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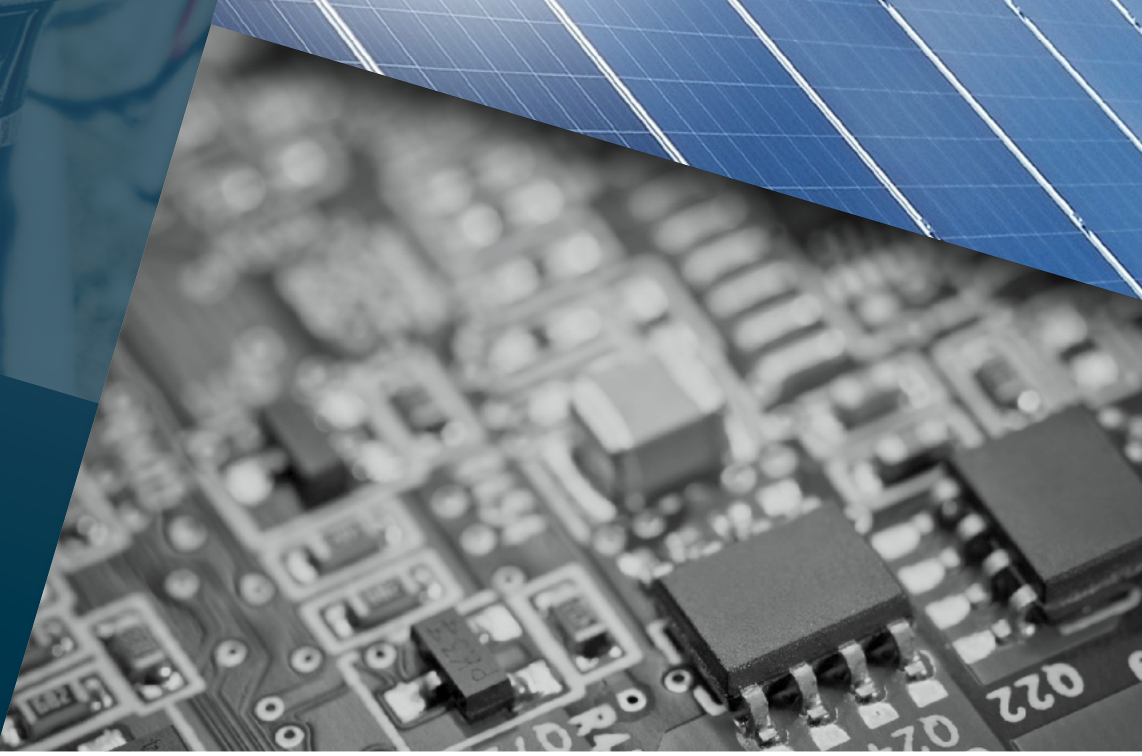
Critical Minerals in Australia: A Review of Opportunities and Research Needs



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Critical Minerals in Australia:
A Review of Opportunities and Research Needs

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MINISTER'S FOREWORD

Senator the Hon Matt Canavan
Minister for Resources and Northern Australia

The new and emerging technologies rapidly changing our day-to-day lives are driving a global demand for critical minerals.

A world of smart phones and laptop computers, solar panels and wind turbines, advanced manufacturing, and health applications have ranked minerals such as antimony, cobalt, lithium and rare earth elements as "critical". To be classified as critical the mineral must be both economically important to society and vulnerable to supply disruption.

Commissioned by Geoscience Australia in collaboration with RMIT University and Monash University, the *Critical Minerals in Australia: A Review of Opportunities and Research Needs* report shows Australia has the potential to become a major global supplier of critical minerals.

The report indicates that we can leverage our leadership in the global mineral resource industry to grow our critical minerals sector.

We have the potential to meet the future needs of our key trading partners. Australia is already one of the world's top five producers of antimony, cobalt, lithium and rare earths—all rated as critical by the United States, United Kingdom or European Union.

However, to reach our full potential, more work is needed.

The report outlines a number of short-, medium- and long-term activities to best position Australia in this sector. One of the report's key findings is that we have only just begun to assess Australia's critical mineral endowment.

For example, the report suggests there may be further resource and production potential for mines and smelters currently in operation. Improving our knowledge base of the critical mineral content in these ores and improving extraction technologies may increase earnings.

The Australian Government is committed to ensuring Australia reaches its potential as a global supplier of critical minerals. Australia's National Resources Statement, released in February 2019, outlined the development of a national strategy through the Council of Australian Governments Energy Council to harness the emerging opportunities offered by the critical minerals sector.

Critical minerals projects are being prioritised in the seventh round of Cooperative Research Centres Projects, being held in the first half of 2019. This funding will help Australian companies take advantage of the sector's potential, which is a focus of the Australian Government's national critical minerals strategy.

We are also engaging with our key trading partners on critical minerals. In December 2018, I signed a Letter of Intent with my counterpart from the United States, agreeing for Geoscience Australia and the United States Geological Survey to collaborate on joint activities in the area of critical minerals.

I look forward to seeing the dividends of our investment in the critical minerals sector: the creation of more jobs and the sustained prosperity of the Australian economy.

EXECUTIVE SUMMARY

Critical Minerals in Australia: A Review of Opportunities and Research Needs was commissioned by Geoscience Australia in collaboration with RMIT University and Monash University to analyse the current state of critical minerals in Australia and highlight key areas that warrant further investigation. The report covers: global demand and supply; Australia's resource potential; an overview of 'criticality' assessment methods; current Australian production; and future research needs for critical minerals in Australia.

Critical minerals are pivotal to modern human society. Many critical minerals are irreplaceable components of technological and industrial advancement, especially for renewable energy systems, electric vehicles, rechargeable batteries, consumer electronics, telecommunications, specialty alloys, and defence technologies.

Critical minerals include metals, non-metals and mineral compounds that are economically important and subject to risks of supply. The 'criticality' of minerals is a subjective concept; countries develop their own lists of critical minerals based on the relative importance of particular minerals to their industrial needs and strategic assessment of supply risks. Lists are reviewed and changed over time. The supply of critical minerals is an area of growth potential due to increasing technological demands and uses at a global level.

Australia is one of the world's principal producers of several major mineral commodities including bauxite, coal, copper, lead, gold, ilmenite, iron ore, nickel, rutile, zircon, and zinc. Although some critical minerals are mined as primary products, many critical minerals are extracted as companion products from major mineral production. Considering Australia's leading expertise in mining and processing as well as extensive mineral resources likely to contain critical minerals, there is potential for Australia to develop into a supplier of critical minerals.

Australia's opportunity to develop into a supplier of critical minerals is significantly affected by a number of factors, including;

- insufficient knowledge of critical minerals in Australian deposits and their behaviour during metallurgical processing
- few geological studies dedicated to assessing and facilitating the discovery of critical mineral resources in Australia
- the need for new mining technology and services to economically extract critical minerals
- gaps in capabilities of domestic smelters/refineries to process critical minerals.

For Australia to reach its full potential and maximise its position in the global critical minerals market, these issues require further research and investigation.

CONTENTS

1 INTRODUCTION TO CRITICAL MINERALS

1.1 Definition

The global economy depends on the steady supply and use of virtually every element on the periodic table. However, some elements require more strategic assessment and management of their resources, supply and use. This is largely because a) some minerals are more useful than others, being essential and often not substitutable in important technologies, and b) some of these minerals are also subject to supply security concerns. Those minerals that are both important to society and vulnerable to supply disruption are usually referred to as 'critical minerals'. In this report, the term 'minerals' includes metallic and non-metallic elements and minerals (sensu stricto), which in most cases are compounds of elements. Critical minerals include the rare earth elements (REEs) used in wind turbines, magnets and battery technologies. Other uses of critical minerals include specialty alloys (e.g. tungsten, rhenium, niobium), chemical catalysts (e.g. rhenium, platinum-group elements or PGEs), renewable energy generation and storage (e.g. indium, lithium, cobalt, vanadium, gallium) or electronics (e.g. hafnium, germanium).

