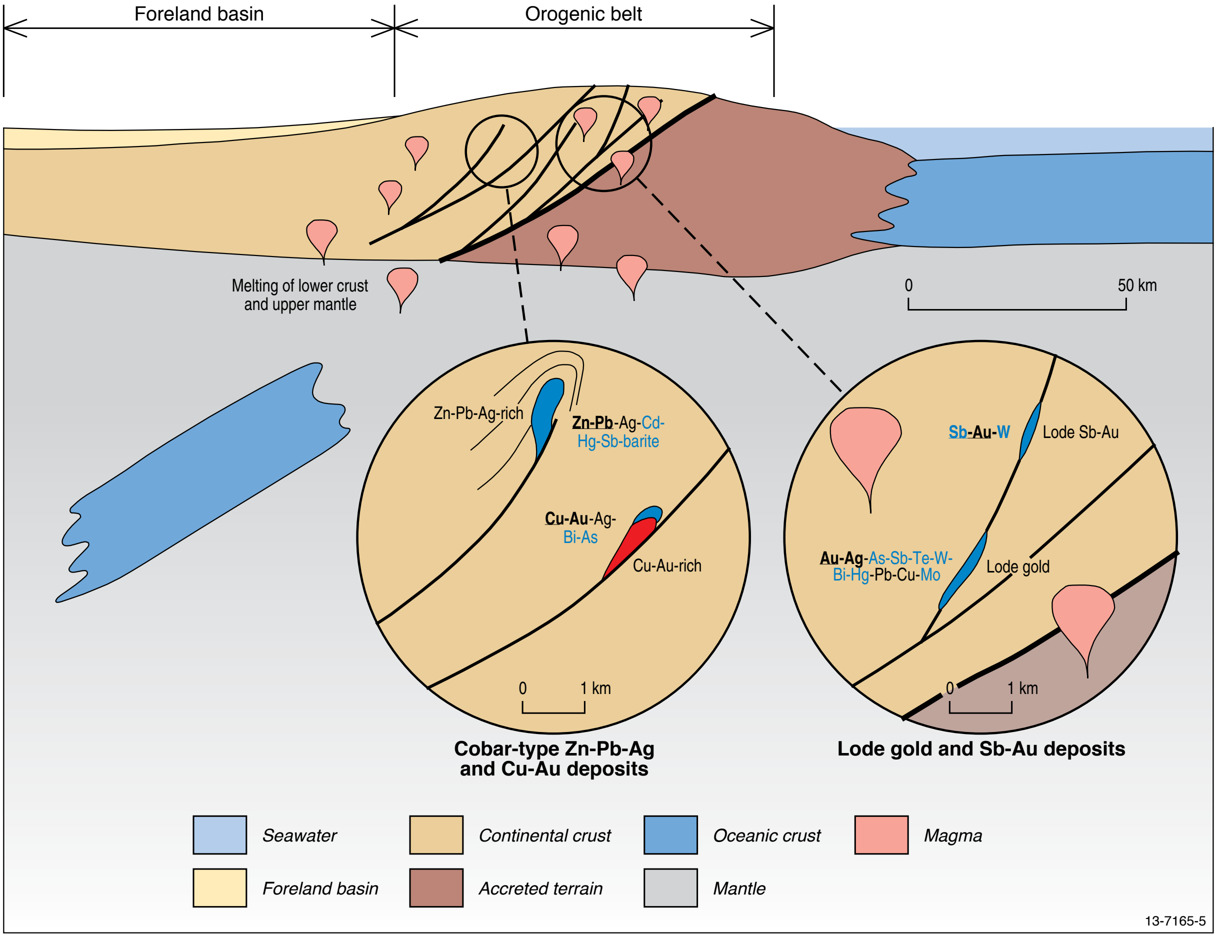

Figure 2.7.1: Diagrammatic sketch of the orogenic mineral system illustrating the relative location of deposits types within the overall setting and the likely distribution of critical and other commodities within and around these deposit types. In the commodity lists, blue indicates critical commodities, underlined bold indicates major products, bold indicates commonly recovered by-products, underlined normal font indicates commodities with limited recovery as a by-product (usually during downstream processing), and normal text indicates commodities that are geochemically anomalous, but not recovered.

The relation between mineralisation in the orogenic mineral system and magmatism is fraught. In several major lode gold provinces, such as the Eastern Goldfields Superterrane and the Tanami province, there is a close temporal and, in some cases, spatial relationship between magmatism and mineralisation (Blewett et al., 2010; Huston et al., 2007), yet in other major gold events, such as the ~440 Ma Benambran event in Victorian goldfields, magmatism has not been found to overlap gold mineralisation, despite extensive geochronologic studies of granites and lode gold deposits (Champion et al., 2009). In the Cobar Cu-Au-Zn-Pb-Ag district, magmatism is not known to overlap in time with mineralisation (e.g., van der Wielen and Glen, 2007; Champion et al., 2009).

2.7.2 Sources of fluid, metals and energy

One of the unifying characteristics of lode gold deposits through time and space are low- to moderate-salinity (generally <10 eq wt % NaCl), CO_2-bearing ore fluids (Ridley and Diamond, 2000). The origin of these fluids is contentious, with some workers inferring a metamorphic origin (Phillips, 1993), but others prefering a magmatic-hydrothermal origin, at least in part (Mueller et al., 1991). Both origins have shortcomings (e.g., difficulties in producing sufficient metamorphic fluids to form some deposits, or the lack of syn-ore magmatism in some lode gold provinces), and the fluid characteristics are not sufficiently diagnostic to distinguish the alternatives.

The source of Au is also contentious, with magmatic, metamorphic and even mantle sources proposed (e.g., Groves et al., 2003; Morelli et al., 2007). As noted by Groves et al. (2003), the constraints are insufficient to resolve the source. The likely energy source is heat associated with orogenesis, in many, but not all, cases indicated by syn-ore magmatism.

Limited data from the Cobar district indicate that Cobar-type fluids have some similarities to the lode gold fluids. The ore fluids have low to moderate salinities (mostly <10 eq wt % NaCl), with higher salinities associated with higher base metals. The homogenisation temperatures are variable, mostly between 200 and 350°C

(Stegman, 2001), and the ore fluids are characterised by the presence of methane and higher order hydrocarbons with variable CO_2 (Lawrie and Hinman, 1998). These fluids are thought to have a basin or metamorphic (basement) origin (Lawrie and Hinman, 1998).

As initially suggested by Lawrie and Hinman (1998) and supported with more precise data by Mernagh (2007), Pb isotope data suggest two Pb sources in the Cobar district, a less evolved, possibly slightly older basement Pb associated with Cu-Au mineralisation and a more evolved, possibly slightly younger basinal Pb associated with Zn-Pb-Ag mineralisation. These data indicate an evolution with time of the Pb source from a more juvenile source to a more evolved source.

Although the Cu-Au and Zn-Pb-Ag ore fluids are generally interpreted as metamorphic and/or basinal fluids (see above), Cleverly and Barnicoat (2007) suggested the possibility of early magmatic-hydrothermal fluids, citing the presence of a very early magnetite-scheelite-cassiterite-bearing vein assemblage (Stegman, 2001). A magmatic origin for main-stage Cu-Au and Zn-Pb-Ag mineralisation is problematic as the timing of mineralisation (401-384 Ma: Perkins et al., 1994) does not overlap periods of local known magmatism (435–420 Ma: van der Wielen and Glen, 2007). A possible origin for the early W-Sn-bearing assemblage could be ~420 Ma magmatism, which is present as a high level (locally peperitic) rhyolitic intrusion at the Peak deposit. The Cobar district is along the northern extension of the Wagga-Omeo Sn belt province (Figure 1.5.2) (Section 2.2.2), which contains Sn deposits of this age. In this interpretation, the Sn-W-bearing assemblage is significantly older (15–20 million years or more) than the main stage Cu-Au and Zn-Pb-Ag mineralising events.

2.7.3 Fluid pathways

It has long been established that the distribution of lode gold deposits is strongly controlled by faults and shear zones, with deposits localised along second or third order structures (e.g., Vearncombe et al., 1989), associated with major regional structures that commonly form boundaries between or within major crustal blocks. In detail, the deposits are commonly associated with transcrustal contractional structures (Vearncombe et al., 1989; Blewett et al., 2010). The major regional structures are zones of regional fluid flow, with tapping of the major regional structures into lower order structures allowing more effective physical and chemical changes to ore fluids and ore deposition.

In the Cobar district, the distribution of deposits is also controlled by regional-scale structures, mostly along the eastern margin of the Cobar Basin (Stegman, 2001). In detail, ore lenses are controlled by areas of higher strain (Stegman, 2001) and anticlinal closures (Lawrie and Hinman, 1998). As with lode gold deposits, these lower-order structures tapped fluid from the regional structures and allowed water-rock reactions, fluid mixing and ore deposition.

2.7.4 Depositional processes

The tapping of ore fluids from regional structures into lower order structures allows for ore deposition through physicochemical reactions that desulfidise or reduce the ore fluid, causing gold deposition. Chemical processes that cause gold deposition commonly involve reaction with iron-rich (e.g., dolerite or banded iron formation) or reduced-carbon-rich (e.g., carbonaceous sediments) rocks. Gold deposition can also occur through phase separation resulting from fault-valve behaviour and fluid mixing. All four processes probably happen in lode gold systems, but fluid mixing is the main depositional mechanism in Cobar-type deposits.

In addition to Au, lode gold deposits typically are anomalous in Ag, As, Ba, oxidised C, K, Rb, S, Sb, Si, Te and W (Eilu and Groves, 2001) and can be anomalous in B, Bi, Cu, Mo and Pb. Greenschist-facies lode gold deposits typically have a proximal sericite-dominated alteration zone, surrounded by carbonate-rich zones (Eilu and Groves, 2001). Sulfide minerals in the ores typically include pyrite and may include arseonpyrite and pyrrhotite.

In addition to base and precious metals, Cobar-type deposits are anomalous in Bi, As, Sb, Ni, Cd, Hg and Ba, and are characterised by silica-chlorite-albite-sericite assemblages that grade outward to carbonate dominated assemblages. The dominant sulfide minerals in Cobar ores are chalcopyrite, sphalerite, galena, pyrrhotite, pyrite and cubanite. Minor magnetite is present locally (Stegman, 2001).

2.7.5 Australian examples

Australia has several world class lode gold provinces. The largest and most productive gold province in Australia is the Yilgarn Craton (including the Eastern Goldfields Superterrane) in Western Australia which has an EDR of 2396 t gold (Geoscience Australia, 2013). Lode gold deposits in the Eastern Goldfields Superterrane formed in the restricted time window of between 2660 and 2620 Ma (Vielreicher et al., 2003). Other major Australian lode gold provinces include the ~450–440 Ma and ~380 Ma Victorian goldfields (Philips et al., 2012), the ~410–400 Ma

Charters Towers district in northern Queensland (Kreuzer, 2005), and the ~1810–1795 Ma Pine Creek and Tanami provinces in the Northern Territory (Cross, 2009). In addition to these major provinces, minor lode gold deposits are present in all Australian States and Territories. As of 31 December 2011, Australia's total EDR for lode gold was 3276 t gold (Geoscience Australia, 2013). The most important example of Cobar-type Cu-Au-Zn-Pb-Ag deposits is the 405-385 Ma Cobar district in New South Wales (Glen et al., 1992; Perkins et al., 1994), with the mined-out Woodcutters deposit in the Pine Creek mineral province another example.

2.7.6 Associated critical commodities

Although Au, Cu, Zn, Pb and Ag, in that order, are the main products of the orogenic mineral system, critical commodities, in particular Sb and W, are presently being recovered from deposits of this mineral system. Lode Sb-Au deposits form a small, but important, subset of lode gold deposits. Antimony-Au deposits form at relatively shallow depths in the continuum model of Groves et al. (1998). The majority of Australia's known antimony resources (~65%) are contained in the Hillgrove Sb-Au deposit in New South Wales. With defined resources of 102 kt Sb (Table 2.2.1), it has the largest identified Sb resource outside China. Other Sb mines and prospects (Table 2.2.1) include the Bielsdown Project (Wild Cattle Creek) in New South Wales (20.5 kt Sb), Costerfield in Victoria (producing mine and not included in Table 2.2.1: 28.8 kt Sb combined resources and reserves at 9 July 1012), and the Blue Spec Shear Au-Sb project (7.8 kt Sb) in the Eastern Pilbara Granite-Greenstone Terrane of Western Australia. In addition to Sb and Au, many of these deposits contain or have produced significant W. For example, historically the Hillgrove district has produced 200 t of W. Unlike other subclasses of lode gold deposits, mining of lode Sb-Au deposits requires the production of a Sb concentrate, which is treated off site at specialised antimony smelters (Anderson, 2012). Other than Sb in Sb-rich lode gold deposits, critical commodities in lode gold deposits are unlikely to be recovered as they have relatively low concentrations and are unlikely to be recovered during heap leaching, which is the dominant method of gold recovery for this class of deposits.

Although geochemical studies indicate that some critical commodities are present in Cobar-type ores, publicly available data as to concentrations in the ores are not available. These deposits should be considered to have unknown potential for Bi, As, Sb, Ni, Cd and Hg.

2.8 Basin-hosted mineral system

Sediment-dominated basins (Figure 2.8.1) contain deposits of many different commodities, including hydrocarbons and coal as well as a range of base, precious and strategic commodities. Many of these deposits form as a response to out-of-basin events, which cause within-basin fluid flow and mineralisation or hydrocarbon accumulation. The lithological characteristics of the basin determine to a large extent the geochemistry of these fluids and the geometry and chemical characteristics of the resulting commodity deposits.

2.8.1 Geological setting

Sedimentary basins form when geographic regions subside and are infilled by sediments eroded from adjacent highs or by volcanic rocks produced during basin formation. Four tectonic settings of basins are generally recognised: divergent, convergent, transform and intraplate. In many of these settings, initiation of the basin involves (commonly bimodal) magmatism as the lithosphere thins and is heated from below—the rift phase of basin formation. When extension stops, the crust cools and increases in density, causing further subsidence—the sag phase of basin formation. If extension continues such that oceanic crust develops, passive margins form along the margins of a widening oceanic basin.

Flexure of the crust in response to tectonic loading also can create basins, in this case lacking early phase volcanism. Perhaps the best example of this basin type are foreland basins, which are common inboard responses to collisional orogenesis along convergent margins.

Basin formation is commonly terminated or interrupted by basin inversion, which is generally triggered when out-of-basin tectonic events place the basin in contraction. In some cases, inversion terminates deposition, but in other cases, sedimentation is interrupted for a short period or even continues in parts of the basin. During basin inversion, extensional faults associated with basin formation commonly invert and become contractional faults and the sedimentary succession is deformed. Basin inversion can provide the impetus and focus for fluid flow.

Hydrothermal mineral systems and petroleum systems can be active through all phases of basin development, although many form during the later phases of basin formation, commonly just before or during basin inversion, in response to out-of-basin tectonic triggers. Some basin-hosted mineral systems, such as phosphate deposits, do not form hydrothermally but involve chemical sedimentation in very special environmental conditions.

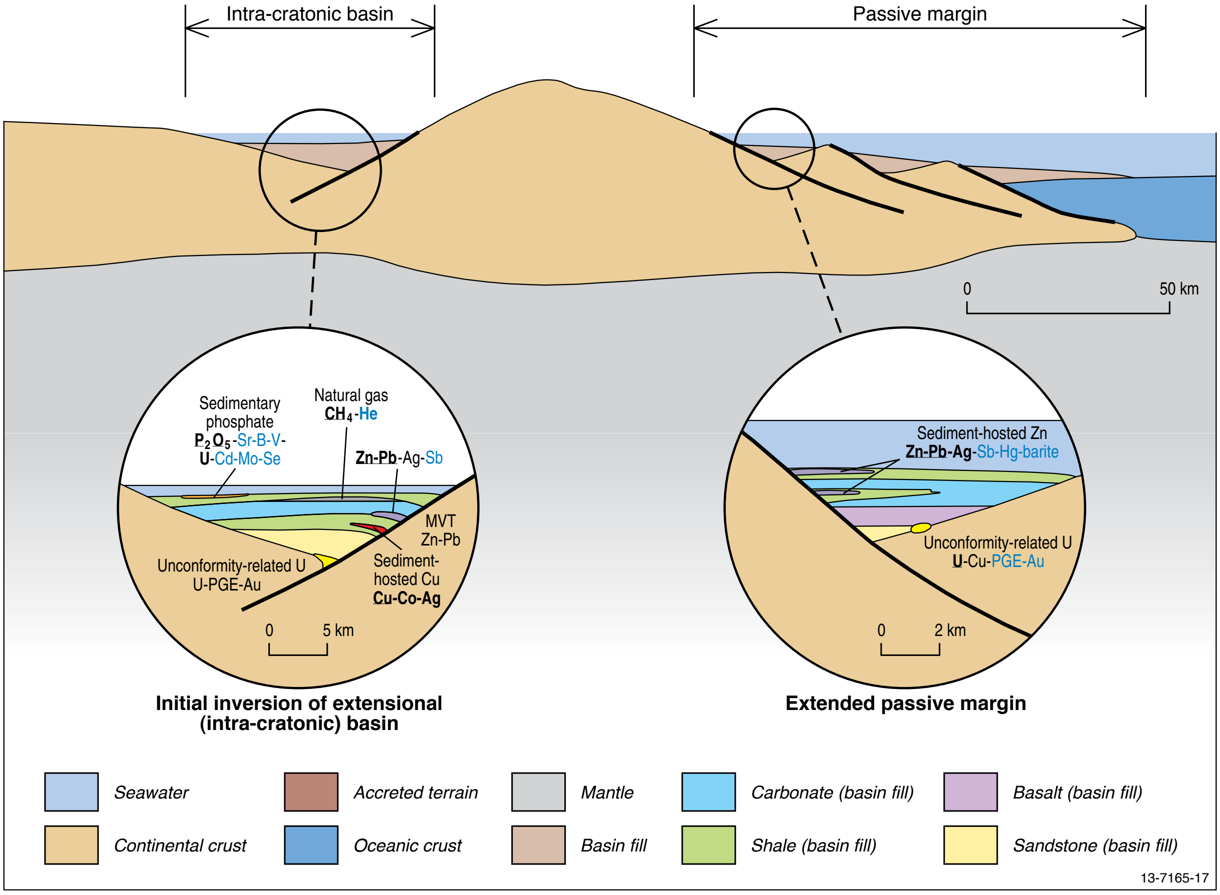

Figure 2.8.1: Diagrammatic sketch of the basin-hosted mineral system illustrating the relative location of deposits types within the overall setting and the likely distribution of critical and other commodities within and around these deposit types. In the commodity lists, blue indicates critical commodities, underlined bold indicates major products, bold indicates commonly recovered by-products, underlined normal font indicates commodities with limited recovery as a by-product (usually during downstream processing), and normal text indicates commodities that are geochemically anomalous, but not recovered.

Finally, other mineral deposits are the result of post-depositional hydrothermal (e.g., iron ore) or metamorphic (e.g., graphite) upgrading of rocks originally deposited during basin formation (e.g., banded iron formation and carbonaceous shale, respectively).

2.8.2 Sources of fluid, metals and energy

By their nature, basins contain a large variety of rocks—mafic volcanic rocks, siliciclastic rocks and carbonate rocks. Because these rocks are deposited in environments dominated by seawater or meteoric water, most late Paleoproterozoic and younger basins are dominated by oxidised rocks, with localised reduced rocks (e.g., carbonaceous shales). Older basins can contain more reduced rocks such as banded iron formation. Basin fill and fluids trapped within the basin determine the chemical characteristics of basin-hosted hydrothermal fluids and can be sources of metals and chlorine.

Studies of modern basinal fluids indicate that generally they are relatively oxidised, H_2S-poor and reasonably saline, and can be metal-rich (Hanor, 1996). Because fluid flow commonly occurs late during basin evolution or during basin inversion, periods that lack magmatism, the ore fluids are generally low temperature (<250°C, and commonly <200°C: Huston et al., 2006).

When they interact with oxidised basinal fluids, volcanic rocks at depth within the basin can be excellent sources of metals such as Cu, Zn and Co, whereas siliciclastic rocks (e.g., arkoses) within the basin succession or the basement can be sources of metals such as U and Pb. This potential is illustrated by leaching of mafic volcanic rocks near the base of the McArthur Basin in the Northern Territory by low temperature, oxidised fluids (Cooke et al., 1998).

If basinal fluids are indeed the most important ore fluid in the basin-hosted mineral system (e.g., Sawkins, 1984 and references therein), a potential constraint on the amount of metal transported is the amount of basinal fluid available. Moreover, Sawkins (1984) suggests that fluid flow must have been pulsed or episodic.

Fluid flow and mineralisation in basin-hosted mineral systems is commonly triggered by out-of-basin tectonic events, which can be manifested directly as basin inversion, or can have more subtle expression. For example, Cu mineralisation in the Neoproterozoic Yeneena Basin in Western Australia is closely associated with early structures (e.g., Anderson et al., 2001) probably related to basin inversion. Paleomagnetic studies in the North Australian Craton suggest a close relationship between bends in apparent polar wander paths and Zn-Pb-Ag and U depositional events (Idnurm, 2001; Huston et al., 2012). This relationship suggest tectonic events linked to changes in plate motion, which causes these bends, trigger mineralisation. Finally, Mississippi Valley-type Zn-Pb-Ag deposits around the world are related to regional orogenic events, with topographic head generated during mountain building driving fluid flow and mineralisation (Leach et al., 2005).

A feature of basin-hosted mineral systems not present in other mineral systems is the presence of hydrocarbon fluids—oil and gas—that can contain gaseous critical commodities such as helium or can act as a reductant, causing deposition of ore minerals.

2.8.3 Fluid pathways

The main fluid pathways in the basin-hosted mineral system are faults, stratigraphic aquifers within the basin and permeable zones within the basement or along unconformities. These fluid pathways, however, are not open to fluid movement at all times. In particular, diagenetic processes, which depend on a number geological parameters, including rock composition and temperature, can occlude or create porosity and permeability in aquifers (c.f., Polito and Kyser, 2006), and fault zones can open or close depending upon stress conditions. Hence, basin-hosted mineral systems can only be active during restricted periods when the fluid pathways are permeable. Out-of-basin tectonic events that trigger fluid flow may also open fluid pathways.

2.8.4 Depositional processes

The basin-hosted mineral system differs from most other hydrothermal mineral systems in that the main ore fluid is H_2S-poor and generally oxidised. These characteristics, particularly the low H_2S concentrations, allow the fluid to transport high concentrations of Cu, Zn, Pb, Ag and U at low temperature (<250°C: Cooke et al., 2001). The main mechanism for ore deposition is reduction of the ore fluid accompanied by provision of H_2S, which causes deposition of sulfide minerals. H_2S can be produced by inorganic or organic reduction of sulfate either in the ore fluid or in the wall rock, with inorganic reduction more likely at higher temperatures (>120°C) and organic reduction more likely at lower temperature (<120°C: Goldhaber and Orr, 1994; Machel, 2001). Alternatively, H_2S can be provided if the ore fluid mixes with a second, ambient fluid enriched in H_2S, for example sour gas. These depositional mechanisms are enhanced in reduced rock packages, for instance carbonaceous sediments, or in hydrocarbon-rich environments.

Uranium deposition, on the other hand, requires only reduction of U^{6+} in the ore fluid to insoluble U^{4+}, which deposits as uraninite or pitchblende (UO_2). Although H_2S is not needed to deposit U, reduced rocks such as carbonaceous sediments or Fe^{2+}-rich rocks, or fluids in equilibrium with such rocks, can cause U deposition (Bastrakov et al., 2009). It must be stressed however, that under the low temperature conditions of most basin-hosted mineral systems, redox reactions are kinetically slow (Ohmoto and Lasaga, 1982), hence, these reactions must be facilitated organically or by the presence of a catalyst such as H_2S or Mn^{2+} (Goldhaber and Orr, 1994; Machel, 2001). Redox gradients produced by the presence of organic-rich sediments or Fe^{2+}-rich rocks (mafic volcanics or iron formation) in an oxidised sedimentary succession are required for metal deposition.

In addition to metallic commodities, sedimentary basins are also the main source of phosphate rock, coal and hydrocarbons. However, formation of these resources does not involve hydrothermal fluids, but occurs in special sedimentary environments.

2.8.5 Australian examples

In Australia, major basin-hosted Zn-Pb-Ag and Cu-Co deposits are hosted by late Paleoproterozoic to early Mesoproterozoic North Australian Basin System (Queensland and Northern Territory), the Neoproterozoic to Paleozoic Central Australian Basin System (Western Australia, South Australia, Northern Territory and Queensland) and the Canning Basin (Western Australia) (Huston et. al, 2012). Uranium deposits are also hosted in Paleoproterozoic basins in the Northern Territory and Cenozoic basins in South Australia (Skirrow, 2011).

The North Australian Basin System contains three of the ten largest Zn-Pb-Ag deposits in the world, Mount Isa, Hilton-George Fisher and McArthur River (HYC), making it the largest global zinc province (Huston et al., 2012). Moreover, unconformity uranium deposits, such as Jabiluka, Ranger, Westmoreland and Coronation Hill, are present in basement near (mostly below) the basal unconformity of this basin system in the Northern Territory

(Mernagh at al., 1998). This uranium province is the second largest in Australia (after the Olympic IOCG Province; see Section 2.4) and one of the largest in the world.

Although not as well mineralised as the North Australian Basin System, the geographically extensive Central Australian Basin System contains a number of significant Cu, and U deposits, particularly in the Yeneena Basin in Western Australia and the Adelaide Rift Basin in South Australia. Shale-hosted Cu±Co±Ag deposits (e.g., Nifty and Maroochydore) are hosted by carbonaceous shale (Broadhurst Formation) near the base of the Yeneena Basin, and are present at several stratigraphic levels in the Adelaide Rift Basin (e.g., Mount Gunson, Burra and Kapunda).

During the latter half of the 19th century, the Adelaide Rift Basin was one of the largest copper producers in the world. Unconformity-related uranium deposits (e.g., Kintyre) and Mississippi Valley-type (e.g., Warrabarty) are also present within the basin or immediately below the basal unconformity of the Yeneena Basin. The Paleozoic section of the Amadeus and Ngalia basins contains several small sandstone-hosted uranium deposits in the Northern Territory (e.g., Bigrlyi and Pamela-Angela). The Amadeus Basin also contains producing oil and gas field at Mereenie and Palm Valley, respectively. These hydrocarbon fields are part of the Larapintine petroleum system, which was active during the Paleozoic (Bradshaw, 1993).

The lower Paleozoic section of the Georgina Basin, the northeastern constituent basin of the Central Australian Basin System, contains a number of phosphate deposits in Queensland and the Northern Territory. The most significant of these are Phosphate Hill, which produced 2.49 Mt of phosphate rock in 2011 (Geoscience Australia, 2013), and Paradise South in Queensland, and Wonarah in the Northern Territory. Although large deposits have not yet been discovered, sedimentary phosphate prospects are present in other constituent basins of the Central Australian Basin System, including the Amadeus Basin and the Adelaide Rift Basin. Economically demonstrated phosphate rock resources, mostly within the Georgina Basin, amounted to 945 Mt at 31 December 2011 (Geoscience Australia, 2013).

The Paleozoic to Mesozoic Canning Basin in Western Australia is host to early Carboniferous and possibly older Mississippi Valley type Zn-Pb-Ag deposits, including those on the Lennard Shelf (~354 Ma: Christensen et al., 1995) and at Admiral Bay (possibly 425-410 Ma: McCracken et al., 1996). The timing of mineralisation on the Lennard Shelf corresponds to the Brewer movement of the Alice Springs Orogeny and the formation of foreland basins in central Australia (Huston et al., 2012). The Canning Basin also hosts producing oil fields on the Lennard Shelf (Blina, Sundown and smaller fields), which form part of the Gondwanan petroleum system (Bradshaw, 1993).

The Eromanga-Carpentaria basin system, which covers much of eastern and south central Australia, and the overlying Lake Eyre basin in South Australia, hosts a number of small U (Beverley (including Beverley North), Four Mile and Honeymoon in South Australia) and V-Mo (Julia Creek in Queensland: Table 2.2.1) deposits associated with paleochannels or stratigraphic units rich in carbonaceous material. Currently, U is being extracted at the Beverley deposit using *in situ* leaching.

Historically, production of hydrocarbons in Australia has been from conventional oil and gas fields, including the Bass-Otway-Gippsland basin system in Bass Strait, the Perth, Carnarvon, Brouse and Bonaparte basins off the coast of Western Australia, and the Cooper, Surat, Canning and Amadeus basins in central and eastern Australia. Following developments elsewhere in the world, non-conventional hydrocarbon resources—coal seam gas, shale gas and shale oil—are currently being explored and developed through large parts of Australia, including the Sydney-Gunnedah-Bowen basin system.

The development of the liquefied natural gas industry in Australia has also allowed the first production of helium in the southern hemisphere. In March 2010, BOC Limited opened a helium production facility in Darwin. This plant produces approximately 4.25 million standard cubic metres of helium a year by refining a waste stream (containing up to 3 mole % helium) released during liquefied natural gas (LNG) processing in the nearby Conoco Phillips plant (Department of Resources and Energy, Minister for Tourism, 2010).

2.8.6 Associated critical commodities

Like the subaqueous volcanic-related mineral system, the basin-hosted mineral system has high potential to contain a number of critical commodities associated with base metals. For example, Cd, Ga, Ge, In and Hg are likely to be hosted by sphalerite in Zn-rich deposits. These Zn-rich deposits may also be sources of semi-metals such as Bi, Sb and As. As an example, using data from McGoldrick (1982) for 12 orebody at Mount Isa, Cd is weakly correlated (correlation statistically significant at 95% confidence) with Zn ($r^2 = 0.212$, $n = 25$, Cd/Zn (by mass) = 1.7×10^{-3}; excludes two Cd-rich outliers) suggesting an overall concentration of 65 ppm, although with high variability (Table 2.6.1). Other sediment-hosted deposits, such as Hilton-George Fisher, Century, HYC

(McArthur River) and Lady Loretta also probably contain significant concentrations of Cd. Carr et al. (1986) indicated that the Hg content of sediment-hosted Zn-Pb-Ag deposits ranged up to 33 ppm, with geometric means of 1.3 ppm, 8.3 ppm and 22 ppm reported for the HYC, Mount Isa and Lady Loretta deposits, respectively.

As discussed in Section 2.6, base metal deposits also can contain significant levels of the semi-metals, As, Sb and Bi. Table 2.6.1 estimates the concentration of Sb at Mount Isa based upon a strong correlation between Sb and Ag ($r^2 = 0.776$, n = 25; data from McGoldrick, 1986) which indicated Sb/Ag (by mass) ~1.03. These results indicate that the Mt Isa resources as of 31 December 2011 contained ~24 kt Sb, although this Sb is not recovered presently (and may not be recoverable). Arsenic concentrations in the ore samples analysed by McGoldrick (1982) were typically between 100 ppm and 450 ppm; a weak but significant correlation ($r^2 = 0.264$, n = 25; excluded two outliers) was noted, suggesting and overall As/Zn of ~ 1.5×10^{-3}. In contrast to volcanic-hosted massive sulfide deposits (Section 2.2.5), very limited data from high-grade ore samples suggest low Bi levels (<1 ppm, n = 2: McGoldrick, 1986) in Zn-Pb ores from Mount Isa.

In addition to the major deposits of the Australian Zinc Belt, Zn and Pb are also present at sub-economic grades in sediment-hosted Cu-Co-Ag deposits (e.g., Anderson et al., 2001; Tonkin and Creelman, 1990). Consequently, elements such as Cd, Ga, Ge, In, Hg, Bi, Sb and As may also be anomalous in these systems.

Platinum-group elements such as Pt and Pd are present in a number of basin-hosted deposits, including unconformity-related U and sediment-hosted Cu-Co. For example, the Coronation Hill unconformity-related deposit has a pre-JORC resource of 4.84 Mt grading 4.31 g/t Au, 0.19 g/t/ Pt and 0.65 g/t Pd, making it one of Australia's largest known PGE deposits[6]. Importantly, the Au-PGE resource is spatially separate from the nearby U resource. A number of other unconformity-related deposits also have anomalous PGE, Au and Cu (Jabiluka, NT, and Cluff Lake, Saskatchewan, Canada: Peterson, 1994). Platinum-group elements are also present in a sediment-hosted Cu-Co-Ag deposits including the Polish Kupferschiefer and some deposits in Zambia. Kucha (1982, 1983) reported Pt and Pd contents of up to 370 g/t and 120 g/t, respectively (and unquantified though anomalous Ir), in the Kupferschiefer, and Peterson (1994) indicated that ore grade rocks at the Musonoi deposit in Zambia contain 0.75 g/t Pt and 6 g/t Pd. No PGE data are available for sediment-hosted Cu-Co-Ag deposits in Australia.

Because of the large redox gradients involved in ore deposition, basin-hosted mineral deposits commonly contain high concentrations of redox sensitive elements such as Co, V, Se and Mo. Of these, Co is the most significant, being recovered as a by-product in sediment-hosted Cu-Co-Ag deposits overseas (e.g., Zambian copper belt), although not in Australia. Vanadium, Se and Mo are commonly found geochemically dispersed around sandstone-hosted U deposits (Nash et al., 1981; not shown in Figure 2.8.1), although not in sufficient quantities to warrant recovery.

Mernagh et al. (1998) indicate that Th, Zr and REE can be enriched in the basin above unconformity-related U deposits, although it is unlikely that the enrichment would be sufficient to allow recovery. Although not as common as in the sub-aqueous volcanic-hosted mineral system, the basin-hosed mineral system can contain significant barite. The most important example is the Lady Loretta deposit, which contains barite lenses spatially associated with the massive Zn-Pb-rich sulfide lenses.

Sedimentary phosphate deposits contain anomalous concentrations of some critical commodities. These metals include Sr, REEs, B, F, Cr, V, Mn, U, Ni, Cd, Mo, Co, Se, Te, As, Th and Sb (Bech et al., 2010; Simandl et al., 2011). Although these commodities are presently not being recovered, and some (e.g., Sr) can be deleterious, phosphorites are potential sources of REEs (Simandl et al., 2011), and historically uranium has been recovered from phosphate rock in several countries, most prominently the United States (http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Uranium-Resources/Uranium-from-Phosphates/).

Graphite deposits (not shown in Figure 2.8.1), which form mostly as the consequence of moderate to high grade metamorphism of carbonaceous sedimentary rocks, are hosted by deformed and metamorphosed basins. The best example in Australia is the Mikkira graphite province on the Eyre Peninsula, South Australia, which contains the Uley deposit (Table 2.2.1). This deposit intermittently produced graphite from the late 1920s to 1993. The total resource for the Mikkara province has been estimated at 350 Mt grading 6–7% graphite (http://www.pir.sa.gov.au/minerals/geological_survey_of_sa/commodities/graphite). The only other deposit of significance in Australia is the Munglinup deposit near Ravensthorpe in Western Australia.