1.2 Criticality

There is a relatively short history of research on critical minerals. The United States National Research Council (2008) presented one of the earliest notable attempts to quantify risk factors and derive criticality ratings for the United States government in 2006. Since then, a number of other studies have been conducted to develop and refine criticality methodologies, and to assess criticality in a number of other country and corporate contexts e.g. British Geological Survey 'Risk List' (2015), General Electric's internal approach (Duclos, 2010). Perhaps the most comprehensive and recognised method for quantifying mineral criticality is given by Graedel et al. (2012), which considers the three primary factors to be supply risk, vulnerability to supply restriction, and environmental implications (Figure 1.1).

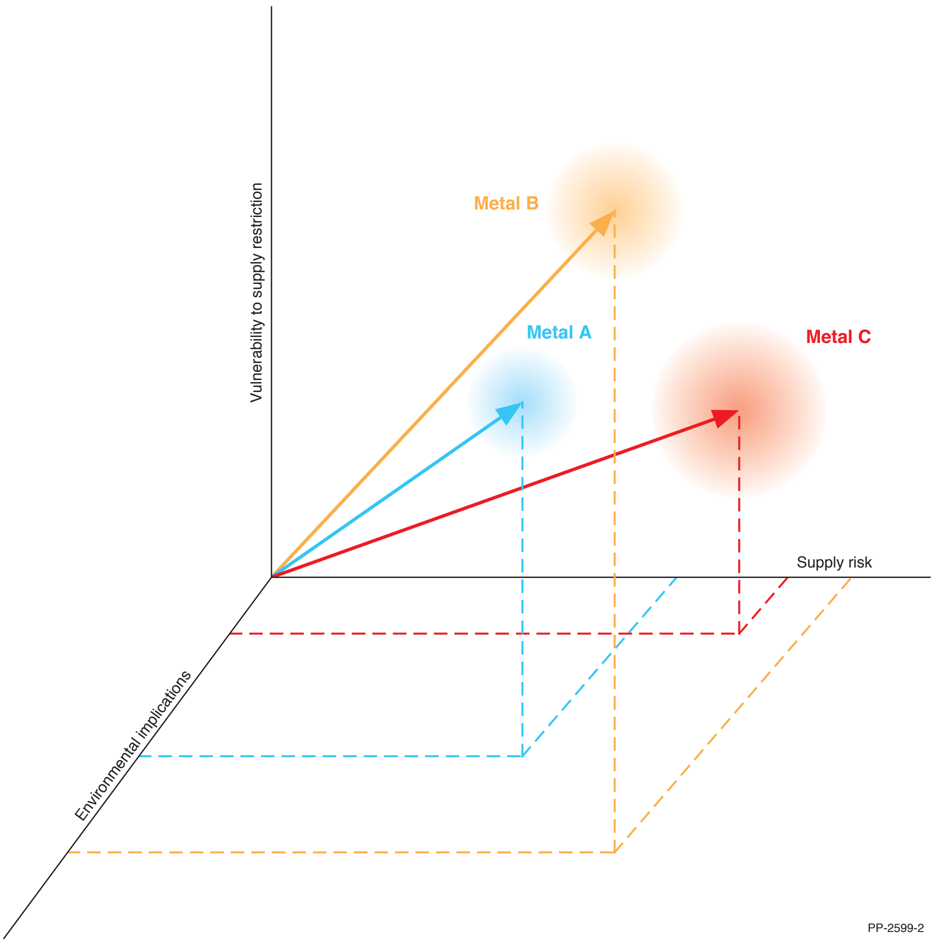

Figure 1.1 Criticality matrix outlining three key areas to be measured to determine the criticality of minerals and metalloids (Graedel et al., 2012).

Essentially, the Graedel et al. (2012) methodology aims to determine the likelihood of a supply disruption, the impacts if supply were disrupted, and the environmental implications of supplying a mineral. These aspects, in turn, consider a number of contributing variables, including (amongst others):

1. whether the mineral is used in important technologies or applications
2. how easily it can be replaced by other minerals in its major applications (substitution)
3. if it is used by a large portion of the population
4. the extent to which the country or corporation examined is highly dependent on imports for supply
5. whether the supply of the mineral derives from a small number of supplier countries or companies that have control over the market
6. whether these countries are also politically stable or have a history of imposing constraints on exports to other countries
7. whether there are limited mineral resources of the mineral
8. if the mineral is produced as a by-product, meaning that production is inelastic to demand
9. the size of the overall market for the mineral, as small markets lead to larger uncertainties in supply-demand dynamics and large fluctuations in price.

1.3 Australian Critical Mineral Studies

Gathering information required for criticality assessment that is both sufficiently detailed and relevant to Australia can be time consuming, and requires specialist expertise to interpret and organise. As such, there are few published studies that have comprehensively examined issues around mineral criticality in an Australian context. Geoscience Australia produced the first report to examine mineral criticality in the Australian economy: *'Critical Commodities for a high-tech world: Australia's potential to supply global demand'* (Skirrow et al., 2013). This report reviewed previous studies of mineral criticality for other countries, and identified a number of critical minerals for which Australia appears to exhibit resource potential in different mineral systems. In the following sections, the present study takes the next step of collating and estimating preliminary data on Australian critical mineral resources and production to provide a stronger basis for understanding the criticality of minerals in Australia now and in the future. Importantly, it also provides a basis for better understanding Australia's resilience to mineral criticality (c.f. Dewulf et al., 2016).

Many critical minerals are produced as by-products of the mining of major commodities. Commonly this is due to the geochemical and geological association of the critical and major ore metals or non-metals, resulting in mixtures of minerals containing the major and critical metals or non-metals. For example, PGEs generally occur as PGE-sulfide minerals intimately associated with nickel sulphide minerals. In other cases of by-products, the critical minerals occur within the major ore minerals themselves, due to elemental substitution between the primary and critical minerals. For example, in the primary zinc ore mineral sphalerite, indium substitutes for zinc, and in the mineral molybdenite, rhenium substitutes for molybdenum. Both types of by-products are also known as 'companion metals' (Nassar et al., 2015; Figure 1.2).

Given that Australia is a major producer of many of the ores that host critical minerals (whether as separate critical metal-rich minerals or substituted within primary ore minerals), it is important to consider the resource and production potential of currently operating mines and smelters. For example, indium is typically produced as a by-product of zinc yet, despite Australia being a major producer of zinc in terms of exported concentrates and domestic refining (~7.6% of world primary zinc production in 2017, and ~12–17% in the previous few decades), there is no known current domestic production of refined indium even though some smelters may have production capability. Other critical minerals, which can be extracted from zinc concentrates, include gallium, germanium and cadmium. A similar situation exists for copper concentrates and associated critical minerals (e.g. tellurium, indium, selenium).

To explore short to medium term opportunities for domestic critical mineral extraction and processing, more detailed data and analysis of critical mineral concentrations and production capability in currently operating mines, tailings, smelters and refineries is required. Huston and Brauhart (2017) have begun to build such a baseline by assessing available Australian ore concentrates for critical mineral abundance. They concluded that there is potential for Australia to produce critical minerals from existing mines but that there are significant technological and economic impediments to realising this potential.

To position Australia as a medium to long-term supplier of critical minerals to the global economy requires the resources pipeline to be maintained through continued resource discovery. Skirrow et al. (2013) highlighted that Australia's geology is favourable for the discovery of many critical mineral deposits but most government pre-competitive geoscience programs are currently focused on securing the resource pipeline, of the economically more significant, non-critical commodities. For example, Australia's current position as the world's leading supplier of Li, through the mining of spodumene deposits, has limited prospect for immediate expansion as the potential for similar deposits in Australia has not yet been investigated.