As helium, a gas produced by radioactive decay of U and Th, is trapped in the subsurface under conditions that also trap natural gas, many natural gas deposits contain economically significant helium. As described above, helium is now being extracted from the waste stream of a liquefied natural gas plant in Darwin. Australia

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[6] Coronation Hill will not be developed as it is within the confines of Kakadu National Park.

has two other currently producing liquefied natural gas plants, the North West Shelf Venture (NWSV) at Karratha and the Pluto LNG project, located 190 km north-west of Karratha, but neither plant is presently extracting helium. Apart from these projects, seven large Australian LNG schemes are currently under construction (APPEA, 2012). Four draw from gas fields in northern Western Australia (Gorgon, Prelude, Wheatstone and Ichthys) and three are in Queensland (Queensland Curtis LNG, Gladstone LNG and Australia Pacific LNG).

Australia has vast conventional gas resources. In 2008, Australia's EDR and subeconomic demonstrated resources (SDR) of conventional gas were estimated at 180,400 PJ (164 tcf) (Geoscience Australia and ABARE, 2010). Based on the above estimate of 3 mole % helium in Australian LNG, this equates to a resource of approximately 4.92 tcf helium. Most (around 92 %) of Australia's conventional gas resources are located in the Carnarvon, Browse and Bonaparte basins off the north-west coast. There are also resources in south-east and central Australia. As well as the conventional gas resources, Australia also has large supplies of unconventional gas. Large coal seam gas (CSG) resources exist in the coal basins of Queensland and New South Wales. Tight gas accumulations are located in onshore Western Australia and South Australia, while potential shale gas resources are located in the Northern Territory (Geoscience Australia and ABARE, 2010). The potential of unconventional gas resources for helium extraction is unknown.

2.9 Alkaline intrusion-related mineral system

In comparison with calc-alkaline or tholeiitic magmatism, magmatic rocks associated with alkaline magmatism are generally small in volume, but can have a large range in composition. For example, alkaline rocks that form the ~1132 Ma (Hoatson and Claoué-Long, 2002) Mordor Complex in the Northern Territory range in composition from pyroxenite to syenite (Hoatson and Claoué-Long, 2002), and alkaline magmatic rocks include kimberlites and related rocks, and carbonatites (igneous rocks with more than 50% modal carbonate). Mineral deposits that form in the alkaline intrusion-related mineral system (Figure 2.9.1) are also quite diverse, ranging from diamond, through REE-P-U, to Ni-Cu-PGE and vermiculite deposits. Moreover, these deposits contain a large number of critical commodities, including REE, PGE, Ni, Th and Zr.

2.9.1 Geological setting

Although small in volume, alkaline igneous rocks are found in a large range of geological settings, including continental rift valleys (the main setting), intraplate magmatic provinces with uncertain tectonic settings, and destructive plate boundaries (Fitton and Upton, 1987). In the latter case, calc-alkaline magmas tend to become more potassic as subduction proceeds and may give way to volcanic rocks of the shoshonitic association (Fitton and Upton, 1987). For this discussion, the shoshonitic association is considered in the porphyry-epithermal mineral system (Section 2.2).

Carbonatites occur in continental shields and are commonly related spatially to fault lineaments such as in rift systems. Locally, they are related to alkaline volcanism. Almost all known carbonatite complexes are intrusive into Precambrian shields, however, the carbonatites themselves may be much younger (Woolley and Kjarsgaard, 2008).

2.9.2 Sources of fluid, metals and energy

Radiogenic and stable isotopic data and geochemical data all suggest that alkaline magmas and carbonatites originated as generally low degree partial melts of metasomatised or crustally contaminated mantle, with the depth of melting and the degree and age of contamination determining the type of geochemical and isotopic characteristics of the magma (Fitton and Upton, 1987; Menzies and Murthy, 1980). Ultimately, this metasomatism and contamination is thought to be a consequence of the subduction of crust into the mantle (Fitton and Upton, 1987).

The parental carbonatite magmas originate by the separation of an immiscible carbonate liquid phase from a CO_2-saturated nephelinite or phonolite magma. The separation of the carbonate liquid from its source leads to strong fractionation between the carbonate liquid and silicate and oxide solid phases. Strontium and Nd isotope ratios indicate that the sources of carbonatites are geologically old, inhomogeneous, and variably depleted in the radioactive parent elements Rb and Sm. This fractional process typically results in strong enrichment in light rare-earth elements, U, Th, and Pb, but much less enrichment in T, Zr, Nb, and Sr.

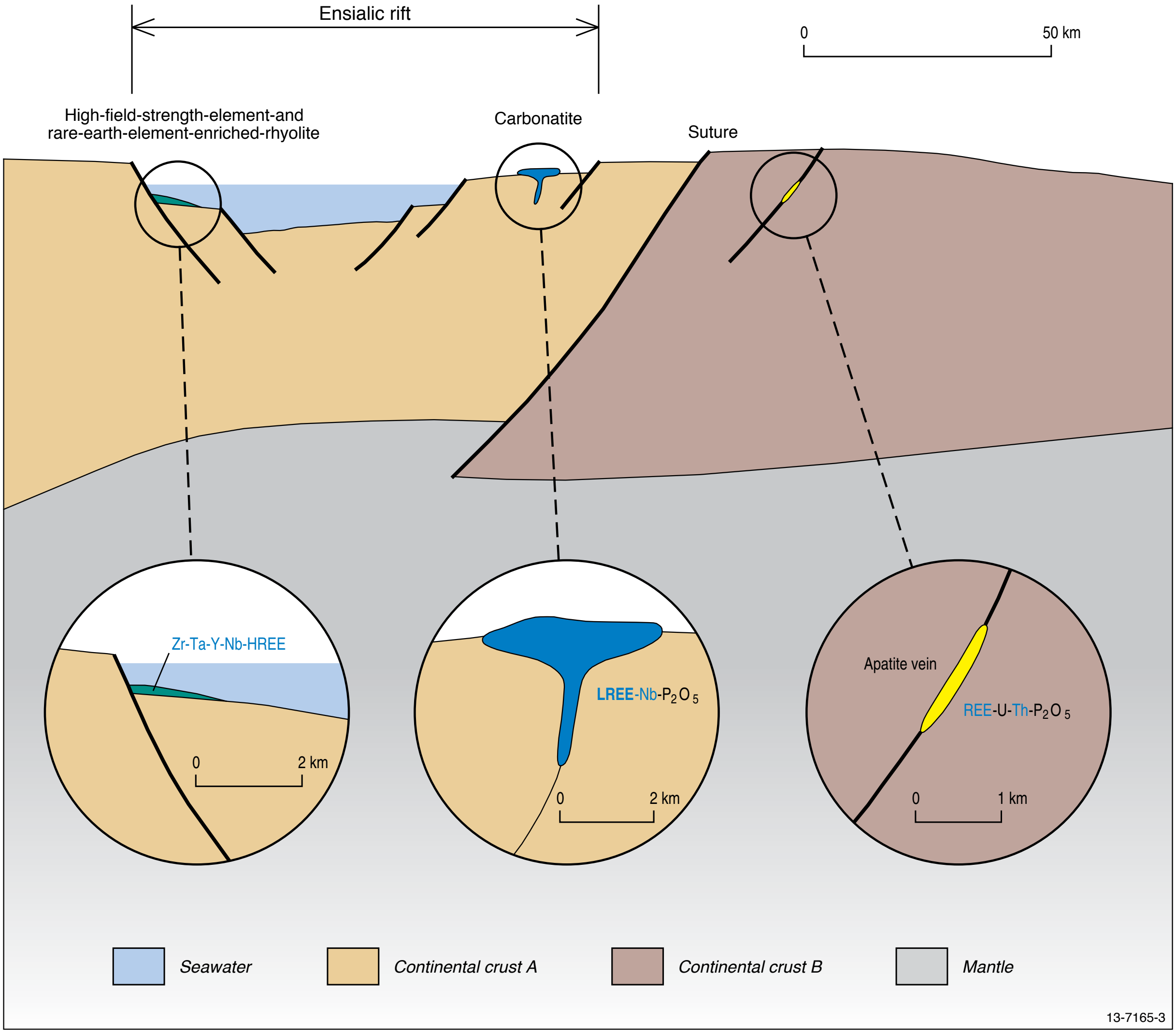

Figure 2.9.1: Diagrammatic sketch of the alkaline intrusion-related mineral system illustrtaing the relative location of deposits types within the overall setting and the likely distribution of critical and other commodities within and around these deposit types. In the commodity lists, blue indicates critical commodities, underlined bold indicates major products, bold indicates commonly recovered by-products, underlined normal font indicates commodities with limited recovery as a by-product (usually during downstream processing), and normal text indicates commodities that are geochemically anomalous, but not recovered.

2.9.3 Fluid pathways

The alkaline intrusion-related mineral system differs from most other mineral systems in that many deposits are orthomagmatic, that is the ore fluid was the magma. Hence, fluid pathways in this mineral system are largely the magmatic pathways, which are generally controlled by larger-scale architecture. For example, young examples of larger volume alkaline magmatic provinces are most closely associated with continental rifts such as the East Africa Rift (Kampunzu and Mohr, 1991), suggesting the pathways for the emplacement of these magmas are provided by the rift architecture and the impetus for magmatism was provided by rifting. Ernst and Bell (2010) suggest that possible drivers for some alkaline magmatic events through time were mantle plume events, which also can initiate rifting.

Kimberlite and related melts are generally emplaced along the margins of old and cold cratons as indicated by lithospheric tomographic data (Begg et al., 2009). An important aspect of the emplacement of many alkaline magmas is a rapid ascent from source (Eggler, 1989), which must occur along weak zones such as the margins of old-cold cratonic blocks.

2.9.4 Depositional processes

Typically, mineralisation is the product of the emplacement of volatile-enriched (F and water) alkaline magmas as hypabyssal intrusions, (pyroclastic) volcanic rocks, or deeper level intrusions. During this process, the volatiles and incompatible elements (e.g., Th, Zr, and REE) are concentrated in the upper parts of the magma chamber. Late-stage hydrothermal fluids, containing F and Cl, are important for enhancing the grades in these deposits.

If a magmatic-hydrothermal fluid evolves from the alkaline magma, depositional mechanisms can include depressurisation, fluid-rock interaction or mixing with ambient fluids.

Carbonatite magma, ascending through lithospheric mantle, commonly is trapped before it can invade the crust. In addition to the factors that can stop the rise of any magma (heat loss, increase of solidus temperature with decrease in pressure, decrease in density and increase in strength of wall rock), carbonatite magma can be halted by reaction with wall rock to form Ca and Ma silicates plus CO_2. In more reducing conditions carbonate can be reduced to elemental carbon (graphite or diamond) or to methane. Both of these changes remove dissolved CO_2 from the magma, causing crystallisation.

Mineralisation is commonly restricted to carbonatite dykes, sills, breccias, sheets, veins, and large masses, but may occur in other rocks associated with the complex rocks. Alteration known as fenitisation (widespread alkali metasomatism of quartzo-feldspathic rock; mostly alkalic feldspar with some aegerine and subordinate alkali-hornblende and accessory sphene and apatite) typically occurs near the contact of carbonatite intrusions (Brøgger, 1921). The fluid-rock interaction recorded by fenitisation may be a prime mechanism for carbonatite crystallisation, as described above. Trace elements typically associated with carbonatites include Th, U, Cu, V, P, Mn, S, La, Sm, Pb, Zr, Ba, and Eu; enrichment of Be, B, Li, Sn, Ta, Hf, and W, though present in some carbonatites, is less common.

2.9.5 Australian examples

Mineral deposits related to alkaline magmatism in Australia are relatively uncommon, but include important current producers, such as the Argyle diamond mine, deposits from which production has just commenced, such as the Mount Weld carbonatite, and deposits in the advanced stages of feasibility, such as the Toongi and Nolans Bore deposits. Much of the information presented herein is based on Hoatson et al., (2011).

The Argyle diamond mine in the Halls Creek Orogen in Western Australia is the world's largest diamond producer. The only other current producer is the Ellendale field, also in Western Australia, although the Merlin field in the Northern Territory may be reopened in the next few years. Total Australian diamond production in 2011 was 7.5 million carats, with Argyle producing over 98% (Geoscience Australia, 2013).

The Toongi Zr-Nb-REE deposit in New South Wales (Table 2.2.1) occurs within an alkaline trachyte plug about 30 km south of Dubbo in NSW. In 2008 a demonstration plant was constructed in collaboration with ANSTO in Sydney, which demonstrated the technical viability for of Zr, Nb, LREE and HREE recovery. The project is currently the subject of a defensible feasibility study scheduled for release in Quarter 1 2013 (alkane.com.au). The peralkaline granitic intrusions of the Narraburra Complex, also in New South Wales, contain anomalous amounts of Zr, REE and low concentrations of Th (Table 2.2.1).

The Hastings-Brockman deposit in Western Australia is a large low-grade Zr-Nb-REE deposit (Table 2.2.1) hosted in altered trachytic tuff of Paleoproterozoic age. It occurs in a Paleoproterozoic sequence (>1000 m thick) of alkaline lavas, volcaniclastic sedimentary rocks, and felsic volcanics that is intruded by subvolcanic sheets and interlayered with greywacke, siltstone and mudstone.

The Mount Weld deposit in Western Australia is a large, high-grade Y, Nb, Ta, P, Zr, Ti and REE resource in the lateritic profile of a large circular Proterozoic carbonatite, which intrudes Archean greenstones of the Yilgarn Craton. The deposit was enriched as a result of supergene enrichment processes in the deep weathering profile. The weathered zone is rich in REE, Nb, and Ta, whereas the unweathered carbonatite at depth contains these elements in lower amounts more typical of carbonatites. Mining commenced in 2008, and in May 2011 the concentrating plant was opened. Currently, a total of 14.365 kt of REO concentrate has been processed and is ready for export to a processing plant in Malaysia. In January 2012 Lynas Corporation announced total resources at the Mount Weld deposit (including the Central Lanthanide and Duncan lenses) of 23.9 Mt grading 7.9% REO (rare-earth oxides).

The Cummins Range carbonatite in Western Australia is a roughly circular body and is about 1400 m in diameter. The complex is deeply weathered and covered by a thin layer of aeolian soil and silicified limonitic collapse breccia mounds. Navigator Resources reported inferred resources for the Cummins Range deposit of 4.17 Mt at 1.72% REO, 11.0% P_2O_5, 187 ppm U_3O_8 and 41 ppm Th (Geoscience Australia, 2012).

Other Australian carbonatites include Yangibana, Ponton Creek, and the Yungul dykes in Western Australia and Mud Tank in the Northern Territory. Carbonatites and/or related veins are also reported at the Mordor Igneous Complex in the Northern Territory and Walloway in South Australia (Hoatson et al., 2011). The Mordor Complex also contains low-grade Au-PGE mineralisation associated with a layered mafic intrusion of lamprophyric affinity (Barnes et al., 2008).

Another Australian deposit that may be associated with alkaline magmatism is the Nolans Bore REE-P-U deposit (Table 2.2.1), which consists of a series of massive apatite veins. This deposit is thought to be a hydrothermal deposit, and a direct relationship to alkaline magmatism has not been established, although it is suspected. This interpretation is supported by radiogenic and stable isotope data, which suggest a metasomatised or contaminated mantle source, possibly like EM1 (Huston et al., 2011b).

2.9.6 Associated critical commodities

As described above deposits associated with alkaline magmatism are Australia's (and the world's) dominant resource for a number of critical commodities, including REE, Nb, Zr and Th. Other critical commodities contained within some of these deposits include Ga (Table 2.2.1) and PGE.

2.10 Surficial Mineral Systems

Surficial systems result from the physical and chemical phenomena which cause concentration of ore material within the regolith, lake, or shallow marine environment, generally by the action of the environment. This occurs as a result of the following processes:

- Supergene enrichment, i.e. weathering via oxidation, biological and/or chemical attack of a rock, either liberating rock fragments or creating chemically deposited minerals, clays, or laterites;
- Deposition by sedimentary processes, including erosion, winnowing, and density separation; and
- Deposition in low-energy environments such as beach and marine environments and terminal lakes.