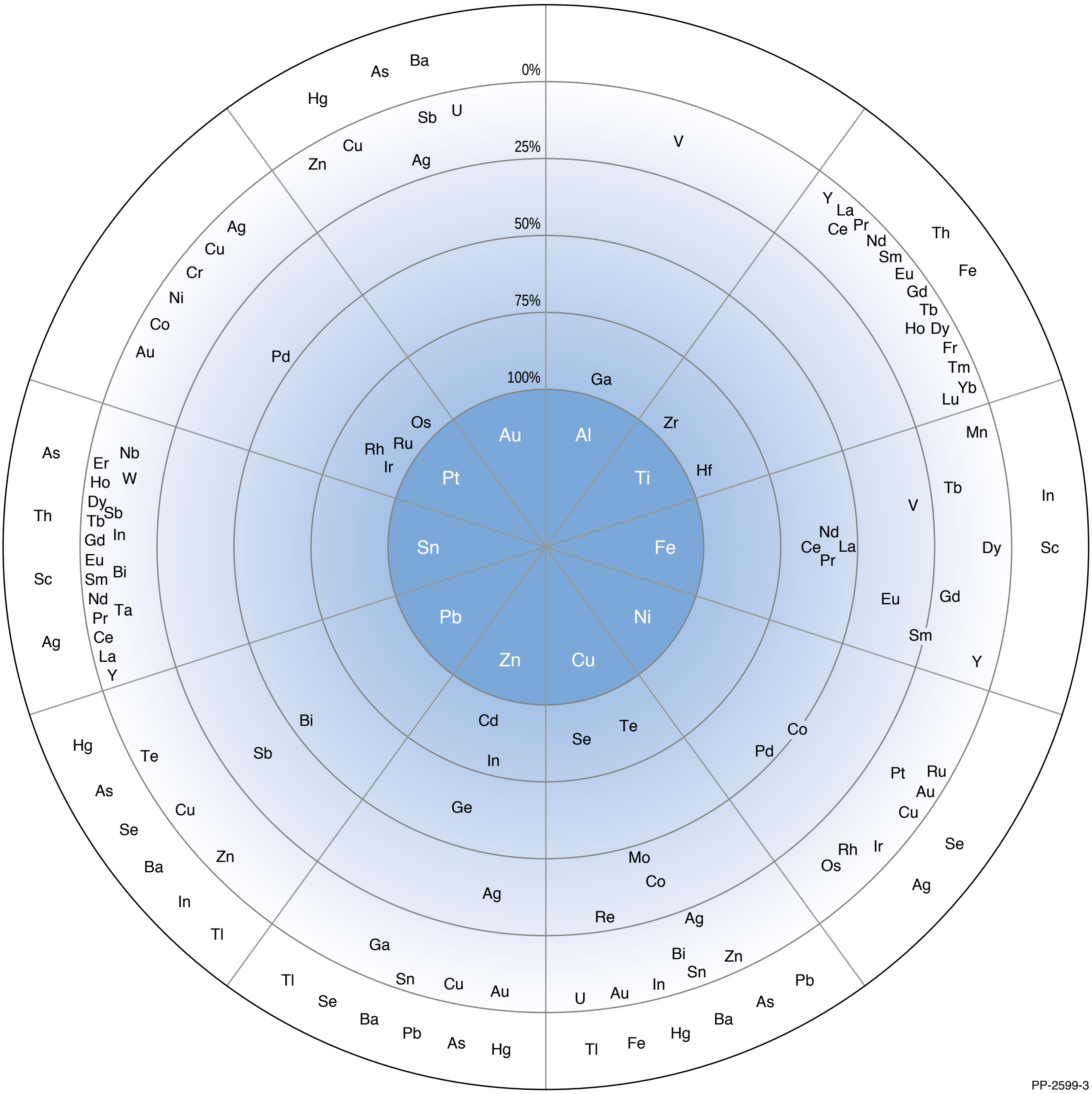

Figure 1.2 The wheel of metal companionality indicates the percentage to which various metals are by-products (or 'companions') and depend on base or precious metals production for continued supply (Nassar et al., 2015).

2 DEMAND AND SUPPLY OF CRITICAL MINERALS

2.1 Demands and Uses

Modern technology such as communications, computers and medical technology increasingly depends on a wider variety of elements to function (e.g. Greenfield & Graedel, 2013). Low-carbon technologies, for example in renewable energy generation, also require specialty minerals that are among the most geologically scarce (e.g. International Resources Panel, 2017). Table 2.1 lists a number of minerals typically considered critical, along with their major uses, and production status in Australia.

Table 2.1 Selected minerals often rated as highly critical and their major uses and status in Australia (2017 data; synthesised from British Geological Survey 2015; European Commission, 2015, 2017; Fortier et al., 2018; Gunn, 2014; Johnson Matthey, 2018; United States Geological Survey, 2018).

Mineral	Considered Critical by	Major Applications	Global Production	Australian Status
Antimony	EU, UK, USA	flame retardants, lead acid batteries, plastics catalyst	150 000 t	Single mine at Costerfield (VIC), ~3000 tpa; other mines on care & maintenance; large resources known
Cobalt	EU, UK, USA	specialty alloys, batteries, catalysts, tyre adhesives, pigments	110 000 t	Significant mine at Murrin Murrin (WA), ~3000 tpa, plus minor production from nickel sulfide mines (WA); large resources known
Gallium	EU, UK, USA	renewable energy, electronics	495 t [A]	No production; major resources expected in bauxite and zinc deposits
Germanium	EU, UK, USA	infrared devices, fibre optics	134 t	No production; major resources expected in zinc deposits
Indium	EU, UK, USA	renewable energy, electronics, specialty alloys, touch screens	680 t	No production at zinc refineries, no value paid for indium in exported concentrates; large resources known
Lithium	UK, USA	renewable energy, electronics, batteries	43 000 t	Major mines at Greenbushes, Pilgangoora, Mount Cattlin, and Mount Marion (WA); Australian production 21 000 t; large resources known
Niobium	EU, UK, USA	specialty alloys	64 000 t	No production; major resources known
PGEs	EU, UK, USA	automotive catalysts, chemical catalysts, jewellery, specialty alloys	~410 t [B]	Minor production from nickel sulfides (WA); modest resources known
Rare earth oxides (REOs)	EU, UK, USA	renewable energy, electric vehicles, military technologies, electronics, specialty alloys, batteries	130 000 t	Single mine at Mount Weld (WA), 2200 tpa; monazite from mineral sands mines not extracted or exported; large resource known at the Olympic Dam deposit but this resource is not recoverable using current technology at present prices; significant REE-only deposits at early stage of production (e.g. Browns Range) or in feasibility studies (e.g. Nolans Bore, Toongi)
Rhenium	UK, USA	specialty alloys, chemical catalysts	52 t	No production; major resource known at Merlin (QLD)
Tungsten	EU, UK, USA	specialty alloys	95 000 t	Minor production 245 t; major resources known

Notes: UK—United Kingdom; EU—European Union; USA—United States of America; t—tonnes; tpa—tonnes per annum; [A] Total of low & high-purity; [B] platinum and palladium only.

2.2 Current Supply Sources of Critical Minerals

The principal source for information on global production and markets for most critical minerals is the United States Geological Survey's annual publication '*Mineral Commodity Summaries*' (United States Geological Survey, 2018). Their preliminary 2017 data are summarised in Table 2.2, including PGE data from Johnson Matthey (2018).

Table 2.2 Global mine production and prices of various critical minerals (2017 data), including dominant country (all data from USGS, 2018; except PGE data from Johnson Matthey, 2018) (sorted from highest to lowest market value).

Critical Mineral	Production	Price	Market Value	Largest Producer		
	Tonnes	US$/tonne	US$million	Country	Tonnes	Percentage
REE	130 000	186 782 [A]	24 281.7	China	105 000	80.8%
Phosphate Rock	263 000 000	75	19 725.0	China	140 000 000	53.2%
Chromite ore	31 000 000	320	9 920.0	South Africa	15 000 000	48.4%
Cobalt	110 000	54 454	5 989.9	Congo-DRC	64 000	58.2%
Tin	290 000	20 282	5 881.9	China	100 000	34.5%
Platinum*	185.8	30 868 167	5 735.3	South Africa	135.7	73.0%
Palladium*	205.2	27 652 733	5 674.3	Russia	82.5	40.2%
Molybdenum	290 000	18 000	5 220.0	China	130 000	44.8%
Tungsten	95 000	24 500	2 935.3	China	79 000	83.2%
Graphite	1 200 000	1400	1 680.0	China	780 000	65.0%
Vanadium	80 000	11 464	1 637.2	China	43 000	53.8%
Antimony	150 000	8840	1 326.1	China	110 000	73.3%
Niobium	64 000	18 000	1 152.0	Brazil	57 000	89.1%
Rhodium*	23.3	33 762 058	786.7	South Africa	19.2	82.4%
Lithium	43 000	13 900	597.7	Australia	18 700	43.5%
Indium	720	360 000	259.2	China	310	43.1%
Tantalum	1300	193 000	250.9	Rwanda	390	30.0%
Iridium*	8.2	29 163 987	239.1	South Africa	nd	nd
Germanium	134	1 358 000	182.0	China	88	65.7%
Bismuth	14 000	10 582	148.1	China	11 000	78.6%
Beryllium	230	630 000	144.9	USA	170	73.9%
Gallium	495	565 000	117.8	China	nd	nd
Rhenium	52.0	1 550 000	80.6	Chile	27.0	51.9%
Selenium	3300	23 810	78.6	China	930	28.2%
Ruthenium*	37.5	1 961 415	73.6	South Africa	nd	nd
Cadmium	23 000	1700	39.1	China	8200	35.7%
Tellurium	420	36 000	15.1	China	280	66.7%
Strontium	202 000	73	14.7	Spain	90 000	44.6%
Hafnium	nd	912 000	nd	nd	nd	nd
Scandium	nd	350 000 [B]	nd	nd	nd	nd

Notes: [A] REE prices are highly variable; value adopted based on individual REE market prices from trade website '*MineralPrices.com*' and using global average REE mineral resources from Weng et al. (2015) to estimate an overall average REE price; [B] Price for aluminium-scandium alloys; nd—not defined; *PGEs.

China holds a dominant global market position in the production of many critical minerals, especially the REE (80.7%), bismuth (78.6%), tungsten (83.2%) and antimony (73.3%) as well as major positions in the production of many others (e.g. graphite, tellurium, indium, vanadium, germanium and gallium). Figure 2.1 shows the long-term sustained growth in market share of REE production by China. For some other critical minerals, single countries dominate such as Brazil (niobium) and South Africa (PGEs). The only critical mineral listed in Table 2.2 for which Australia has a leading position is lithium, with 2017 production of 18 700 t Li recently overtaking Chile's 14 100 t Li.

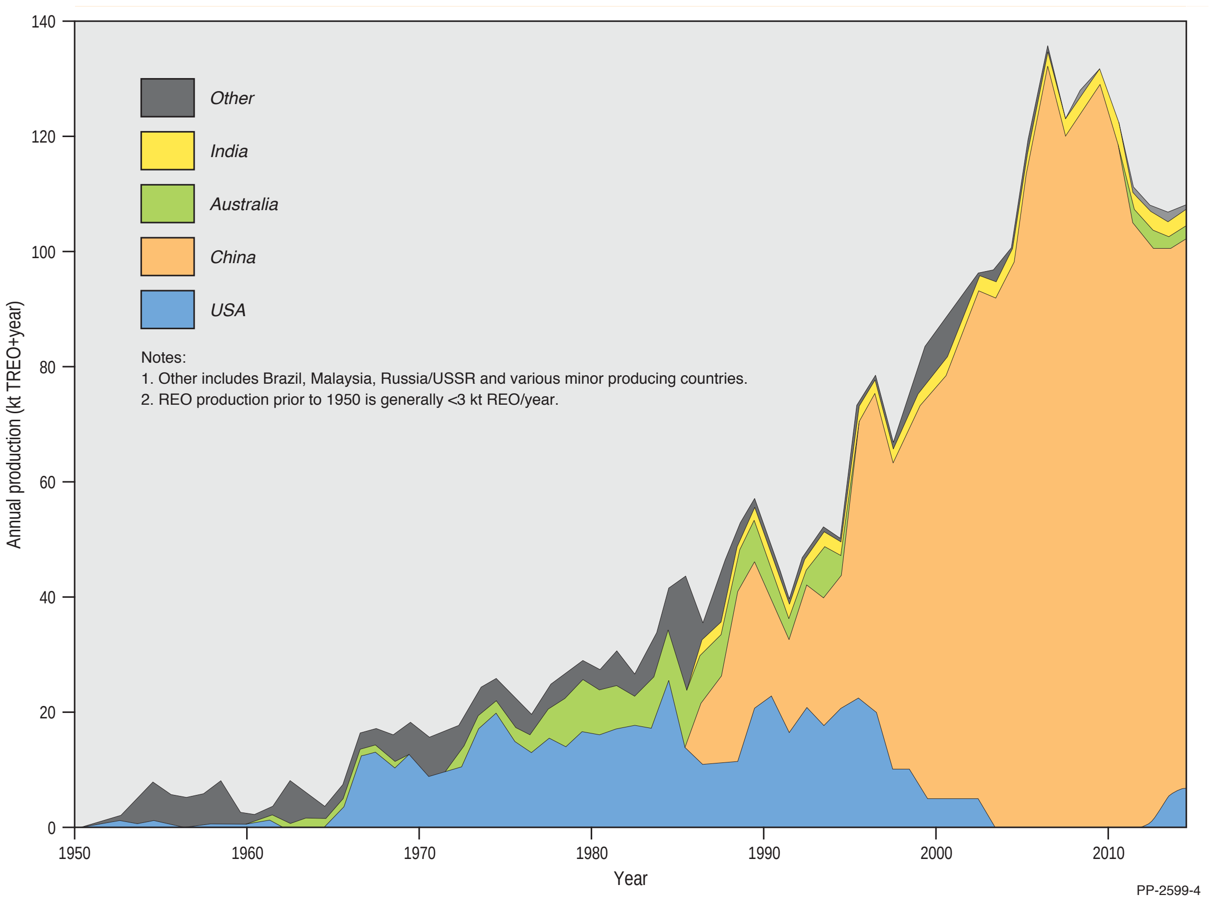

Figure 2.1 Evolution of global rare earth production by country (adapted from Weng et al., 2015).

Information on the sources of critical mineral supply is subject to several uncertainties. For example, in instances where mineral concentrate with a reported critical mineral component (e.g. indium in zinc concentrate) is processed at a smelter or refinery that does not have the capacity to extract the critical mineral, or chooses not to extract the critical mineral the reported critical mineral becomes a waste product in slags or residues and is lost to the supply chain. Conversely, concentrates with unreported critical mineral components may be processed at smelters or refineries able to extract the critical mineral in other countries and report its production. Both these scenarios tend to skew the reported information on critical mineral resources and production. For example, in the case of indium (Figure 2.2) Japan, Belgium and France are significant producers (in addition to China) but do not have mines producing zinc concentrates; the sources of the ores and concentrates are in fact the major zinc-mining countries such as Australia who export the ores and concentrates to processing facilities in Europe and Asia.