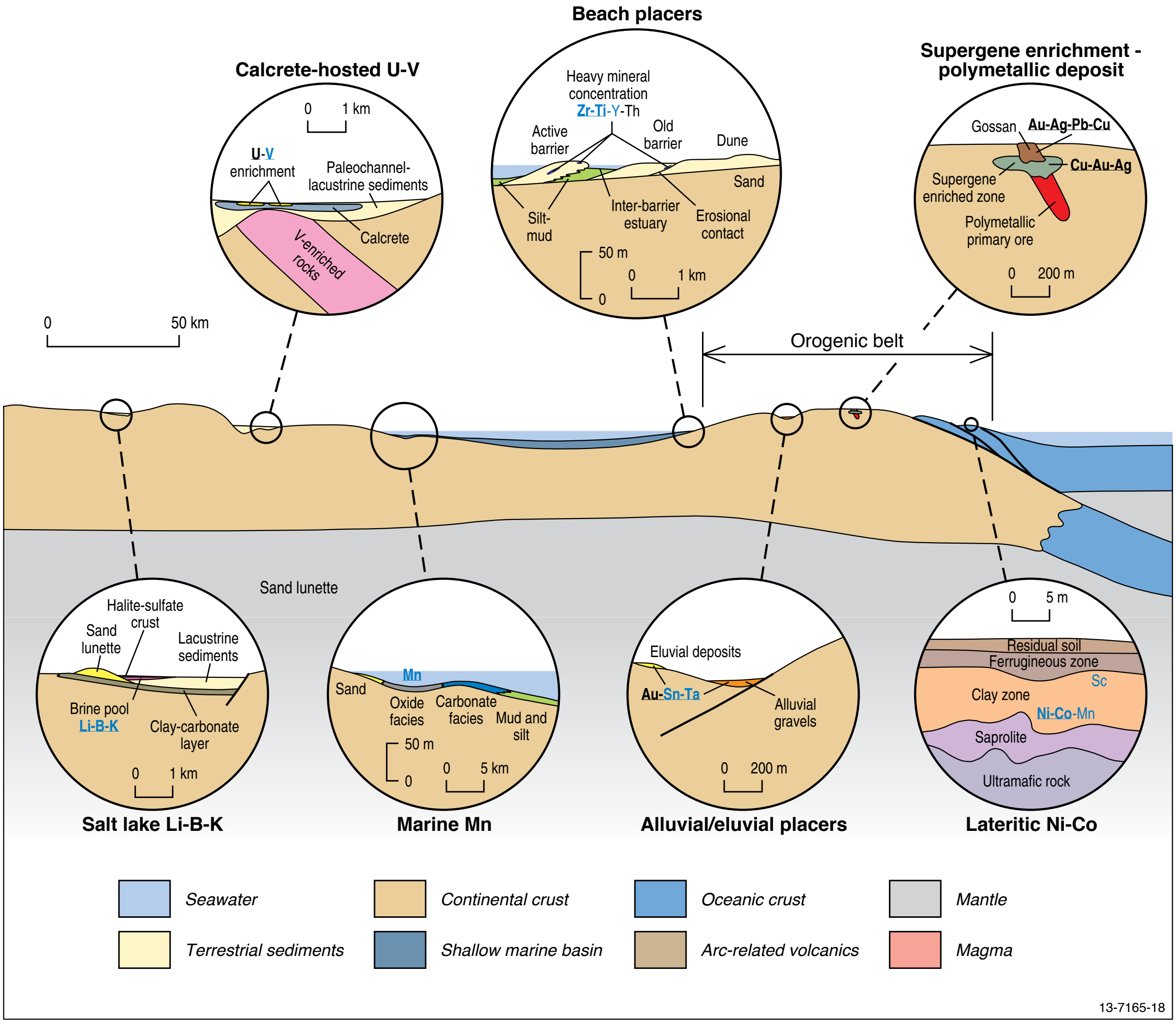

Figure 2.10.1: Diagrammatic sketch of the surficial mineral system illustrating the relative location of deposits types within the overall setting and the likely distribution of critical and other commodities within and around these deposit types. In the commodity lists, blue indicates critical commodities, underlined bold indicates major products, bold indicates commonly recovered by-products, underlined normal font indicates commodities with limited recovery as a by-product (usually during downstream processing), and normal text indicates commodities that are geochemically anomalous, but not recovered.

Due to the different depositional environments we have divided surficial systems into three main types: (i) those formed by supergene enrichment process, (ii) placer deposits formed by density separation during sedimentary processes, and (iii) salt lakes and calcrete uranium systems (Figure 2.10.1).

2.10.1 Supergene enrichment

2.10.1.1 Geological setting

Lateritic Ni-Co deposits are associated with ophiolites and mafic/ultramafic complexes in mobile belts and Archaean/Proterozoic greenstone terranes. Uplift is required to expose these rocks to weathering.

Lateritic P-REE deposits are associated with carbonatites and alkaline igneous complexes. Carbonatites occur in cratons while alkaline igneous rocks may occur in continental rift valleys, intraplate magmatic provinces and at destructive plate boundaries as discussed above.

Primary Cu, Pb and Zn deposits form in a number of tectonic settings as described above. Secondary mineralisation occurs when the primary sulfide minerals are oxidised at the surface and acidified meteoric water carries the Cu and Zn down to the water table where Cu is commonly deposited. Lead and Ag are commonly retained in the weathered profile as they are insoluble in most surficial conditions. Zinc is generally lost during weathering, although under some conditions, it can be deposited to form non-sulfide Zn deposits. Bauxite requires intense weathering conditions and is best developed in tropical climates.

Manganese deposits generally form in shallow marine depositional environments (15–300 m), commonly in sheltered sites around islands along some areas of continental shelf and the interior basins. Most deposits overlie oxidised substrates, but basinward, carbonate deposits may be in reducing environments. Many deposits are in within transgressive stratigraphic sequences near or at black shale pinchouts.

2.10.1.2 Sources of fluid, metals and energy

Supergene processes involve predominantly meteoric water circulation. The descending meteoric waters oxidise the primary sulfide and other minerals and redistribute ore elements. The phenomenon is most common in arid or semi-arid regions. The sources of metals are the protoliths that are being weathered. For example, ultramafic and mafic rocks are the sources of Ni, Co, Cr, Sc and PGE in lateritic deposits, whereas pre-existing hypogene ores are the sources of supergene Cu, and carbonatites can be sources of light REE, U, Th, Sr, Ba, Nb, Ta, Pb, Zn, V and P. Bauxite can form from any aluminous silicate rock and Mn is sourced from seawater.

2.10.1.3 Fluid pathways

Meteoric waters flow in the weathering profile under moderate topography with concomitant oxidation and chemical weathering of pre-existing ore minerals.

2.10.1.4 Depositional processes

Lateritic Ni-Co, lateritic P-REE and secondary Cu, Pb and Zn deposits are the result of supergene processes. Supergene enrichment occurs at or near the base of the weathering profile developed over hypogene sulfide deposits or rocks enriched in Ni and Co. Metals that have been leached from the oxidised part of the profile are carried downward by percolating groundwater, where they are deposited either by a change in redox as the water table is reached or through reactions with hypogene sulfide minerals. These reactions produce secondary oxides and/or sulfides with metal contents higher than those of the primary ore or protolith.

Bauxite formation requires climates that provide relatively high rates of chemical weathering and relatively low rates of physical erosion. In this case Al enrichment is residual and involves removal of other constituents of the rocks, leaving a residua composed of bauxite.

Manganese precipitation is believed to take place in stratified water masses at the interface between anoxic seawater and near surface oxygenated waters. Extreme Fe fractionation is caused by a low solubility of Fe in low Eh environments where Fe precipitates as iron sulfide. A subsequent increase in Eh and/or pH of Mn-rich water may produce Mn-rich, Fe-depleted chemical sediments. The Mn oxide facies is preserved on oxidised substrates. The Mn ore is commonly further enriched by supergene process.

2.10.1.5 Australian examples

The Murrin Murrin lateritic Ni-Co deposit developed from thoroughly serpentinised peridotite in the Late Archean Norseman-Wiluna greenstone belt in Western Australia (Monti and Fazakerley, 1996; Wells and Butt, 2006). At Murrin Murrin the laterite profile consists of five zones, including: unweathered country rock at the base, saprolite, smectite, limonite, and a cap of colluvium. The highest Ni concentrations occur in the smectite zone. The cobalt occurs in Mn-oxides in the limonite zone and upper part of the smectite zone.

The SCONI project in Queensland includes five key lateritic Ni-Co deposits, with the Greenvale deposit being an historic mine. Recent exploration in this area by Metallica Resources indicates that this region also contains significant reserves of Sc. Other lateritic Ni-Co deposits include Wingella and the Kalgoorlie Nickel Project in Western Australia and the Barnes Hill project in Tasmania.

Mount Weld is the only currently operating lateritic phosphate-REE mine in Australia. It contains some of the highest REE grades (8.1% Rare-Earth Oxides) for this style of deposit making it a world-class deposit. Mount Weld also hosts significant resources of Nb, Ta, and P_2O_5. The Crown deposit in the northern part of the complex has an indicated and inferred resource of 37.7 Mt at 1.07% Nb_2O_5, 1.16% total lanthanide oxides, 0.09% Y_2O_3, 0.3% ZrO, 0.024% Ta_2O_5, and 7.99% P_2O_5 (as of January, 2010), while P mineralisation in the Swan deposit in the northern half of the complex has an indicated and inferred resource of 77 Mt at 13.5% P_2O_5. The Anchor deposit in the southwest of the Mount Weld complex contains Nb-Ta mineralisation (Hoatson et al., 2011).

Bauxite is currently mined at Weipa (Qld), Gove (NT) and the Darling Range (WA), but other areas of potential include the Mitchell Plateau and Cape Bougainville (WA), Cape York (Qld), central New South Wales and parts of Tasmania.

The Groote Eylandt Mn mine in the Gulf of Carpentaria accounts for about one quarter of the world's total Mn production. The mine had proven, probable reserves of 109 Mt grading 46.6 % Mn for 50.794 Mt of manganese at June 30, 2010 (Miningoilgas, 2013). Mn is also being mined at Bootu Creek in the Northern Territory and Woodie Woodie in Western Australia (Geoscience Australia, 2012).

2.10.1.6 Associated critical commodities

The limonite in lateritic Ni-Co deposits commonly contains other elements such as Ca, Zn, Cu, Mn, Cr and, depending on the separation of the lateritic layers, Mg as well. All of these elements are commonly present as oxides and hydroxides. As mentioned above, Sc is also associated with lateritic Ni-Co deposits in north Queensland and Metallica Minerals Limited has announced a total (measured + indicated + inferred) Sc resource of 3827 tonnes for its combined SCONI southern deposits (Metallica Minerals Ltd., 2012). Other deposits are known near Young and Nyngan in New South Wales.

At Mount Weld, the lateritic phosphate-REE zone contains abundant insoluble phosphates, aluminophosphates, clays, crandallite-group minerals, Fe and Mn-bearing oxides that contain elevated concentrations of REE, Y, U, Th, Nb, Ta, Zr, Ti, V, Cr, Ba, and Sr. Very high-grade lanthanide concentrations (up to 45% combined lanthanide oxides) occur in the regolith and are attributed to secondary monazite. Churchite contains considerable amounts of high-grade Y (up to 2.5% Y_2O_3). Niobium- and Ta-bearing pyrochlore, ilmenite, and rutile in the primary carbonatite are concentrated in the apatite and magnetite-rich residual zone. Grades are typically variable and locally high (up to 1.5% Nb_2O_5 and 0.05% Ta_2O_5). Higher grades of niobium (up to 6% Nb_2O_5) occur in the supergene zone.

Significant reserves of Ga occur in oxide minerals derived from surficial weathering of polymetallic ore deposits (U.S. Geological Survey, 2013). Other trace elements include Ge, Se, Ag, Cd, and Sb.

More than 30 different trace elements occur in bauxite and they range widely in abundance. Bauxite residues may contain up to 9% TiO_2 and analysis of bauxite from Weipa (Jepsen and Schellmann, 1974) shows these ores contain 73 ppm Ce, 120 ppm Cr, 67 ppm Ga, 37 ppm La, 198 ppm P, 38 ppm Th, 490 ppm V, 37 ppm Y and 966 ppm Zr. A Russian patent has demonstrated that a resin-in-pulp method can be used for the recovery of Ti, Sc, U and Th from Australian bauxite residues (Klauber et al., 2009), and processes for recovering REE and Sc are being developed in the Philipines and Indonesia.

A wide range of trace elements have been reported (Parcejus and Bolton, 1992) from the Mn oxide ores at Groote Eylandt, including B, As, P, Cr, Co, Cu, Mo, Ti, U, Th, Zr, V, Zn, Pb, Sc, Yb, Ce, Gd, Eu, La, Nd, P, and Sm. Parcejus and Bolton (1992) suggest that some of these elements are correlated with certain minerals. For example, they suggest that Ti and Zr are correlated with kaolinite, whereas Gd is correlated with goethite, and Pb with gibbsite.

2.10.2 Placer Deposits

2.10.2.1 Geological setting

Diamond placers most commonly form in stable cratonic settings. Tin placers form in Paleozoic to Cenozoic accreted terranes or stable cratonic foldbelts that contain highly evolved granitoid plutons or their extrusive equivalents. Channel iron deposits usually occupy meandering palaeochannels in the Early to Mid-Tertiary palaeosurfaces of Western Australia. Gold placers may form in Cenozoic conglomerates along major fault zones, in cratonic areas where erosion has proceeded for a long time producing multicycle sediments, and in high-level terrace gravels.

Heavy mineral sand deposits containing rutile (TiO_2), ilmenite ($FeTiO_3$), zircon ($ZrSiO_4$) and monazite ($[Ce,La,Th,Nd,Y]PO_4$) occur on the margins of cratons. They usually form in beach environments and require crustal stability during deposition and preservation of the deposits.

2.10.2.2 Sources of fluid, metals and energy

Diamonds are sourced from kimberlite pipes but alluvial diamond deposits may be up to 1000 km from the source. The source of iron for channel iron deposits is thought to be iron-rich soils which developed upon a palaeosurface during hot, humid conditions. Placer Au is usually sourced from pre-existing hydrothermal gold deposits which are eroded by rivers and more rarely glaciers. Tin is sourced from highly evolved granitic plutons or their extrusive equivalents.

Heavy mineral sand deposits come from granitic and volcanic rocks within the erosional areas of rivers which carry the sediment into the ocean, where it is caught up in littoral drift or longshore drift near beaches.

2.10.2.3 Fluid pathways

Glacial and fluvial processes provide a mix of depositional environments including high-energy bench (or terrace) gravels and lower-energy deposits on the valley floor. Near-shore (beach) deposits result from the efficient sorting and winnowing action of the surf. Deposits in arid climates may form by the winnowing action of the wind.

2.10.2.4 Depositional processes

Alluvial placers are formed by the deposition of dense particles at a site where water velocity remains below that required for further transport. Tin placers form where stream gradients lie within the critical range for deposition of cassiterite (for instance, where stream velocity is sufficient to result in good gravity separation but not enough so the channel is swept clean). Diamond and Au placers form on the inside bends of rivers and creeks; in natural hollows; at the break of slope on a stream; and at the base of an escarpment, waterfall or other barrier. Channel iron deposits are formed by the erosion of an iron-rich palaeosurface into palaeodrainage systems, where the Fe becomes consolidated within the existing river courses.

Heavy mineral sand deposits essentially fall into two categories depending on the mode of deposition: alluvial or aeolian. Alluvial deposits are further split into marine beach placers (or strandlines) and lacustrine heavy mineral accumulations. Aeolian deposits are generally closely associated with marine beach placers, having been formed by the erosion, transport and deposition of heavy minerals from adjacent marine beach placers by prevailing winds.

2.10.2.5 Australian examples

Discovery of alluvial diamonds at Smoke Creek in Western Australia in the late 1970s led to the discovery of the currently mined Argyle diamond pipe. Thus, the Smoke Creek alluvial diamonds are most likely derived from erosion of the Argyle pipe, and therefore represent a possible new source of valuable pink diamonds. North Australian Diamonds Limited is also examining the diamond-bearing potential of gravels near Borroloola in the Northern Territory (Geoscience Australia, 2012).

Tin placer deposits include the Karaula alluvial-tin-tungsten deposit near Inverell, and the the Giants Den alluvial deposits near Bendemeer in New South Wales. In Tasmania exploration for alluvial Sn is continuing at Scotia, Endurance and in Ringarooma Bay (Geoscience Australia, 2012).

Channel iron deposits are only known to occur in Western Australia and Kazahkstan. Australian examples include the Yandicoogina South deposit and the Blacksmith and Anvil tenements in the Pilbara region.

Alluvial Au deposits were historically mined in the major goldfields in Victoria, New South Wales, Western Australia, Queensland and Tasmania. In Western Australia, current alluvial Au projects include Ivanhoe Yalgoo, Mount Sholl East, Nemisis, Nicholsons Find, Sharks Gully and Womerina (not shown in Figure 2.1.1). Until recently, alluvial Au was being mined from the Georgetown gold mine in Queensland (ERO Mining, 2010). Queensland Bauxite Limited has also identified an alluvial Au system near Tamworth, New South Wales.

Heavy mineral sand deposits represent a major source of rutile, ilmenite, zircon, and in the past, monazite. Australian examples include Enabba, Cooljaroo, Dardanup, Gwindinup and Calypso (Western Australia), Jacinth-Ambrosia and Cyclone (South Australia), Douglas and the various WIM deposits (in the Murray Basin, Victoria), Ginko and Snapper (New South Wales), and North Stradbroke Island (Queensland). The latest emerging heavy mineral sand province is the Eucla Basin in South Australia where zircon is the dominant commercial mineral rather than the titanium-rich minerals.

2.10.2.6 Associated critical commodities

Diamond placers are commonly associated with Cr, Ti, Mn, Ni, Nb Co, PGE, and Ba, some of which are used to indicate the proximity to diamond deposits. Tin placers are associated with anomalous amounts of As, B, F, W, Be, Cu, Pb, Zn, Mn, Nb, Ti, and Y (Ogwuegbu et al., 2011). Gold placer deposits have anomalous amounts of Ag, As, Hg, Sb, Cu, Fe, W, Ti, Zr, S and Cr. Heavy mineral sand deposits have associated REE, Cr, Sn, Th and U.

2.10.3 Salt Lakes (Li-K-B) and Calcrete Uranium

The following is based upon a preliminary assessment of the potential of Australian salt lakes to host Li, B and potash deposits. Readers are referred to the assessment (Mernagh, 2013) for a comprehensive review of Australian salt lake systems, and a preliminary assessment of their critical commodity potential.

2.10.3.1 Geological setting

The processes that lead to salt build-up may occur on the flanks of continental uplifts, within extensional basins, in endorheic basins, and in glaciated terrain. The majority of salt lakes are found in the semi-arid to arid regions of the world as evaporation in excess of precipitation plays a critical role in the development of salt lakes. Three basic conditions are needed to form salt lakes (Eugster and Hardie, 1978). First, outflow must be absent or severely restricted to ensure hydrological closure. Second, evaporation must exceed inflow, and thirdly, inflow must be sufficient to form a body of water at or very close to the surface. Therefore, favourable locations for the formation of salt lakes are arid basins in the rain-shadows of mountain ranges or highland areas, which provide the catchment for precipitation. In areas of lower relief, shallow basins may act as the focus of local discharge and evaporation from regionally extensive groundwater systems. Some of the world's largest salt lakes are found at elevations exceeding 1000 m, such as Salar de Uyuni (Bolivia), Salar de Atacama (Chile), Qinghai Lake (Tibet), and the Great Salt Lake (US). This reflects the tendency for these systems to form in tectonically active regions. Even some large saline lakes nearer to sea level (e.g. the Caspian and Dead Seas) are associated with active tectonism.

Calcrete uranium is associated with calcrete or dolocrete formed within Cenozoic drainage systems incised into rocks containing leachable U and V. Non-pedogenic calcrete (also known as groundwater or valley calcrete) is formed predominantly near the water table from groundwater moving along extremely low gradients. The formation of non-pedogenic calcrete is generally controlled by climate and the type of soil. In the Yilgarn Craton, in Western Australia, the distribution of non-pedogenic and pedogenic calcretes is defined by the Menzies Line. North of the Menzies Line, the zone dominated by non-pedogenic calcretes, the soils are generally neutral to acid and the groundwaters are less saline and neutral to alkaline. South of the Menzies Line, dominated by pedogenic calcretes, the soils are neutral to alkaline and the groundwaters are saline and neutral to acidic.

2.10.3.2 Sources of fluid, metals and energy

Climate plays a critical role in the water balance of salt lakes. The amount of inflow to a closed basin, including precipitation, must be closely balanced by evaporative loss in the basin in order to produce elevated salinities. The sources of fluids are mainly direct precipitation, associated surface flow, and/or groundwater. Groundwater may be derived from a local or regional meteoric system, interstitial water from sediments, or deep basinal or hydrothermal fluids. Hydrothermal discharge (e.g. from geothermal springs), though often small in volume can be significant in terms of its contribution of solutes.

Lithium can be sourced from volcanic glasses and felsic rocks, particularly andesitic to rhyolitic tuffs and ash flows. Another source is Li-bearing clays (e.g., hectorite) formed from the weathering of feldspars and micas. The occurrence of Li and B in salt lakes is also correlated with recent or concurrent volcanic activity and/or areas that have a higher than average geothermal gradient. Borate deposits, in particular, appear to be associated with long-lasting, high-B geothermal springs with a long-lasting volcanic period or a high underlying magmatic temperature (Garrett, 1998).

Sources of K are most commonly felsic to intermediate volcanic rocks, but also include older evaporites and continental sedimentary rocks (Alonso and Risacher, 1996; Risacher and Fritz, 2009). Sources of K in these rocks are weathered minerals, such as orthoclase, microcline, biotite, leucite, and nepheline. Studies have found a positive correlation between K, Li, and B in brines (Carmona et al., 2000; Orris, 1997; Zheng, 1984), which is probably indicative of the fact that many salt lakes occur in volcaniclastic terranes that typically are associated with convergent plate boundaries (Orris, 1997).

All known calcrete-hosted uranium deposits are located in palaeochannels incised into potential source rocks of K, U and V. Intensive weathering and erosion of felsic rocks can provide U as well as K to the calcrete system.

Mafic igneous rocks, sediments with V-rich clays, ironstone such as banded iron-formation and ferricrete are often enriched in V. Such rocks are generally present in the vicinity of calcrete-hosted uranium deposits and can provide the V needed for formation of the mineral carnotite $[K(U^{+6}O_2)(V^{+5}O_4).xH_2O]$ commonly associated with calcrete uranium deposits.

2.10.3.3 Fluid pathways

Most of the surface and groundwater is dominantly controlled by gravity-driven fluid flow. Gradients in potential energy (hydraulic head) drive fluid flow from regions of higher hydraulic head to regions of lower hydraulic head. Capillary forces may also affect fluid flow in the capillary fringe (a saturated zone above the water table). Geothermal gradients may lead to the discharge of hydrothermal fluids into the system. These higher temperature fluids not only add thermal energy to the system but potentially carry higher concentrations of solutes than other fluids.

The calcrete uranium system is driven by shallow groundwater drainage with extremely low gradients, ca. 10 m/km. The drainage in the region is controlled by a recharge area upstream and a system of playa lakes in the discharge area. In addition of the infill sediments, calcretes formed near the water table also function as aquifers which allow groundwaters to actively interact with the calcretes. The presence of playa lakes creates conditions where groundwaters in the palaeovalleys can mix with relatively more saline waters in the playas.

2.10.3.4 Depositional processes

The ultimate pathway of brine evolution of any salt lake may be associated with a few fundamental rock types, their mode of reaction with the dilute inflow waters, and the resulting relation of major cations and anions. By the time the surface and/or groundwaters have reached the periphery of the endorheic basin, water-rock reactions are superseded by other processes. From then on evaporative concentration normally plays the dominant role leading up to mineral precipitation but other factors (e.g., wetting and drying cycles and the precipitation of efflorescent crusts) may also influence brine evolution.

Carnotite is the principal U-bearing mineral in calcrete uranium deposits. The formation of carnotite in valley calcretes is closely related to the seasonal fluctuation of the groundwater table. The fluctuation is associated with evaporation of groundwaters which can lead to an increase in the concentration of dissolved K, V and U. It can also change the concentration carbonate ions in the water affecting the solubility of uranium. Evaporation is also important in the playa deposits where it can control the salinity of lake waters. The mixing of more saline lake waters, relatively enriched in K and Ca, and the incoming groundwaters from the drainage channel can be equally important in the formation of carnotite.

2.10.3.5 Australian examples

In Australia the salt lakes occupy features of the landscape that have changed little tectonically and have not been transgressed by seawater since at least the Paleogene (De Deckker, 1983). The playa lakes in Western Australia have been the sites of periodic lacustrine deposition since the mid-Miocene (Van de Graaff et al., 1977). Potash resources have been identified at Lake Dissappointment, Lake Chandler, Lake Mackay and the Dandaragan Greensands Project in Western Australia and at the Karinga Creek Project in the Northern Territory. Lakes that may be prospective for Li include Lake Tyrrell in Victoria, Lake Frome, Lake Eyre, Lake Torrens, Pernatty Lagoon, Lake Gilles and Lake Windabout in South Australia and Lake Austin, Lake Irwin and Lake Yindarlgooda in Western Australia.

The Yeelirrie calcrete uranium deposit in Western Australia is Australia's second largest undeveloped uranium deposit with a measured and indicated mineral resources of approximately 48 kt of U_3O_8, and an average grade of approximately 0.13% U_3O_8. Other calcrete uranium resources include Lake Way, Centipede, Lake Maitland and Thatcher Soak in Western Australia and the Napperby deposit in the Northern Territory (Geoscience Australia, 2013).

2.10.3.6 Associated critical commodities

The by-products of brine evaporation processes are all natural minerals, some of which are in common use. The major by-products include halite (NaCl), sylvinite (NaCl + KCl), carnallite ($KMgCl_3.6H_2O$), Li-carnallite ($LiMgCl_3.7H_20$) and bischofite ($MgCl_2.6H_2O$). However, the large algal mats commonly found on the edges of salt lakes have the potential to scavenge particular metals from the surrounding environment. Draper and Jensen (1976) have documented the close association between Mn and the presence of algal mats at Lake Frome.

Analysis of carnotite ore from Western Australia has shown that it also contains minor amounts of Na, Si, Ca, Mg, Al and Fe (Aral, 2010). Gangue minerals include quartz, kaolin, smectite, albite, calcite, dolomite, gypsum, barite and halite. The presence of gypsum, barite and halite indicate the prevelance of an arid environment.

2.11 Potential for Australian critical commodity production

Consideration of the geological occurrences of the critical commodities described in Part 2 of this report together with the assessments of criticality of commodities documented in Part 1, leads us to conclude that almost all of the critical commodities considered in this study can be grouped into three families of mineral systems. The potential for each of these groups of critical commodities are summarised below.

Mineral system family (1): Mafic-ultramafic-related nickel, platinum-group elements, chromium and cobalt—These commodities are among the most critical commodities for the world's major economies, and are assessed in this study as high potential for Australia. Their geological occurrence is closely related to mafic-ultramafic igneous intrusions, particularly for Ni, PGE and Cr. Based on known resources in Australia, the continent appears to be under-represented in world-class intrusion-hosted Ni, PGE and Cr deposits. However, the country's geology and in particular the presence of many previously unrecognised large igneous provinces leads us to conclude that Australia is highly prospective for major deposits of Ni, PGE and Cr. Nevertheless, there are significant challenges for mineral exploration companies targeting intrusion-hosted Ni and/or PGE and/or Cr deposits, including: (a) locating the host mafic-ultramafic igneous complexes in remote areas where the prospective rocks are concealed beneath regolith and sedimentary basins, and (b) targeting the most prospective parts of these complexes.

Mineral system family (2): Felsic igneous-related rare-earth elements, tungsten, niobium, tantalum, molybdenum, beryllium, tin and bismuth—These commodities are ranked as high or medium potential in this study, and are mostly of high criticality for major economies. All of these metals occur (albeit not exclusively) in association with felsic igneous intrusions, in particular with either highly-fractionated granitic rocks and/or with alkaline igneous rocks. Potential exists in the regions where deposits of these metals are already known in Australia (brownfields), and in the under-cover extensions of these mineral provinces (brownfields to greenfields). Understanding the distribution of alkaline-igneous rocks in Australia is rudimentary at present, but information available from diamond explorers in their search for kimberlites, carbonatites and other alkaline-igneous intrusive rocks may assist in identifying new greenfields targets for commodities such as REE, Nb and Cu.

Mineral system family (3): Heavy mineral sand-hosted zirconium, titanium, rare-earth elements and thorium—These commodities rank as high to moderate potential and criticality (except for a low criticality ranking for Th). They are either major commodities (Zr, Ti) or are potential by-products (REE, Th) of heavy mineral sand mining. New discoveries of heavy mineral sand provinces recently in Australia attest to the potential of the continent for further delineation of major resources of heavy mineral sands.

In addition to these mineral system families, a group of metals and semi-metals including **antimony**, **indium**, **gallium**, **germanium**, **cadmium**, **tellurium** and **selenium** are primarily the by-products of the refining of the major commodities Zn, Cu, Pb, Au, Al and Ni. Australia's high global ranking in resources of all of these major commodities implies that there is significant potential for new or increased production of the minor-element by-products listed above. However, some of the impediments in exploiting this potential include: (a) lack of (public) knowledge of minor-element compositions of Zn, Pb, Cu, Au, Al and Ni ores and concentrates from many of Australia's major mines and refineries, (b) metallurgical issues in extracting the by-products, and (c) economic viability of extracting the by-products.

Appendix

Critical commodities summaries: Characteristics, supply, demand, and criticality

Information for metals, non-metals and minerals in the following tables was compiled by Geoscience Australia from the sources listed below.

- Geological and mineral systems information:
  - Rudnick and Gao (2003) and Section 2 of this report and references therein.
- Data on production and resources:
  - United States Geological Survey (2012) and Geoscience Australia (2013) for 2011 resources and production data.
- Demand data:
  - UNComtrade database, www.comtrade.un.org/db, for data as of December 2012.
- Information on properties, usages, recycling and substition:
  - European Commission (2010), United States Geological Survey (2012), United States Department of Energy (2010), and Willis and Chapman (2012).

Antimony (Sb)

CHARACTERISTICS	
Properties	Silvery white, shiny, very brittle metal that is a semi-conductor and resistant to acids.
Usages	Antimony is used in flame retardants, as an alloying material for Pb and Sn, and in micro capacitors.
Geological occurrence	Crustal abundance is 0.2 ppm; major Sb-bearing minerals include stibnite and tetrahedrite.
Mineral system groups	Porphyry-epithermal, subaqueous volcanic-related, orogenic and basin-hosted.
Extraction	Main product or co-product (with Au).

SUPPLY	
Global production	169 kt
Major producing countries	China (150 kt) 89% Bolivia (5 kt) 3%
Global resources	1800 kt
Major resource holders	China (950 kt) 53% Russia (350 kt) 19% Bolivia (310 kt) 17%
Australian production	1.6 kt (1%)
Australian resources (EDR)	106 kt (6%)
Australian exports	Not available
Australian potential for new resources	Developments in processing technologies allowing recovery from Zn-Pb-Ag ores, and discovery of new Sb-Au deposits in the orogenic mineral system.
Recycling	Small amounts recycled from Pb-acid batteries.

DEMAND	Country	Import value ($US)
Ores and concentrates	China	205 748 533
	India	20 038 298
	Italy	10 754 572
	Thailand	8 626 003
	Kyrgyzstan	5 210 119

SUBSTITUTION	Flame retardant substitutes are organic compounds and hydrated aluminium oxide.
CRITICALITY (SCORE)	High (14)

Arsenic (As)

CHARACTERISTICS	
Properties	Grey, brittle metal that has low hardness and is a semiconductor.
Usages	High-purity As (99.9999%) is used in gallium-arsenide semiconductors for solar cells, space research, and telecommunication. Arsenic is also used in germanium-arsenide-selenide specialty optical materials and indium-gallium-arsenide short-wave infrared technology. Arsenic trioxide is used in the production of chromated copper arsenate (CCA) wood preservatives.
Geological occurrence	Crustal abundance is 2.5 ppm; major As-bearing minerals include arsenopyite, realgar, orpiment, arsenical pyrite and tennantite.
Mineral system group	Porphyry-epithermal, granite-related, subaqueous volcanic-related, orogenic and basin-hosted
Extraction	By-product of non-ferrous metal and Au smelting.

SUPPLY	
Global production	52 kt
Major producing countries	China (25 kt) 48% Chile (11.5 kt) 22% Morocco (8 kt) 15%
Global resources	Quantitative global estimates are not available. Arsenopyrite is the primary ore mineral. Arsenic is also reclaimed as a by-product of nonferrous metal and Au smelting.
Major resource holders	Global resources are thought to be 20 times annual global production.
Australian production	Not available
Australian resources (EDR)	Not available
Australian exports	Not available
Australian potential for new resources	Recovery of As from ores, concentrates and tails from existing mining operations.
Recycling	Arsenic metal is recycled from gallium-arsenide semiconductor manufacturing, and arsenic trioxide is also recycled in wood treatment plants.

DEMAND	**Country**	**Import value ($US)**
	Japan	5 518 044
	China	2 700 348
	US	2 256 152
	France	1 342 726
	India	1 282 216

SUBSTITUTION	Arsenic substitutions for CCA wood treatments include alkaline copper quaternary, ammoniacal copper quaternary, ammoniacal copper zinc arsenate, copper azole, and copper citrate. In addition, CCA treated wood alternatives include concrete, steel, and plastic composite material.
CRITICALITY (SCORE)	Low (3)

Barium (Ba)

CHARACTERISTICS	
Properties	Soft, silvery-white metal that oxidises rapidly and has good electrical conductivity.
Usages	Barium is used in metal alloys including solders and to remove gases from vacuum tubes. Barium compounds are used in medicine, fluorescent lighting electrodes, glass, ceramics and fireworks. Barite is used in drilling muds.
Geological occurrence	Crustal abundance is 456 ppm; the most important Ba-bearing minerals is barite.
Mineral system group	Porphyry-epithermal, granite-related, subaqueous volcanic-related and basin-hosted.
Extraction	Main product

SUPPLY	
Global production	7800 kt (reported as barite [$BaSO_4$]).
Major producing countries	China (4000 kt) 51% India (1100 kt) 14% Morocco (650 kt) 8%
Global resources	240 000 kt
Major resource holders	China (100 000 kt) 42% India (32 000 kt) 13% Algeria (29 000 kt) 12%
Australian production	Not available
Australian resources (EDR)	Not available
Australian exports	Not available
Australian potential for new resources	Recovery of barite from barite lenses associated with Zn-Pb-Ag deposit from the volcanic-related and basin-hosted mineral systems.
Recycling	None

DEMAND	Country	Import value ($US)
(Reported as barite [$BaSO_4$] and witherite [$BaCO_2$])	US	147 781 979
	Germany	58 888 240
	Colombia	25 180 978
	Canada	24 064 231
	Netherlands	23 307 218

SUBSTITUTION	Few suitable substitutes exist.
CRITICALITY (SCORE)	Low (3)

Beryllium (Be)

CHARACTERISTICS		
Properties	Steel gray, low density metal that is hard and brittle at room temperature, is highly toxic, and has a high melting point (1287°C).	
Usages	Beryllium is used in telecom equipment, automotive electronics, aerospace and defence, and industrial components.	
Geological occurrence	Crustal abundance is 1.9 ppm; major Be-bearing minerals include bertrandite, beryl, chrysoberyl and phenakite.	
Mineral system group	Granite-related.	
Extraction	Main product.	
SUPPLY		
Global production	240 t	
Major producing countries	US (210 t) 88% China (22 t) 9% Mozambique (2 t) 1%	
Global resources	World Be resources are not sufficiently well delineated to report consistent figures for all countries.	
Major resource holders	Not available	
Australian production	Not available	
Australian resources (EDR)	Not available	
Australian exports	Not available	
Australian potential for new resources	Discovery of new pegmatitic resources in the igneous-related mineral system.	
Recycling	Beryllium is recycled mostly from new scrap generated during the manufacture of Be products. About 19% of Be consumption is recycled from scrap.	
DEMAND	**Country**	**Import value ($US)**
	US	4 529 343
	Singapore	3 613 880
	France	3 012 436
	Germany	1 882 597
	United Kingdom	1 678 668
SUBSTITUTION	A few substitutes can substitute for Be, but are less effective.	
CRITICALITY (SCORE)	Medium (7)	

Bismuth (Bi)

CHARACTERISTICS	
Properties	Silvery-white, brittle metal that has low thermal conductivity and is diamagnetic.
Usages	Bismuth is often used in free-machining steels, brass, pigments and solders (as a non-toxic replacement for lead), in pharmaceuticals, as an additive to enhance metallurgical quality in foundry, and as a triggering mechanism in fire sprinklers. Substitution of Pb by Bi in solders may result in increased demand.
Geological occurrence	Crustal abundance is 0.18 ppm; major Bi-bearing minerals include bismuthinite, athough Bi can be an important trace to minor constituent of galena.
Mineral system group	Porphyry-epithermal, granite-related, subaqueous volcanic-related, orogenic and basin-hosted.
Extraction	By-product of Pb smelting.