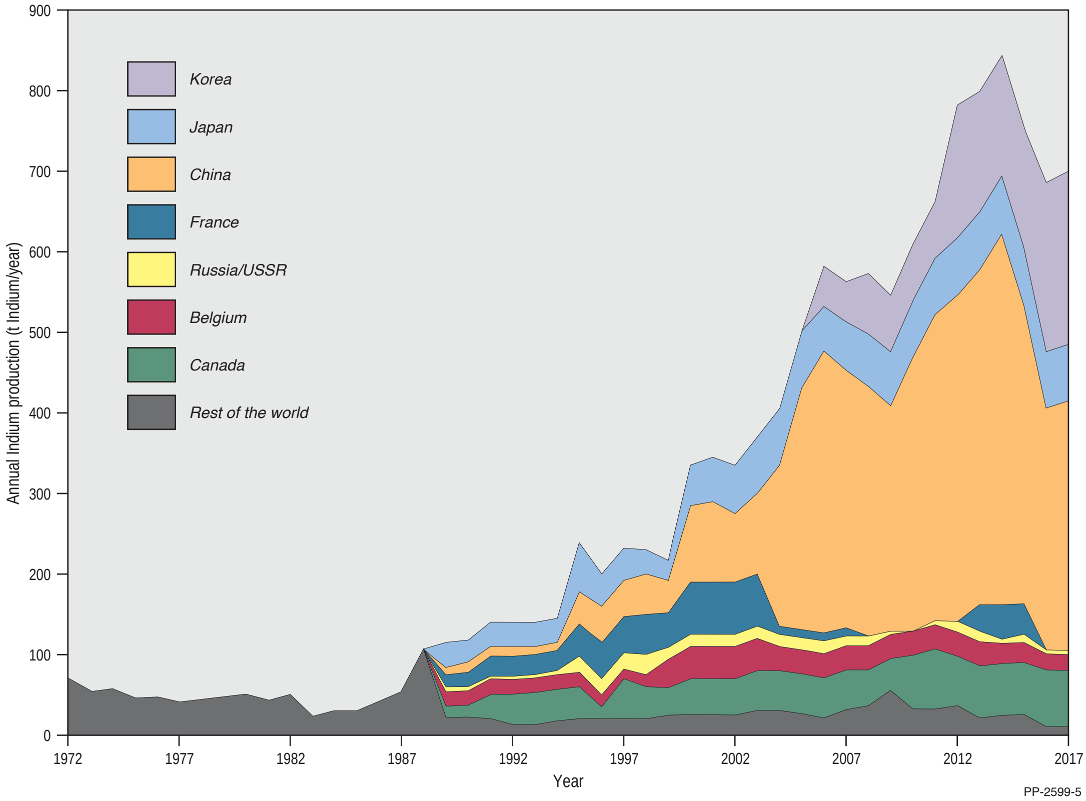

Figure 2.2 Recent evolution of global refined indium production by country (updated from Werner et al., 2015).

2.3 Current Supply Sources of Major Minerals and Metals

The production and value for economically major metals and minerals is presented in Table 2.3. As noted above, the ores and concentrates of many of these commodities are also the sources of numerous critical mineral by-products. Of particular note are the scales of the zinc, alumina/bauxite, copper and gold sectors—with annual market values from $36.7 to $127.6 billion. Australia also holds major positions in the production of heavy mineral sands concentrates (rutile, ilmenite, zircon), manganese, lead and nickel.

It should be noted, however, that the annual growth in these traditional sectors of the global mining industry is typically slower but less volatile than the growth rates in many of the critical minerals. The percentage difference for both sectors between 2000 and 2017 of world production is reported in Table 2.4. For critical minerals, the average growth was 199% —meaning production has doubled since 2000—and for major metals and minerals, growth was 182%. The difference in production growth rates is related to evolving demands for more complex technology and infrastructure, which require more critical minerals. However, production of few critical minerals did decrease, while for all major metals and minerals, production increased.

Table 2.3 Global mine production and prices of various common metals and minerals (2017), including dominant country (all data from USGS, 2018; except uranium from the World Nuclear Association, 2018) sorted from highest to lowest market value.

Common Metal / Mineral	Production	Price	Market Value	Largest Producer		
	Tonnes	US$/tonne	US$million	Country	Tonnes	Percentage
Iron Ore	2 400 000 000	75	180 000.0	Australia	880 000 000	36.7%
Gold	3150	40 514 469	127 620.6	China	440	14.0%
Copper	19 700 000	6173	121 605.7	Chile	5 330 000	27.1%
Alumina	130 000 000	450	58 500.0	China	72 300 000	55.6%
Zinc	13 200 000	2780	36 696.0	China	5 100 000	38.6%
Potash	39 300 000	790	31 047.0	Canada	10 800 000	27.5%
Nickel	2 100 000	10 144	21 302.4	Indonesia	400 000	19.0%
Silver	25 000	553 055	13 826.4	Mexico	5600	22.4%
Lead	4 700 000	2258	10 610.3	China	2 400 000	51.1%
Bauxite	300 000 000	30	9000.0	Australia	83 000 000	27.7%

Common Metal / Mineral	Production	Price	Market Value	Largest Producer		
	Tonnes	US$/tonne	US$million	Country	Tonnes	Percentage
Sulfur	83 000 000	60	4 980.0	China	17 750 000	21.4%
Boron	9 800 000	500	4 900.0	Turkey	7 300 000	74.5%
Uranium	59 531	60 682	3 612.5	Kazakhstan	23 391	39.3%
Manganese Ore	16 000 000	203.6	3 257.8	South Africa	5 300 000	33.1%
Fluorspar	6 000 000	270	1 620.0	China	3 800 000	63.3%
Zircon conc.	1 600 000	953	1 524.8	Australia	600 000	37.5%
Barite	7 700 000	170	1 309.0	China	3 100 000	40.3%
Titanium-Ilmenite conc.	6 200 000	170	1 054.0	South Africa	1 300 000	21.0%
Titanium-Rutile conc.	900 000	740	666.0	Australia	450 000	50.0%
Mercury	2500	29 008	72.5	China	2000	80.0%
Garnet	1 100 000	nd	nd	Australia	400 000	36.4%

Table 2.4 Percentage difference of world mine production from 2000 to 2017 for major and critical minerals (all data from USGS, 2018; except PGE data from Johnson Matthey, 2018 and uranium data from the World Nuclear Association, 2018) sorted from highest to lowest ratio.

Critical Mineral	Production (t)		% difference	Major Metal / Mineral	Production (t)		% difference
	2000	2017			2000	2017	
Gallium (total)	110	495	450	Garnet	291 000	1 100 000	378
Tellurium	125	420	336	Alumina	51 700 000	130 000 000	251
Cobalt	33 300	110 000	330	Titanium-Rutile conc.	390 000	900 000	231
Lithium	14 000	43 000	307				
Ruthenium*	13.8	37.5	271	Iron Ore	1 060 000 000	2 400 000 000	226
Tungsten	37 400	95 000	254	Boron	4 370 000	9 800 000	224
Bismuth	5880	14 000	238	Bauxite	135 000 000	300 000 000	222
Selenium	1410	3300	234	Manganese Ore	7 280 000	16 000 000	220
Molybdenum	129 000	290 000	225	Mercury	1350	2500	185
Niobium	~29 118[A]	64 000	220	Nickel	1 250 000	2 100 000	168
Chromite ore	14 400 000	31 000 000	215	Zircon conc.	1 040 000	1 600 000	154
Indium	335	720	215	Lead	3 100 000	4 700 000	152
Iridium*	3.9	8.2	211	Zinc	8 730 000	13 200 000	151
Graphite	571 000	1 200 000	210	Copper	13 200 000	19 700 000	149
Phosphate Rock	133 000 000	263 000 000	198	Sulfur	57 200 000	83 000 000	145
Germanium	71	134	189	Titanium-Ilmenite conc.	4 300 000	6 200 000	144
Vanadium	43 000	80 000	186				
Rhenium	28.4	52.0	183	Silver	17 700	25 000	141
REE	83 500	130 000	156	Uranium	42 457	59 531	140
Tantalum	836	1300	156	Fluorspar	4 520 000	6 000 000	133
Antimony	118 000	150 000	127	Barite	6 200 000	7 700 000	124
Tin	238 000	290 000	122	Gold	2550	3150	124
Cadmium	19 700	23 000	117				
Platinum*	164.5	185.8	113				
Rhodium*	23.9	23.3	98				
Palladium*	242.6	205.2	85				
Beryllium	280	230	82				
Strontium	520 000	202 000	39				
Hafnium	nd	nd	nd				
Scandium	nd	nd	nd				
		Average	199			Average	182

Notes: conc. = concentrate; [A] Assumes Brazil and Canada only; nd = not defined; *PGEs.