SUPPLY	
Global production	8.5 kt
Major producing countries	China (6 kt) 71% Peru (1.1 kt) 13% Mexico (1 kt) 12%
Global resources	320 kt
Major resource holders	China (240 kt) 75% Peru (11 kt) 3% Mexico (10 kt) 3%
Australian production	Not available
Australian resources (EDR)	Not available
Australian exports	Not available
Australian potential for new resources	Recovery of Bi from ores and concentrates from existing mining operations; minor potential for skarn and related deposit types in the porphryry-epithermal and granite-related mineral systems.
Recycling	Bismuth is recycled from both new and old scrap, accounting for 10% of U.S. consumption (80 tons).

DEMAND	**Country**	**Import value ($US)**
	US	41 343 577
	Germany	32 812 564
	China, Hong Kong SAR	15 237 058
	China	12 402 843
	Republic of Korea	10 836 391

SUBSTITUTION	Titanium dioxide coated mica flakes are substitutes in pigments; In can replace Bi in low-temperature solders; resins can replace Bi in machining; and glycerine-filled glass bulbs can replace Bi alloys in fire sprinkler triggering devices.
CRITICALITY (SCORE)	Medium (6)

Cadmium (Cd)

CHARACTERISTICS	
Properties	Bluish-white, soft, malleable metal that is dutile and resistant to corrosion.
Usages	The dominant use for Cd is in Ni-Cd batteries; it is also used in pigments, coatings and plating, stabilisers for PVC, nonferrous alloys and specialised uses including photovoltaic devices.
Geological occurrence	Crustal abundance is 0.08 ppm; major Cd-bearing minerals include greenockite and sphalerite (as a trace element).
Mineral system group	Porphyry-epithermal, granite-related, subaqueous volcanic-related, orogenic and basin-hosted.
Extraction	By-product of Zn smelting. Typical Zn:Cd ratios in Zn ores range from 200:1 to 400:1.

SUPPLY	
Global production	21.5 kt (refinery production)
Major producing countries	China (7.5 kt) Korea, Republic of (2.5 kt) Japan (2 kt)
Global resources	640 kt
Major resource holders	India (130 kt) China (92 kt) Australia (61 kt)
Australian production	0.38 kt
Australian resources (EDR)	61 kt
Australian exports	Not available
Australian potential for new resources	Recovery of Cd from ores and concentrates from existing mining operations.
Recycling	Most Cd is recycled from spent consumer and industrial Ni-Cd batteries. Cadmium also recovered from Cu-Cd alloy and some complex nonferrous alloy scrap.

DEMAND	Country	Import value ($US)
	China	26 842 371
	Belgium	16 874 896
	Malaysia	4 917 003
	Sweden	3 752 573
	US	2 220 400

SUBSTITUTION	Li-ion and Ni-metal hydride batteries can replace Ni-Cd batteries, however their higher cost restricts use in low-cost products. Zinc or vapour-deposited Al can substitute in plating applications where Cd is non-essential. Cerium sulphide can substitute in paints and Ba/Zn or Ca/Zn stabilisers can replace Ba/Cd stabilisers in PVC applications.
CRITICALITY (SCORE)	Low (2)

Chromium (Cr)

CHARACTERISTICS		
Properties	Hard metal with a high melting point (1907°C) that is resistant to tarnish. Chromium is antiferromagnetic at room temperature and paramagnetic above 38°C. It is passivated by oxygen making it stable to acids.	
Usages	Chromium is used in stainless and heat resistant steels, super alloys, non-ferrous alloys, and pigments.	
Geological occurrence	Crustal abundance is 135 ppm; major Cr-bearing minerals include chromite.	
Mineral system group	Mafic-ultramafic orthomagmatic and surficial.	
Extraction	Main product.	
SUPPLY		
Global production	24 000 kt	
Major producing countries	South Africa (11 000 kt) 46% Kazakhstan (3900 kt) 16% India (3800 kt) 16%	
Global resources	>480 000 kt	
Major resource holders	Kazakhstan (220 000 kt) 46% South Africa (200 000 kt) 42% India (54 000 kt) 11%	
Australian production	66.1 kt (0.3%)	
Australian resources (EDR)	Not available	
Australian exports	Not available	
Australian potential for new resources	Development of known deposits and discovery of new deposits in large igneous provinces.	
Recycling	Recycled from scrap Cr-bearing steel and alloys. Recycled Cr accounts for about 30% of consumption.	
DEMAND	**Country**	**Import value ($US)**
Ores and concentrates	China	2 663 968 517
	Germany	72 478 097
	US	68 873 106
	Russia	60 035 206
	Netherlands	54 774 762
SUBSTITUTION	Chromium has no substitute in stainless steel. Chromium-containing scrap can substitute for ferrochromium in some metallurgical uses.	
CRITICALITY (SCORE)	High (12)	

Cobalt (Co)

CHARACTERISTICS	
Properties	Ferromagnetic metal that is hard and lustrous.
Usages	Emerging technologies the could use Co include Li-ion batteries and synthetic fuels. The most important present use for Co is superalloys, steel, and magnets.
Geological occurrence	Crustal abundance is 26.6 ppm; major Co-bearing minerals include cobaltite and cobaltian pyrite.
Mineral system group	Mafic-ultramafic orthomagmatic and basin-hosted.
Extraction	By-product, co-product of Cu mining (e.g., Congo and Zambia).

SUPPLY	
Global production	98 kt
Major producing countries	Congo (52 kt) 53% Canada (7.2 kt) 7% China (6.5 kt) 7% Russia (6.3 kt) 6%
Global resources	7 334 kt
Major resource holders	Congo (3400 kt) 46% Australia (1204 kt)16%[1] Cuba (500 kt) 7%
Australian production	3.85 kt (4%)
Australian resources (EDR)	1204 kt (16%)
Australian exports	Not available
Australian potential for new resources	Development of known deposits and discovery of new deposits in large igneous provinces. Extraction of Co from basin-hosted Cu deposits.
Recycling	Cobalt can be recycled from scrap Co-bearing steel and superalloys. Recycling amounted to 25% of Co comsumption.

DEMAND	Country	Import value ($US)
Ores and concentrates	China	850 265 891
	Zambia	119 262 698
	Finland	55 161 351
	India	28 211 094
	Republic of Korea	19 217 981

SUBSTITUTION	Nickel-based superalloys can substitute Co superalloys; various metals can substitute in steel; and various substitutions are possible in batteries. In some applications, substitution results in a loss of performance.
CRITICALITY (SCORE)	High (21)

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[1] Includes pre-JORC and JORC-compliant (422 kt) resources.

Copper (Cu)

CHARACTERISTICS

Properties	Highly ductile and malleable metal that has very high thermal and electrical conductivity.
Usages	Copper is used in electronics and power cabling, household and commercial plumbing, refrigeration, cooling and radiator tubing, and telecommunications.
Geological occurrence	Crustal abundance is 27 ppm; major Cu-bearing minerals include chalcopyrite, bornite, chalcocite.
Mineral system group	Porphyry-epithermal, granite-related, mafic-ultramafic orthomagmatic, iron-oxide copper-gold, subaqueous volcanic-related, orogenic, basin-hosted, alkaline intrusion-related and surficial.
Extraction	Main product.

SUPPLY

Global production	16 100 kt
Major producing countries	Chile (5420 kt) 34% Peru (1220 kt) 8% China (1190 kt) 7% US (1120 kt) 7%
Global resources	690 000 kt
Major resource holders	Chile (190 000 kt) 28% Peru (90 000 kt) 13% Australia (86 600 kt) 13%
Australian production	960 kt (6%)
Australian resources (EDR)	86 600 kt (13%)
Australian exports	Ore and Concentrates 1818 kt (China 579 kt, India 586 kt, Japan 386 kt, Republic of Korea 191 kt.) Refined 395 kt (China 146 kt, Chinese Taipei 54 kt, Malaysia 89 kt, Thailand 44 kt.)
Australian potential for new resources	Further discoveries in most mineral provinces from many different mineral systems.
Recycling	Copper is recycled from both new and old scrap. Recycling of scrap yielded approximatly 820 000 tons of Cu. Recycling of Cu in U.S. totalled 33% of supply.

DEMAND	**Country**	**Import value ($US)**
	China	15 338 994 191
	Japan	11 513 173 899
	Republic of Korea	5 634 034 192
	India	5 283 700 367
	Spain	3 667 855 826

SUBSTITUTION	Aluminium substitutes for Cu in power cables, electrical equipment, automobile radiators, cooling and refrigeration tube; Ti and steel are used in heat exchangers; optical fibre substitutes for Cu in telecommunications; and plastics substitute for Cu in water pipe, drain pipe, and plumbing fixtures.
CRITICALITY (SCORE)	Low (2)

Fluorine (F)

CHARACTERISTICS		
Properties	Pale-yellow, highly reactive and toxic gas.	
Usages	The F used indistrially is mostly in the form of the mineral fluorite (or fluorspar). Flourite is used for the production of hydrofluoric (HF) acid for the production of virtually all F-bearing chemicals; fluorite is used in processing of U and as a flux in steel making, iron and steel casting, Al production, glass, enamels, and cement production.	
Geological occurrence	Crustal abundance is 553 ppm; major F-bearing minerals include fluorite (also known as fluorspar).	
Mineral system group	Granite-related and basin-hosted.	
Extraction		
SUPPLY		
Global production	6200 kt (reported as fluorite [CaF_2])	
Major producing countries	China (3300 kt) 53% Mexico (1080 kt) 17% Mongolia (430 kt) 7%	
Global resources	240 000 kt fluorite	
Major resource holders	South Africa (41 000 kt) 17% Mexico (32 000 kt) 13% China (24 000 kt) 10%	
Australian production	Not available	
Australian resources (EDR)	Not available	
Australian exports	Not available	
Australian potential new resources	Extraction of fluorite from known occurrences, possibly including some operating mines.	
Recycling	Some synthetic fluorite is recovered from U enrichment. HF and fluorides are routinely recycled by Al smelting operations. A few thousand tonnes are recycled in the US.	
DEMAND	**Country**	**Import value ($US)**
	China	78 226 486
	Belgium	48 533 300
	India	20 799 646
	United Kingdom	14 795 018
(Reported with bromine)	France	13 311 769
SUBSTITUTION	Borax, $CaCl_2$, Fe oxides, Mn ore, silica sand and TiO_2 have been used as substitutes for fluorite fluxes.	
CRITICALITY (SCORE)	Medium (6)	

Gallium (Ga)

CHARACTERISTICS	
Properties	Silvery white metal that has a low melting point (29.7°C), a high boiling point (2204°C), and is a semiconductor.
Usages	Gallium is used in integrated circuits (ICs), laser diodes, LEDs, photodetectors, and thin layer photovoltaics.
Geological occurrence	Crustal abundance is 16 ppm; in nature Ga occurs as a trace element in bauxite and sphalerite.
Mineral system group	Subaqueous volcanic-related, orogenic, basin-hosted and surficial.
Extraction	By-product of Zn smelting.

SUPPLY	
Global production	216 t (primary production) 270 t (refinery production) 198 t (recycling production)
Major producing countries	China, Germany, Kazakhstan, and Ukraine.
Global resources	Quantitative estimates are not available. Gallium is a by-product of treating bauxite, and from Zn-processing residues.
Major resource holders	Not available
Australian production	Not available
Australian resources (EDR)	Not available
Australian exports	Not available
Australian potential for new resources	Extraction from ores and concentrates from existing mining operations, particularly Zn and bauxite mines.
Recycling	Recycled from scrap generated in the manufacture of Ga-As-based devices.

DEMAND	Country	Import value ($US)
(Total of Ga, Hf, In, Nb and Re metal, including waste and scrap, powder and unwrought)	Japan	420 186 347
	US	311 426 717
	United Kingdom	193 412 096
	Republic of Korea	105 816 585
	Germany	98 629 086

SUBSTITUTION	Organic compounds substitution for LEDs in visual displays, indium phosphide components can substitute Ga-As-based infrared laser diodes in some cases and silicon substitutes in solar cell technology.
CRITICALITY (SCORE)	High (29)

Germanium (Ge)

CHARACTERISTICS	
Properties	Grey-white metalloid that is hard, lustrous and semiconducting.
Usages	Germanium is used in fibre and infrared optics, as polymerisation catalysts, and in electronic and solar electric applications.
Geological occurrence	Crustal abundance is 1.3 ppm; in nature Ge occurs as a trace element in sphalerite and coal.
Mineral system group	Subaqueous volcanic-related, orogenic and basin-hosted.
Extraction	By-product of Zn smelting.

SUPPLY	
Global production	118 t (refinery production)
Major producing countries	China (80 t) 68% Russia (5 t) 4% US (3 t) 3%
Global resources	Quantitative global estimates are not available. By-product of Zn, and Zn-Pb sulfides.
Major resource holders	US (450 t)
Australian production	Not available
Australian resources (EDR)	Not available
Australian exports	Not available
Australian potential for new resources	Extraction from ores and concentrates from existing mining operations, particularly Zn and possibly coal mines.
Recycling	Germanium metal used in the optics industry is routinely recycled from new scrap. Worldwide approximatly 30% consumed Ge is produced from recycled materials.

DEMAND	Country	Import value ($US)
(2010 data for articles thereof waste or scrap/ powders)	Ukraine	101 889
	Morocco	968

SUBSTITUTION	Silicon substitutes for Ge in some electronic applications. Zinc selenide can be substituted in infrared applications but at performance loss. Tantalum, Sb and Ti can be substituted as a polymerisation catalyst.
CRITICALITY (SCORE)	Medium (8)

Graphite (C)

CHARACTERISTICS	
Properties	Iron-black mineral with a metallic-earthy luster that is an electrical and thermal conductor, has high thermal resistance, is inert and can be used as a lubricant.
Usages	Uses of graphite include carbon-graphite composites, electronics, foils, friction materials and special lubricant applications. Flexible graphite products and large-scale fuel cell application developments may become high users of graphite.
Geological occurrence	Crustal abundance is 1800 ppm (total C); in nature graphite is one of a number of forms of C.
Mineral system group	(Metamorphosed) basin-hosted.
Extraction	Main product.

SUPPLY	
Global production	925 kt
Major producing countries	China (600 kt) 65% India (140 kt) 15% Brazil (76 kt) 8%
Global resources	77 000 kt
Major resource holders	China (55 000 kt) 71% India (11 000 kt) 14% Mexico (3100 kt) 4%
Australian production	Not available
Australian resources (EDR)	Not available
Australian exports	Not available
Australian potential for new resources	Development of existing resources and new discoveries in metamorphosed reduced-C-rich basins.
Recycling	Refractory graphite material is recycled into products including brake linings and thermal insulation. Recovery of high-quality flake graphite is technically feasible but not currently practiced.

DEMAND	Country	Import value ($US)
Natural mineral	Japan	133 830 815
	US	86 833 498
	Germany	65 432 230
	China	33 523 090
	Austria	31 904 446

SUBSTITUTION	Graphite has few suitable substitutes.
CRITICALITY (SCORE)	Medium (8)

Helium (He)

CHARACTERISTICS	
Properties	Colourless, odorless, tastless, non toxic and inert gas that has the lowest boiling and melting points.
Usages	Helium is used in cryogenics, cooling systems in MRI scanners, LCD and fibre optics
Geological occurrence	Helium, a product of radioactive decay, accumulates with natural gas in hydrocarbon traps.
Mineral system group	Basin-hosted.
Extraction	By-product of natural gas production

SUPPLY	
Global production	180 *hm^3
Major producing countries	US (57 hm^3) 32% US extracted from natural gas (83 hm^3) 46% Algeria (20 hm^3) 11%
Global resources	World helium resources are not sufficiently well delineated to report consistent figures for all countries.
Major resource holders	US (4000 hm^3) Algeria (1800 hm^3) Russia (1700 hm^3)
Australian production	Not available
Australian resources (EDR)	Not available
Australian exports	Not available
Australian potential for new resources	Extraction of He from existing and new natural gas developments.
Recycling	Helium is seldom recycled. Japan and Western Europe recycle when economically viable.