2.4 Dependence of Various Countries on Current Supply Sources of Critical Minerals and Metals

A key issue for many industrialised and developing countries is the extent to which they are reliant on imports of the major and critical mineral commodities underpinning their economies. In order to explore this issue further, a series of tables have been developed to show the import reliance by the United States (Appendix 1), the European Union with the United Kingdom (Appendix 2) and China (Appendix 3), combined with an assessment of Australia's medium to long-term geological potential to supply the various critical minerals (extended from previous work by Skirrow et al., 2013 and Huston and Brauhart, 2017).

From these appendices, the following points stand out:

- **United States—**heavily reliant on imports for most critical minerals—many of which derive from China, but Australia has significant opportunity to increase supply of many of these commodities;
- **European Union—**heavily reliant on imports for most critical minerals—many of which derive from China, but Australia has significant opportunity to increase supply of many of these commodities;
- **United Kingdom—**almost entirely reliant on imports for nearly all critical minerals—many of which derive from China, Japan, the United States, Australia and South Africa, but Australia has significant opportunity to increase supply of many of these commodities.

Overall, the dependence of industrialised nations on imports to maintain supplies of critical minerals is very clear, as well as the geological potential of Australia to increase supply of many of these critical minerals.

3 AUSTRALIA'S POTENTIAL CRITICAL MINERALS RESOURCES

3.1 Economic Geology of Critical Minerals

Given the wide variety of minerals commonly considered to be critical, there is a correspondingly large variety of mineral resources that are known to contain different critical minerals. The economic geology of most critical minerals remains poorly understood and documented, but knowledge is growing.

In Australia, Skirrow et al. (2013) reviewed the economic geology of various mineral deposit types in Australia that could host critical minerals. Other global studies include those by Gunn (2014) and Verplanck and Hitzman (2016). In short, the principal mineral deposit types of relevance for Australia include (further details in the references cited):

- **Magmatic sulfide—**commonly contains variable amounts of nickel, copper, cobalt, chromium, PGEs (examples include Munni Munni, Nebo-Babel, Kambalda district)
- **Porphyry-epithermal—**commonly contains copper, gold and/or silver and variable amounts of molybdenum, indium, rhenium, tellurium, tungsten, tin, bismuth, lithium, zinc, lead, antimony, gallium, germanium, arsenic, mercury, selenium (examples include Spinifex Ridge, Cadia Valley, Northparkes)
- **Granite-related—**depending on deposit type, commonly contains tin, tungsten, tantalum, niobium, lithium, beryllium, molybdenum, indium (examples include King Island, Unicorn, Mount Carbine, Molyhil, Wodgina, Greenbushes)
- **Iron oxide copper-gold (IOCG)—**commonly contains iron oxides, copper, gold, silver and variable amounts of uranium, REEs, cobalt, barium, molybdenum, bismuth (examples include Olympic Dam, Prominent Hill, Ernest Henry)
- **Volcanic-related—**commonly contains copper, lead, zinc, gold, silver, and variable amounts of indium, antimony, mercury, arsenic, gallium, germanium, cadmium, bismuth, selenium, tellurium (examples include Rosebery, Woodlawn, Gossan Hill (Golden Grove), Mount Lyell, Mount Morgan)
- **Orogenic-related—**commonly contain gold, copper, silver, and variable amounts of lead, zinc, tellurium, tungsten, arsenic, antimony, bismuth, mercury, cadmium (examples include Kalgoorlie, Bendigo, Hillgrove, Charters Towers, Pine Creek, Tanami, Cobar)
- **Basin-related—**commonly contains copper, lead, zinc, gold, silver, uranium and variable amounts of vanadium, cobalt, molybdenum, indium, antimony, mercury, arsenic, gallium, germanium, cadmium, bismuth, selenium, tellurium, PGE (examples include Mount Isa, McArthur River, Walford Creek, Nifty, Admiral Bay, Lennard Shelf district, Broken Hill, Cannington, Ranger, Coronation Hill)
- **Alkaline intrusion-related—**can contain diamonds, uranium, REEs, phosphate, copper, zirconium, niobium, lead, tin, barium, hafnium, tungsten (examples include Cummins Range, Mount Weld, Toongi, Argyle)
- **Surficial and placer-related—**commonly contain aluminium (bauxite ore), manganese, uranium, nickel, titanium minerals (rutile, ilmenite), monazite (REE-bearing), zircon, cobalt, scandium, gallium (examples include Murrin Murrin, Greenvale/SCONI, Weipa, Groote Eylandt, WIM150).

It is also important to note that mineralogy is crucial in understanding not only the potential resources of critical minerals but also economic recoverability. Many of the critical minerals do not occur as easily recoverable minerals but as noted earlier may occur as substitution elements in common minerals. For example, indium is substituted in various base metal sulfides, such as sphalerite, galena and chalcopyrite (see Werner et al., 2015). Understanding the mineralogy, formation and association of critical minerals with other metals and minerals requires substantial further research.

3.2 Known Mineral Resources Containing Critical Minerals

At present, there are a number of deposits that have reported critical minerals in mineral resources (under the Joint Ore Reserves Committee (JORC) Code), as well as some that are not JORC-compliant but based on reasonable geological and geochemical data (e.g. REEs at Olympic Dam). A partial list, by critical mineral (Mudd & Jowitt, 2016; Mudd et al., 2014; Werner et al., 2017b), includes the following commodities and deposits (see also Figure 3.1):

- **Molybdenum and rhenium—**Kalman (Queensland), Merlin (Queensland)
- **Scandium—**SCONI: Greenvale/Kokomo/Lucknow (Queensland), Owendale-Cincinnati (New South Wales), Gilgai-Nyngan (New South Wales), Hurll's Hill (New South Wales), Syerston (New South Wales), Mulga Rock (Western Australia)
- **Antimony—**Costerfield (Victoria), Hillgrove (New South Wales), Bielsdown (Wild Cattle Creek) (New South Wales), the Spec deposits (Western Australia), Mount Clement-Eastern Hills (Western Australia)
- **Hafnium—**Toongi (New South Wales), Hastings (Western Australia), Narraburra (New South Wales)
- **Lithium—**Greenbushes (Western Australia), Mount Marion (Western Australia), Mount Cattlin (Western Australia), Pilgangoora (Western Australia), Earl Grey (Western Australia)

- **Rare earth elements—**Mount Weld (Western Australia), Toongi (New South Wales), Charley Creek (Northern Territory), Nolans Bore (Northern Territory), Browns Range (Western Australia), Narraburra (New South Wales), Yangibana (Western Australia), Olympic Dam (South Australia)
- **Indium—**Baal Gammon (Queensland), Conrad-King Conrad (New South Wales), Zeehan slag (Tasmania)
- **Tungsten—**Watershed (Queensland), Mount Carbine (Queensland), Mount Mulgine and O'Callaghans (Western Australia), Dolphin (Tasmania)
- **Platinum-group elements—**West Musgrave (Nebo-Babel) (Western Australia), Rosie (Western Australia), Munni Munni (Western Australia), Panton (Western Australia).