DEMAND	Country	Import value ($US)
(No specific trade data on helium, data are for rare gases other than argon)	Japan	86 206 708
	France	85 876 005
	Germany	80 049 816
	United Kingdom	78 146 893
	Republic of Korea	73 681 134

SUBSTITUTION	There is no substitute for He in cryogenic applications if temperatures are below –256°C. Argon can substitute in welding and H in lighter than air applications.
CRITICALITY (SCORE)	Not assessed

* hm^3 – million cubic metres

Indium (In)

CHARACTERISTICS	
Properties	Silvery white, dense metal that forms alloys with most other metals and generally increases strength, corrosion resistance and hardness.
Usages	Indium tin oxide (ITO) thin-film coatings are used for electrically conductive purposes in flat-panel, TV and smart phone devices. Other uses include electrical components and semiconductors, solders, alloys and compounds.
Geological occurrence	Crustal abundance is 0.052 ppm; In occurs mostly as a trace element in sphalerite.
Mineral system group	Subaqueous volcanic-related, orogenic and basin-hosted.
Extraction	By-product of Zn-Pb, Cu and Sn mining and smelting.
SUPPLY	
Global production	0.64 kt
Major producing countries	China (0.34 kt) 53% Korea, Republic of (0.10 kt) 16% Japan (0.07 kt) 11% Canada (0.065 kt) 10%
Global resources	Not available
Major resource holders	Not available
Australian production	Not available
Australian resources (EDR)	Not available
Australian exports	Not available
Australian potential for new resources	Extraction from ores and concentrates from existing mining operations, particularly Zn mines.
Recycling	Indium is recycled from scrap W-bearing steel and superalloys. Recycling is very inefficient, and constitutes a very small (<1%) fraction of supply.

DEMAND	**Country**	**Import value ($US)**
(Total of Ga, Hf, In, Nb and Re metal, including waste and scrap, powder and unwrought)	Japan	420 186 347
	US	311 426 717
	United Kingdom	193 412 096
	Republic of Korea	105 816 585
	Germany	98 629 086

SUBSTITUTION	Antimony can substitute for In in ITO. Carbon nanotube coatings and organic compounds substitutes for ITO in solar cells, flexible displays and touch screens; Hf can replace In in nuclear reactor control rod alloys.
CRITICALITY (SCORE)	High (26)

Lithium (Li)

CHARACTERISTICS	
Properties	Shiny, silvery, tough and soft metal that forms strong alloy, is very reactive and has the lowest denisty of all know solids at room temperature.
Usages	Lithium is used in batteries, ceramics and glass.
Geological occurrence	Crustal abundance is 16 ppm; Li occurs mostly in spodumene and lepidolite, but also in salt lake and oil field brines.
Mineral system group	Intrusion-related and surficial.
Extraction	Main product.

SUPPLY	
Global production	34 kt (excludes US production figures).
Major producing countries	Chile (12.6 kt) 37% Australia (11.7 kt) 34% China (5.2 kt) 15%
Global resources	13 000 kt
Major resource holders	Chile (7500 kt) 58% China (3500 kt) 27% Australia (1006 kt) 8%
Australian production	11.7 kt (34%)
Australian resources (EDR)	1006 kt (8%)
Australian exports	Not available
Australian potential for new resources	Identification of Li resources associated with known and new pegmatite fields, and discovery of Li-enriched salt lakes.
Recycling	Small amounts of Li were recycled from batteries, recycling is increasing. EU has set a target of 45% of batteries recycled by 2016.

DEMAND	**Country**	**Import value ($US)**
Lithium oxide and hydroxides	Japan	26 659 300
	Belgium	15 760 658
	India	11 056 408
	US	9 092 107
	Republic of Korea	8 451 205
Lithium carbonates	Japan	80 810 031
	US	58 435 216
	Republic of Korea	52 903 670
	Germany	41 792 911
	China	33 569 842

SUBSTITUTION	Battery substitution includes Ca, Mg, Hg, and Zn. Various substitutions available for ceramics and glass.
CRITICALITY (SCORE)	High (14)

Manganese (Mn)

CHARACTERISTICS	
Properties	Silvery-grey metal, that is hard, very brittle and paramagnetic.
Usages	Manganese is alloyed in steel and Al, and is used in batteries and fertiliser.
Geological occurrence	Crustal abundance is 770 ppm; the main Mn mineral is pyrolusite.
Mineral system group	Basin-hosted and surficial.
Extraction	Main product.

SUPPLY	
Global production	14 000 kt Mn metal
Major producing countries	South Africa (3400 kt) 24% China (2800 kt) 20% Australia (2400 kt) 17%
Global resources	630 000 kt Mn metal
Major resource holders	South Africa (150 000 kt) 24% Ukraine (140 000 kt) 22% Brazil (110 000 kt) 17%
Australian production	6960 kt (manganese ore)
Australian resources (EDR)	197 000 kt (manganese ore)
Australian exports	6876 kt (2011–12)
Australian potential for new resources	Further discoveries possible in shallow environments of marine basins.
Recycling	Minor amounts of Mn are recovered along with Fe from steel slag.

DEMAND	Country	Import value ($US)
(including waste and scrap)	Germany	199 380 657
	US	192 053 084
	Canada	166 801 825
	Japan	139 696 543
	United Kingdom	67 874 738

SUBSTITUTION	Manganese has no satisfactory substitute in major applications.
CRITICALITY (SCORE)	High (12)

Mercury (Hg)

CHARACTERISTICS

Properties	Heavy, silvery-white liquid at room temperature that is a poor conductor of heat but can conduct electricity, and has low melting (−38.8290°C) and boiling (356.73°C) points.
Usages	Mercury is used in fluorescent and neon lamps, Hg-Zn batteries and during the production of Cl and caustic soda.
Geological occurrence	Crustal abundance is 0.03 ppm; major Hg-bearing minerals include realgar and sphalerite (as a trace element).
Mineral system group	Porphyry-epithermal, granite-related, subaqueous volcanic-related, orogenic and basin-hosted.
Extraction	Main product.

SUPPLY

Global production	1.93 kt
Major producing countries	China (1.4 kt) 73% Kyrgyzstan (0.25 kt) 13% Chile (by product) (0.10 kt) 5%
Global resources	93 kt
Major resource holders	Mexico (27 kt) 29% China (21 kt) 23% Kyrgyzstan (7.5 kt) 8%
Australian production	Not available
Australian resources (EDR)	Not available
Australian exports	Not available
Australian potential for new resources	Further discoveries of epithermal deposits in the porphyry-epithermal system and recovery from Zn concentrates from subaqueous volcanic-related and basin-hosted systems.
Recycling	Mercury can be recycled from all Hg-containing products. However, the use of non-Hg substitutes has resulted in a reduction in Hg-containing products for recycling.

DEMAND	**Country**	**Import value ($US)**
Metal	Singapore	28 279 980
	India	12 552 446
	China, Hong Kong SAR	11 656 390
	Peru	9 858 781
	Netherlands	7 867 004

SUBSTITUTION	An alloy of Ga, In, and Sn now replaces the Hg used in traditional Hg thermometers; LED lighting can substitute fluorescent lamps; Li, Ni-Cd, and Zn-air batteries replace Hg-Zn batteries.
CRITICALITY (SCORE)	Low (3)

Molybdenum (Mo)

CHARACTERISTICS	
Properties	Lustrous silver-white, hard and brittle metal that has high mechanical strength, a low coefficient of thermal expansion and good heat conductivity.
Usages	Molybdenum is used in steel and superalloys and as a lubricant.
Geological occurrence	Crustal abundance is 0.8 ppm; the major Mo-bearing mineral is molybdenite.
Mineral system group	Porphyry-epithermal, granite-related and iron-oxide copper-gold.
Extraction	Main product, co-product, by-product.

SUPPLY	
Global production	250 kt
Major producing countries	China (94 kt) 38% US (64 kt) 26% Chile (38 kt) 15%
Global resources	10 100 kt
Major resource holders	China (4300 kt) 43% US (2700 kt) 27% Chile (1200 kt) 12%
Australian production	0%
Australian resources (EDR)	167 kt (1.6%)
Australian exports	Not available
Australian potential for new resources	Further discoveries of Mo-dominated deposits from granite-related and iron-oxide copper-gold systems, and recovery as by-product from porphyry-epithermal systems (porphyry copper deposits).
Recycling	Small amounts of Mo metal and superalloys are recovered. Molybdenum is reutilised through recycling of Mo bearing steel. Up to 30% of the supply of Mo is recycled.

DEMAND	**Country**	**Import value ($US)**
Ores and concentrates	Japan	814 862 216
	Netherlands	781 967 149
	Chile	681 702 979
	Belgium	675 128 036
	US	462 792 400

SUBSTITUTION	Few substitutes exist for the major applications of Mo.
CRITICALITY (SCORE)	High (15)

Nickel (Ni)

CHARACTERISTICS	
Properties	Hard, ductile and malleable metal.
Usages	Nickel is used in stainless steel and super alloys, and in non-ferrous alloys
Geological occurrence	Crustal abundance is 59 ppm; the major Ni-bearing minerals include pentlandite, millerite and violarite.
Mineral system group	Mafic-ultramafic orthomagmatic and surficial.
Extraction	Main product.

SUPPLY	
Global production	1810 kt
Major producing countries	Russia (280 kt) 16% Philippines (230 kt) 13% Indonesia (230 kt) 13% Australia (215 kt) 12% Canada (200 kt) 11%
Global resources	76 000 kt
Major resource holders	Australia (20 400 kt) 27%[1] New Caledonia (12 000 kt) 16% Russia (6000 kt) 8%
Australian production	215 kt (12%)
Australian resources (EDR)	20 400 kt (27%)
Australian exports	240 kt (2011–2012)
Australian potential for new resources	Further discoveries in known districts and greenfields areas associated with major large igneous provinces. Production from Ni laterites dependent on advances in extraction technology.
Recycling	Nickel is recycled from scrap Ni bearing steel and alloys. 95 000 tonnes were recycled from scrap in 2012.

DEMAND	Country	Import value ($US)
Ores and concentrates	China	4 905 363 978
	Finland	535 272 036
	Canada	423 498 212
	Japan	355 426 043
	Netherlands	209 679 103

SUBSTITUTION	Nickel-free specialty steels are sometimes used in place of stainless steel, ultra-high-Cr can replace Ni in stainless steels and other alloys can substitute for Ni metal or Ni-based alloys.
CRITICALITY (SCORE)	High (13)

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[1] Includes pre-JORC and JORC-compliant (5500 kt) data.

Niobium (Nb)

CHARACTERISTICS

Properties	Soft and ductile metal with good resistance to organic and inorganic acids.
Usages	Niobium is used in micro capacitors, steel and ferroalloys.
Geological occurrence	Crustal abundance is 8 ppm; Nb occurs as a minor element in minerals such as columbite, pyrochlore and euxinite.
Mineral system group	Granite-related and alkaline intrusion-related.
Extraction	Co-product, by-product.

SUPPLY

Global production	63 kt
Major producing countries	Brazil (58 kt) 92% Canada (4.4 kt) 7%
Global resources	3000 kt
Major resource holders	Brazil (2900 kt) 97% Canada (200 kt) 3%
Australian production	Not available
Australian resources (EDR)	205 kt (7%)
Australian exports	Not available
Australian potential for new resources	Production as a by-product of rare-earth element mining operations in alkaline intrusion-related systems, and also from pegmatites from granite-related mineral systems.
Recycling	Recycled from scrap Nb-bearing steel and superalloys, possibly up to 20%.

DEMAND	**Country**	**Import value ($US)**
(Total of Ga, Hf, In, Nb and Re metal, including waste and scrap, powder and unwrought)	Japan	420 186 347
	US	311 426 717
	United Kingdom	193 412 096
	Republic of Korea	105 816 585
	Germany	98 629 086

SUBSTITUTION	Substitution by Mo and V in high-strength, low alloy steel and by Ta and Ti in stainless and high-strength steels is possible but it may involve higher costs and/or a loss in performance.
CRITICALITY (SCORE)	High (20)

Platinum Group Elements (PGE) - Platinum (Pt) and Palladium (Pd)

CHARACTERISTICS	
Properties	Metals characterised by catalytic properties, resistance to wear, tarnish, and chemical attack, and by stable electrical properties.
Usages	Platinum and Pd are both used in catalytic converters. Platinum is used in electronic applications and fuel cells, and Pd is used in seawater desalination.
Geological occurrence	Crustal abundances of platinum-group elements (PGE) are 0.57 ppb, 0.2 ppb, 1.5 ppb, 0.041 ppb, 0.037 ppb, and 1.5 ppb for Ru, Rh, Pd, Os, Ir and Pt, respectively. Platinum-group elements occur as metallic alloys, sulfide and arsenide minerals.
Mineral system group	Mafic-ultramafic orthomagmatic, alkaline intrusion-related, and surficial.
Extraction	Main product, by-product.

SUPPLY	
Global production	Platinum: 195 t Palladium: 215 t
Major producing countries	South Africa 227 t (Pt and Pd) Russia 111 t (Pt and Pd)
Global resources	6 600 t PGEs
Major resource holders	South Africa (6 300 t PGE) 95% Russia (1 100 t PGE) 17% US (900 t PGE) 14%
Australian production	0.441 t
Australian resources (EDR)	4.7 t
Australian exports	Not available
Australian potential for new resources	Greatest potential for PGE production is from mafic-ultramafic bodies associated with major large igneous provinces. Platinum group elements can be produced as by-product from existing Ni mines.
Recycling	Recycling from industrial process catalysts and of PGE equipment. 150 000 kg were recovered from scrap in 2012.

DEMAND	Country	Import value ($US)
(Total including Pt, Pd, Rh, Ir and Ru—unwrought, semi-manufactured or powder form)	Japan	5 960 513 378
	US	5 564 267 162
	China	5 438 225 080
	Switzerland	4 084 208 327
	United Kingdom	3 812 285 084

SUBSTITUTION	Motor vehicles substitute Pd for Pt in catalytic converters. Some PGEs can be substituted for the other PGEs.
CRITICALITY (SCORE)	High (22)

Rare-earth elements (REE), including scandium (Sc) and yttrium (Y)

CHARACTERISTICS	
Properties	There are 17 rare-earth elements (REE) each with different properties.
Usages	Rare-earth elements are used in magnets, catalysts, metal alloys, polishing powders, phosphors, energy storage and superconductors.
Geological occurrence	Crustal abundances are 20 ppm, 43 ppm, 4.9 ppm, 20 ppm, 3.9 ppm, 1.1 ppm, 3.7 ppm, 0.6 ppm, 3.6 ppm, 0.77 ppm, 2.1 ppm, 0.28 ppm, 1.9 ppm, 0.30 ppm, 21.9 ppm and 19 ppm for La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tr, Yb, Lu, Sc and Y, respectively. Rare-earth elements occur as minor to trace elements in many minerals, but major REE-bearing minerals include carbonates (e.g. bastnäsite), phosphates (e.g. monazite, xenotime) and silicates (e.g. allanite).
Mineral system group	Granite-related, iron-oxide copper-gold, alkaline intrusion-related, surficial (lanthanides and Y) and mafic-ultramafic orthomagmatic (Sc only).
Extraction	Main product, co-product.

SUPPLY	
Global production	REO (rare-earth oxides): 133 kt, Y_2O_3 8.9 kt
Major producing countries	REO: China (130 kt) 97.7%, India (3 kt) 2.25%. Y_2O_3: China (8.8 kt) 98.88%
Global resources	REO: 114 000 kt Y_2O_3: 540 kt
Major resource holders	**REO:** China (55 000 kt) 48% CIS (19 000 kt) 17% US (13 000 kt) 11% **Y_2O_3:** China (220 kt): 40.7% US (120 kt): 22.2% Australia (100 kt): 18.5%
Australian production	None as of December 2011
Australian resources (EDR)	REO and Y_2O_3: 2070 kt
Australian exports	Not available
Australian potential for new resources	Alkaline intrusion-related and iron-oxide copper-gold systems have high potential for rare-earth and associated elements. The Olympic Dam mine one of the two largest REE deposits globally but currently these elements are not recovered.
Recycling	Small amounts mostly magnet scrap.

DEMAND	**Country**	**Import value ($US)**
(Rare-earth metals, scandium and yttrium only)	Japan	714 949 741
	US	70 814 886
	China, Hong Kong SAR	38 338 569
	Germany	24 408 750
	Austria	17 100 656

SUBSTITUTION	Substitutes are available, but less effective.
CRITICALITY (SCORE)	High (29)

Rhenium (Re)

CHARACTERISTICS	
Properties	Very dense metal with a very high melting point (3186°C).
Usages	Rhenium is used in superalloys for high-temperature turbine engine components and in catalytic converters.
Geological occurrence	Crustal abundance is 0.188 ppb; the major source of Re is as a minor element in molybdenite.
Mineral system group	Porphyry-epithermal and iron-oxide copper-gold.
Extraction	By-product.

SUPPLY	
Global production	49 t
Major producing countries	Chile (26 t) 53% US (6.3 t) 12% Peru (5 t) 10%
Global resources	2.5 kt
Major resource holders	Chile (1.3) 52% US (0.39) 16% Russia (0.31) 12.4%
Australian production	Not available
Australian resources (EDR)	Not available
Australian exports	Not available
Australian potential for new resources	Further discovery of Mo-rich deposits in the iron-oxide copper-gold mineral system, and possible recovery as a by-product from existing porphyry Cu mines.
Recycling	Rhenium in spent Pt-Re catalysts are routinely recycled. Some Re is recycled from other alloys.