Some of the above deposits are modest in size compared to their international cousins, for example Australia's known PGE deposits in contrast to the giant Bushveld complex in South Africa (Mudd et al., 2018) and the Mount Weld REE deposit in contrast to the Bayan Obo deposit in China (Weng et al., 2015). And some are large resources (e.g., lithium and tantalum at Greenbushes). In some cases where large geological resources are present, they are not recoverable using current extraction technologies and commodity prices (e.g. REEs at Olympic Dam).

At present, from this list, only the Costerfield (antimony) and the lithium deposits at Greenbushes, Pilgangoora, Mount Cattlin and Mount Marion are operating and producing critical minerals, although Baal Gammon (indium) recently operated briefly and Olympic Dam is operating but does not produce REE. For many projects, existing technology is available to process the ores and produce critical minerals (e.g. the Panton process developed for the Panton PGE deposit; the process flow sheet developed for the Toongi multi-mineral project; tungsten; rhenium contained in molybdenum concentrates). Conversely, some projects have developed process technology for their projects but there are no previous operating examples of this technology to demonstrate viability (especially capital and operating costs), an example being scandium at the SCONI project. Finally, for some minerals, it is reasonable to expect that they would deport to a concentrate produced with standard flotation technology (e.g. indium in zinc concentrates or tellurium in copper concentrates), but there remain a lack of studies and data. In other words, for some projects no new process technology is needed (e.g. flotation concentrates containing critical minerals such as indium, palladium or tellurium), whilst others require research and development for additional technology to be developed and constructed (e.g. REE at Olympic Dam). Overall, process technology needs to be linked closely with capital and operating costs as well as market demands and prices. Whilst some projects are highly prospective in the short term or next few years (e.g. Toongi, Browns Range, Merlin), others are much longer-term prospects (e.g. Olympic Dam, SCONI).

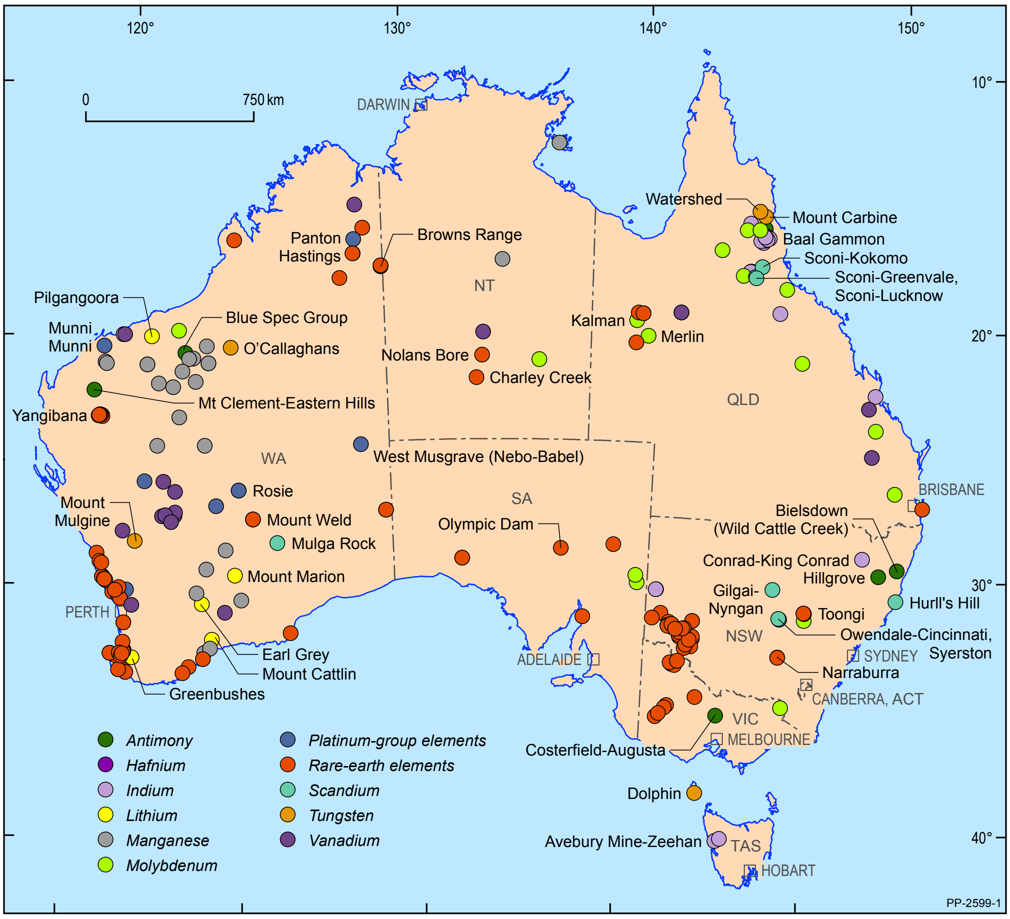

Figure 3.1 Mineral deposits across Australia with known critical mineral resources (data updated from Mudd et al., 2014).

3.3 Reporting and Potential Mineral Resources Containing Critical Minerals

To assess Australia's extraction potential of critical minerals, Huston and Brauhart (2017) conducted a geochemical assessment of critical mineral distributions within Australian ores by compiling analyses of 321 ore samples from both the OSNACA (Ore Samples Normalised to Average Crustal Abundance) and OREAS (ORE Research & Exploration Pty Ltd) databases. Some additional analyses were also undertaken for several elements not reported in the OSNACA and OREAS data sets. They found strong correlations between critical mineral concentrations and major element concentrations (e.g. Pt, Pd vs. Ni, Co vs. Ni) from many Australian ore samples, highlighting Australia's high potential for critical mineral extraction as by/co-products from existing mines. They also reported many surprising results such as significantly elevated PGEs within Porphyry Cu deposits from the Macquarie Arc in New South Wales, which could represent a significant resource. However, Huston and Brauhart (2017) also stated the production of these companion commodities is not only dependent on critical mineral concentrations but also on technical and economic limitations. To effectively assess the true potential of Australia's critical mineral potential, significantly more data are required. In particular, analyses of concentrates and a larger range of deposits and ore types are needed to complement the research into economic extraction of these critical minerals.

Given that many critical minerals are extracted from base metal concentrates at smelters or refineries, Australia's existing base metal mines and mineral resources could be important sources of numerous critical minerals. A major challenge in this area is that mines rarely receive payments for the presence of such minerals in concentrates, meaning they are not 'material' to report in mineral resources based on the JORC Code—and hence there are few data on the presence of numerous critical minerals in mineral resource and mine production. This lack of data can be misconstrued as a lack of resources (e.g. Mudd et al., 2017) or wrongly interpreted as an inability to meet existing and future demands.

However, there are complexities in reporting where, for example, companies report minor metals but not critical minerals. The best case in point is Olympic Dam. The long-term proportional value is simply the sum of the economic value of each metal produced over time. By 2017, the long-term proportional value of the copper, uranium, gold and silver produced by Olympic Dam is 74.0%, 17.9%, 7.1%, 1.0%, respectively (data updated from Mudd, 2014). However, if REE are added to the resources (using a low price for the light REE mix present), the values change to 28.4%, 7.4%, 0.4%, 13.3%, 50.6% for copper, uranium, gold, silver and REEs, respectively (Mudd & Jowitt, 2018). That is, the REEs are equal to the value of all extracted metals combined, or the REEs are some 1.8, 3.8, 6.9, 133.6 times the copper, uranium, gold and silver values, respectively. As noted earlier, however, the REEs are not extracted at Olympic Dam, due mainly to the lower value mix of 'light' REE (i.e. lanthanum and cerium are the dominant REE at Olympic Dam) rather than the higher value 'heavy' REE (such as neodymium or terbium) combined with volatile global markets and the uncertainty in the economics of available process technology. Another case is the Cadia Valley Operations, where gold, copper and silver are extracted and the proportional value in 2017 is 34.0%, 66.2%, 0.8%, respectively (data from Newcrest Mining reporting)—showing that low value metals such as silver are reported despite its relative value of <1%.