DEMAND	Country	Import value ($US)
(Total of Ga, Hf, In, Nb and Re metal, including waste and scrap, powder and unwrought)	Japan	420 186 347
	US	311 426 717
	United Kingdom	193 412 096
	Republic of Korea	105 816 585
	Germany	98 629 086

SUBSTITUTION	Rhodium and Rh-Ir can substitute in high-temperature thermocouples; numerous metals may substitute for Re in catalyst applications.
CRITICALITY (SCORE)	Low (1)

Selenium (Se)

CHARACTERISTICS

Properties	Non-metal semiconductor.
Usages	An emerging use for Se is thin film photovoltaic copper-indium-gallium-diselenide (CIGS) solar cells. Other uses include alloys for free-machining metals, as an additive, with Ca, in plastics, ceramics and glass to produce a ruby red colour, as an oxidation catalyst, and as a dietary supplement in humans and livestock.
Geological occurrence	Crustal abundance is 0.13 ppm; the major source of Se is as a minor element in chalcopyrite, but there are a large range of selenide, selenate and selenite minerals.
Mineral system group	Porphyry-epithermal, granite-related, mafic-ultramafic orthomagmatic, iron-oxide copper-gold and subaqueous volcanic-related.
Extraction	Selenium is a by-product of Cu and to a lesser extent Ni.

SUPPLY

Global production	2 kt
Major producing countries	Germany (0.65 kt) 33% Japan (0.63 kt) 32% Belgium (0.20 kt) 10%
Global resources	93 kt
Major resource holders	Chile (20 kt) 22% Russia (20 kt) 22% Peru (13 kt) 14%
Australian production	Not available
Australian resources (EDR)	Not available
Australian exports	Not available
Australian potential for new resources	Recovery from Cu concentrates produced from existing Cu mines.
Recycling	Very small amounts of selnium are recovered from obsolete xerographic machines and electronic materials.

DEMAND	Country	Import value ($US)
	China	185 867 890
	US	71 072 261
	China, Hong Kong SAR	51 737 739
	United Kingdom	44 938 044
	Germany	28 570 942

SUBSTITUTION	High-purity silicon is a major substitute for low- and medium-voltage rectifiers and solar photovoltaic cells. Organic pigments can substitute for cadmium sulfo-selenide pigments.
CRITICALITY (SCORE)	Medium (11)

Strontium (Sr)

CHARACTERISTICS	
Properties	Soft silver-white or yellow metal that is chemically highly reactive and pyrophoric in powdered form.
Usages	Strontium is used in fireworks, ferrite ceramic magnets, glass and ceramics, metal alloys, and pigments
Geological occurrence	Crustal abundance is 320 ppm; the major Sr minerals include strontianite and celestite, although Sr is a trace element in many other minerals.
Mineral system group	Basin-hosted.
Extraction	

SUPPLY	
Global production	380 kt
Major producing countries	China (210 kt) 55% Spain (120 kt) 32% Mexico (35 kt) 9%
Global resources	6 800 kt
Major resource holders	Not available
Australian production	Not available
Australian resources (EDR)	Not available
Australian exports	Not available
Australian potential for new resources	Uncertain but most likely in the basin-hosted mineral system.
Recycling	None

DEMAND	Country	Import value ($US)
Strontium carbonate	Japan	23 994 166
	US	15 376 670
	Republic of Korea	14 249 084
	France	3 324 116
	India	2 823 942

SUBSTITUTION	Barium can replace Sr in ferrite ceramic magnets but reduces operating temperatures.
CRITICALITY (SCORE)	Medium (9)

Tantalum (Ta)

CHARACTERISTICS	
Properties	Blue grey, lustrous, hard, tough and dutile metal that is very resistant to corrosion from acids, has high thermal and electrical conductivity, and a high melting point (3107°C).
Usages	Tantalum is used in electronic micro-capacitors and medical technology.
Geological occurrence	Crustal abundance is 0.7 ppm; the major source of Ta is tantalite and columbite, although there are a number of other rare Ta minerals.
Mineral system group	Granite-related.
Extraction	Main product, co-product, by-product.

SUPPLY	
Global production	0.79 kt
Major producing countries	Brazil (0.18 kt) 23% Mozambique (0.12 kt) 15% Rwanda (0.11 kt) 14% Australia (0.08 kt) 10%
Global resources	131 kt
Major resource holders	Brazil (65 kt) 50% Australia (62 kt) 47% Mozambique (3.2 kt) 2%
Australian production	Not available
Australian resources (EDR)	62 kt
Australian exports	Not available
Australian potential for new resources	Reopening of historic mines, (e.g. Wodgina) and discovery of Ta-bearing permatites in known and greenfields pegmatite fields.
Recycling	Recycling is limited, mostly from new scrap, Ta bearing steel and superalloys.

DEMAND	Not available
SUBSTITUTION	Tantalum is difficult to substitute, with the possibility of performance loss.
CRITICALITY (SCORE)	High (13)

Tellurium (Te)

CHARACTERISTICS	
Properties	Metallic, silvery-white metalloid that is brittle and easily pulverised, is a semiconductor, and resists oxidation by air.
Usages	Uses of Te include high performance photovoltaics and steel alloys.
Geological occurrence	Crustal abundance is approximately 1 ppb; the major source of Te is a trace element in chalcopyrite, but it occurs in a large range of telluride minerals.
Mineral system group	Porphyry-epithermal, granite-related, mafic-ultramafic orthomagmatic, iron-oxide copper-gold, subaqueous volcanic-related, and orogenic.
Extraction	By-product.

SUPPLY	
Global production	Not available
Major producing countries	Not available
Global resources	Quantitative estimates are not available, by-product of Cu mining
Major resource holders	Not available
Australian production	Not available
Australian resources (EDR)	Not available
Australian exports	Not available
Australian potential for new resources	Recovery as a by-product from the processing of copper concentrates.
Recycling	Small amounts of Te are recovered from scrapped Se-Te photoreceptors employed in older photocopiers. Recycling amounts to < 10% of supply but is growing.

DEMAND	**Country**	**Import value ($US)**
	China, Hong Kong SAR	108 811 101
	Canada	31 699 268
	Germany	26 597 710
	Malaysia	23 754 768
(Reported in combination with boron)	Belgium	19 920 944

SUBSTITUTION	Substitutes, including Se, are available, but are less effective.
CRITICALITY (SCORE)	High (13)

Thorium (Th)

CHARACTERISTICS	
Properties	Soft, very ductile metal that is dimorphic.
Usages	Thorium's most important emerging technology is in nuclear reactor cores where some properties are seen as being more favourable than U. Thorium is also used in a Mg alloy for application in aircraft engines and rockets, in lamp mantles and in gas tungsten arc welding.
Geological occurrence	Crustal abundance is approximately 5.6 ppm; the major source of Th is monazite and related minerals, although it occurs in a large range of rare oxide and silicate minerals.
Mineral system group	Iron-oxide copper-gold, alkaline intrusion-related and surficial (heavy mineral sand deposits).
Extraction	Co-product.

SUPPLY	
Global production	Not available
Major producing countries	Not available
Global resources	1 400 kt (ThO_2)
Major resource holders	US (440 kt ThO_2) 31% Australia (410 kt ThO_2) 29% India (290 kt ThO_2) 21%
Australian production	Not available
Australian resources (EDR)	Not available
Australian exports	Not available
Australian potential for new resources	Recovery of monazite from heavy mineral sand deposits and certain alkaline intrusion-related deposits.
Recycling	None

DEMAND	**Country**	**Import value ($US)**
	China	20 516 699
	Thailand	3 770 935
	China, Hong Kong SAR	1 048 114
	France	79 311
	Spain	59 865

SUBSTITUTION	Nonradioactive substitutes for Th include Y compounds in incandescent lamp mantles; a Mg alloy containing lanthanides; Y, and Zn can substitute for Mg-Th alloys in aerospace applications.
CRITICALITY (SCORE)	Low (3)

Tin (Sn)

CHARACTERISTICS	
Properties	Silvery, malleable and ductile metal that is not easily oxidised in air and has a low melting point (232°C).
Usages	Tin is used in industrial and electronic solders, flat and touch screen technologies (as indium tin oxide (ITO)), alloys and compounds.
Geological occurrence	Crustal abundance is approximately 1.7 ppm; the major source of Sn is cassiterite, although it occurs in a large range of sulfide and silicate minerals.
Mineral system group	Granite-related, subaqueous volcanic-related and surficial.
Extraction	Main product, co-product.

SUPPLY	
Global production	253 kt
Major producing countries	China (110 kt) 43% Indonesia (51 kt) 20% Peru (34.6 kt) 14%
Global resources	4 863 kt
Major resource holders	China (1500 kt) 31% Indonesia (800 kt) 17% Brazil (590 kt) 12%
Australian production	5 kt (2%)
Australian resources (EDR)	243 kt (5%)
Australian exports	4909 t (2011–2012)
Australian potential for new resources	New discoveries and redevelopment of historic mines/districts, particularly in the Tasmanides Belt.
Recycling	Recycled from scrap tin bearing steel and alloys. 13 000 tons recovered from recycling in 2012 in the US.

DEMAND	Country	Import value ($US)
Ores and concentrates	Malaysia	433 854 861
	China	113 037 598
	Thailand	8 362 160
	Rwanda	5 741 020
	Russia	5 300 055

SUBSTITUTION	Metal substitutes include aluminium alloys, Cu-based alloys. Plastics also substitutes for Sn in some applications.
CRITICALITY (SCORE)	Medium (8)

Titanium (Ti)

CHARACTERISTICS

Properties	Low density metal with high mechanical strength, high melting point, low thermal expansion coefficient and a high resistance to saltwater and acids.
Usages	Titanium is used in TiO_2 pigments, carbides, chemicals and as an alloy in steel and superalloys.
Geological occurrence	Crustal abundance is approximately 0.43%; the major source of Ti is ilmenite but other significant Ti-minerals include titanite and rutile (and other TiO_2 polymorphs).
Mineral system group	Mafic-ultramafic orthomagmatic and surficial.
Extraction	Main product, co-product.

SUPPLY

Global production	Metal sponge: 186 000 kt (Ti) (excludes US production) Ilmenite: 6000 kt (TiO_2) Rutile: 700 kt (TiO_2) (excludes US production)
Major producing countries	Metal sponge (Ti): China (60 000 kt) 32%, Japan (56 000 kt) 30% Ilmenite: South Africa (1030 kt (TiO_2) 17%, Australia (900 kt TiO_2) 15% Rutile: Australia (400 kt TiO_2) 57%, South Africa (131 kt TiO_2) 19%
Global resources	Metal sponge: 283 000 kt (Ti) Ilmenite: 650 000 kt (TiO_2) Rutile: 42 000 kt (TiO_2)
Major resource holders	Metal sponge (Ti): China (114 000 kt) 40%, Japan (62 200 kt) 22% Ilmenite: China (200 000 kt TiO_2) 31%, Australia (100 000 kt TiO_2) 15% Rutile: Australia (18 000 kt TiO_2) 43%, South Africa (8 300 kt TiO_2) 20%
Australian production	Metal sponge: Not available Ilmenite: 1277 kt concentrate Rutile: 474 kt concentrate
Australian resources (EDR)	Metal sponge: Not available Ilmenite: 188 900 kt concentrate Rutile: 27 200 kt concentrate
Australian exports	Ilmenite concentrate: 2045 kt Leucoxene concentrate: 31 kt Rutile concentrate: 334 kt Titanium dioxide pigment: 179 kt
Australian potential for new resources	Discovery of new heavy mineral sand deposits and lesser potential from mafic-ultramafic orthomagmatic systems.
Recycling	Titanium is recycled from scrap Ti-bearing steel and alloys (approximatly 35 000 tons in 2012).

DEMAND	**Country**	**Import value ($US)**
Ores and concentrates	China	549 455 455
	US	296 219 208
	Germany	251 624 351
	Japan	191 942 639
	Belgium	145 458 552

SUBSTITUTION	Substitution for high-strength applications includes Al, composites, intermetallics, steel, and superalloys. Corrosion resistance substitutions include Al, Ni, and Zr alloys. Pigment substitutions are $CaCO_3$, talc and kaolin.
CRITICALITY (SCORE)	Medium (10)

Tungsten (W)

CHARACTERISTICS	
Properties	Steel-grey metal that is brittle, has a very high melting point (3422°C), the lowest vapor pressure (at temperatures above 1 650°C) and the highest tensile strength. Tungsten has the lowest coefficient of thermal expansion of any pure metal.
Usages	Major uses of W include electronic applications, lighting, construction, steel and alloys, and mining,
Geological occurrence	Crustal abundance is approximately 1 ppm; the major source of W is wolframite and scheelite.
Mineral system group	Granite-related and surficial.
Extraction	Main product.

SUPPLY	
Global production	72 kt (excludes US production figures)
Major producing countries	China (60 kt) 83% Russia (3.1 kt) 4% Canada (2 kt) 3%
Global resources	3300 kt
Major resource holders	China (1900 kt) 58% Australia (376 kt) 11% Russia (250 kt) 8% US (140 kt) 4% Canada (120 kt) 4%
Australian production	0.015 kt (0.02%)
Australian resources (EDR)	376 kt (12%)
Australian exports	Not available
Australian potential for new resources	New discoveries and redevelopment of historic mines/districts, particularly in the Tasmanides Belt.
Recycling	Recycled from scrap W bearing steel and superalloys. 35% to 40% of W is recycled Globally.

DEMAND	**Country**	**Import value ($US)**
	China	159 073 668
	US	121 547 126
	Austria	73 851 567
	Germany	15 136 212
	Japan	7 802 238

SUBSTITUTION	Substitutes for tungsten carbide include molybdenum carbide, titanium carbide, ceramics, ceramic-metal composites and tool steel. Molybdenum steel can substitute for tungsten steel, and there are several substitutes for W in lighting. Depleted U can be substituted in armaments, and Pb can be used for radiation shielding.
CRITICALITY (SCORE)	High (23)

Vanadium (V)

CHARACTERISTICS

Properties	Silver-grey ductile and malleable metal that is hard, not brittle, and has good resistance to corrosion and acids.
Usages	Vanadium is used as alloy in Fe and steel, superalloys, chemical catalysts and batteries.
Geological occurrence	Crustal abundance is approximately 138 ppm; the major source of V is from V-bearing magnetite, although it also occurs as vanadinite, carnotite and other uncommon minerals.
Mineral system group	Mafic-ultramafic orthomagmatic, basin-hosted and surficial.
Extraction	Co-product.

SUPPLY

Global production	60 kt
Major producing countries	China (23 kt) 38% South Africa (20 kt) 33% Russia (15 kt) 25%
Global resources	15 000 kt
Major resource holders	China (5100 kt) 34% Russia (5000 kt) 33%
Australian production	Not available
Australian resources (EDR)	1519 kt (10%)
Australian exports	Not available
Australian potential for new resources	Development of known V-rich magnetite deposits, e.g. Windimurra and Balla Balla, and sediment-hosted deposits, e.g. Julia Creek, and discovery of new deposits associated with large igneous provinces.
Recycling	The majority of recycled V comes from spent chemical process catalysts, a small amount are recycled from V bearing tool scrap metal.

DEMAND	**Country**	**Import value ($US)**
(2006 data: articles thereof, waste or scrap/powders)	United Kingdom	16 031 908
	Japan	14 725 206
	Russia	9 789 370
	China	7 527 518
	Germany	7 217 000

SUBSTITUTION	Manganese, Mo, Nb, Ti, and W are interchangeable with V as alloying elements in steel to some degree. Platinum and Ni can replace V compounds as catalysts.
CRITICALITY (SCORE)	High (13)

Zirconium (Zr)

CHARACTERISTICS	
Properties	Soft metal that is resistant to corrosion, with a melting point of 1855°C, and a boiling point of 4371°C.
Usages	Zirconium metal is used for cladding nuclear reactor fuels and Zr compounds are used in a variety high temperature applications such as moulds for molten metals.
Geological occurrence	Crustal abundance is approximately 132 ppm; the major source of Zr is zircon ($ZrSiO_4$), although there are a number of other minor to trace Zr-bearing minerals.
Mineral system group	Alkaline intrusion-related and surficial (heavy mineral sand deposits).
Extraction	Main product, co-product.

SUPPLY	
Global production	975 kt (ZrO_2)
Major producing countries	Australia (512 kt ZrO_2) 53% South Africa (255 kt ZrO_2) 26% China (67 kt ZrO_2) 7%
Global resources	62 320 kt (ZrO_2)
Major resource holders	Australia (31 320 kt ZrO_2) 50% South Africa (14 000 kt ZrO_2) 22% Ukraine (4000 kt ZrO_2) 6%
Australian production	512 kt (ZrO_2)
Australian resources (EDR)	31 320 kt (ZrO_2)
Australian exports	Zircon ($ZrSiO_4$) concentrate: 846 kt (2011–2012)
Australian potential for new resources	Discovery of new heavy mineral sand deposits; possible by-product of certain REE deposits (e.g. Hastings).
Recycling	Most recycled from new scrap, during metal production and fabrication. Some old scrap is also recycled.

DEMAND	**Country**	**import value ($US)**
Ores and concentrates	China	1 174 489 142
	Spain	252 948 694
	Italy	144 044 422
	Japan	131 175 779
	India	101 572 807

SUBSTITUTION	Chromite and olivine can be substituted for some foundry applications. Dolomite and spinel can also substitute in high temperature applications. Niobium, stainless steel and Ta provide limited substitution in nuclear applications.
CRITICALITY (SCORE)	Medium (6)

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