Due to current reporting requirements, assessment of the impact of critical minerals on the economics of mining and smelting at a national scale is difficult. Consultation with industry and other stakeholders is required to develop a framework whereby such assessments can be robustly made. At present, Australia's existing smelters and refineries extract very few of the critical minerals, and this could present an opportunity at these sites.

Considering Australia's existing and extensive mineral resources across the numerous mineral deposit types, which are expected to potentially contain critical minerals, it is realistic to expect that existing mineral resources would contain a variety of critical minerals and often at potentially recoverable concentrations (e.g. see Huston and Brauhart, 2017). Where direct data are unavailable, one approach to assess which deposits may contain critical minerals is to develop statistical relationships between existing data and the unknown contents of the critical minerals. To achieve this, Werner et al. (2017a) developed a method of using geochemical databases to determine regressions between known metal concentrations and critical minerals—such as copper, zinc, gold, lead, etc. to predict indium concentrations in a given deposit. In this way, an estimate can be made of potential critical mineral resources, allowing for a more comprehensive assessment of Australia's mineral inventory. Applying this method to indium, Werner et al. (2017b) showed there are abundant mineral resources around the world that could reasonably be expected to contain indium. There are noted uncertainties with this method, as critical mineral concentrations can be highly variable even within similar mineral deposit types. However, notwithstanding these uncertainties, it is clear that total critical mineral resources exceed previous global estimates.

In addition to mineral deposits, former mine and smelter/refinery wastes could be potential sources of economically useful quantities of critical minerals. For example, tailings at the inactive Mary Kathleen uranium mine are known to be rich in REEs and smelter slags at Zeehan in Tasmania contain indium (with zinc, silver and lead). The initial uranium oxide concentrates produced at Mary Kathleen were almost rejected in 1958 due to their enriched REE content which would act as neutron absorbers and interfere with fission reaction (Harding, 1992).

In summary, there are a variety of mineral resources that are likely to contain a diversity of critical minerals at potentially economic concentrations at existing and old mines, smelters and refinery wastes. This is an area that requires further documentation and research to assess controls on critical mineral concentrations in different deposit types so that national critical mineral endowment can be better assessed and predicted.

4 PRELIMINARY CRITICALITY STUDIES AND DATA NEEDS FOR AUSTRALIA

It is important to assess the criticality of mineral supply to ensure that these supplies are maintained for the various services, technology and infrastructure of the modern world. In the absence of such assessments and the consequent management strategies that are developed, countries, companies and communities are at greater risk of disruptions to supply and the impacts that can follow. For example, cobalt is used in various specialty alloys, especially in the telecommunications, battery and aerospace industries, and civil unrest in 1980 in Zaire (now the Democratic Republic of the Congo or DRC) led to major disruption to cobalt supply and consequent price increases (Mudd et al., 2013). This situation forced companies dependent on cobalt to find alternatives. More recently, China's restrictions on the export of REEs led to extremely high prices, especially heavy REEs such as neodymium, leading to concerns world-wide about the ability to meet REE supply needs for renewable energy (e.g. magnets for wind turbines), consumer electronics and military technology. Therefore, it is important to ensure that assessments of the criticality of minerals are regularly updated, especially given the ever-changing nature of mining and commodity markets. This section reviews the main methodologies developed for assessing the criticality of minerals.

4.1 Criticality Methodology and Prior Studies

The most widely respected approach to assessing mineral criticality was developed by Prof. Thomas Graedel and his team at the Centre for Industrial Ecology at Yale University (USA), which this report calls the 'Yale Methodology' (Graedel et al., 2012). It is derived from the two-dimensional criticality matrix developed by the US National Research Council (2008), which considers supply risk and vulnerability to supply disruption, and differs from other studies (e.g. European Commission, 2014) in that it is more quantitative, comprehensive and easy to apply. The Yale Methodology examines mineral criticality in a three-dimensional space, adding the dimension concerning environmental implications of supply disruption to the NRC approach, as well as specifying various aspects that need to be examined for each dimension.

In the dimension of supply risk, both medium-term and long-term time horizons are considered. It is believed that the focus of supply risk varies significantly as time progresses and therefore one single time scale is not able to clearly and precisely depict the reality of mineral criticality. Due to the differences of scoping, the medium-term supply risk assessment is more suitable to corporations and nations, whereas the long-term supply risk assessment will be more applicable for those who are examining the matter of mineral criticality from a global view. The medium-term supply risk has three components and each component has two indicators. These three components are:

1. geological, technological, and economic considerations
2. social and regulatory considerations
3. and geopolitical considerations.

Each of these components is assigned one-third importance in the aggregation of components.

The vulnerability to supply restriction of a mineral is assessed at three different levels, namely the corporation level, the national level and the global level. The vulnerability to supply restriction at national level assesses the following components: importance, substitutability, and susceptibility. The importance component has two indicators: national economic importance and percentage of population utilisation. The substitutability component has four indicators: substitute performance, substitute availability, environmental impact ratio, and net importance reliance ratio. The susceptibility component has two indicators: net import reliance and global innovation index.

The environmental implication dimension assesses the cradle-to-gate risks to human health and ecosystems of a mineral using the ReCiPe endpoint method (Goedkoop et al., 2009; Huijbregts et al., 2017) and inventory data from the EcoInvent database (Frischknecht et al., 2005).

The criticality space is designed to be flexible, which means that future users of the Yale Methodology can disassemble and then reassemble indicators in all three dimensions to focus on different aspects depending on their own needs. In determining the indicators on all these axes, both quantitative means, such as data collection and mathematical modelling, and qualitative means such as expert opinion, are used. Such an approach aims to maintain analytical integrity even if data are in short supply.

Moving forward, more research into the trade, consumption and production of products and intermediates containing critical minerals is key for Australia. Such data are collected for material flow analysis (MFA) studies, which typically aim to quantify the material efficiency of a system, or identify the parts of an economy where interventions are needed to minimise material wastage. Many such studies have been conducted at a global scale or in the context of the United States, but the number of these studies applied to Australia is minimal. Of particular note is a study by Ciacci et al. (2016) that used MFA data on Al, Fe, Cu, Zn, Ni and In to assess mineral criticality in Australia. There will be a continuing need to update criticality assessments periodically to reflect changes in production and usage patterns over time. Thus, what might be deemed most critical today could change drastically in the future (Ciacci et al., 2016).

4.2 Assessing Australia's Minerals Criticality—From a Consumer's Perspective

Australia is reliant on imports of a wide variety of industrial and consumer products, many of which contain critical minerals. Given the high-tech applications for a number of the critical minerals, it is likely that the critical metal and non-metal components of imported high-tech products will have at least partly originated from Australian mineral deposits, from where the ores in some cases will have been exported overseas for processing. Currently, there are limited industrial manufacturing capabilities in Australia to transform those minerals into industrial and consumer products. Further analyses of critical mineral material flows would provide greater clarity on which critical minerals are reimported in the form of products. This analysis would contribute to generation of an Australian Critical minerals list preferably using the Yale criticality assessment methodology.

4.3 Assessing Australia's Minerals Criticality—From a Supplier's Perspective

Australia is well positioned to benefit from supplying increasing quantities of critical minerals to those trading partner countries that most need such commodities. Realising this benefit will require a wide range of actions, from policy to mineral processing technology development and manufacturing capability. A starting point, however, is to undertake a comprehensive assessment of Australia's endowment of critical minerals.

For example, the estimates for Australia's potential production of gallium, germanium, and antimony from various host metals and geological settings for 2013 have been determined by examining the ratio of produced base metals to their reported economically demonstrated resources in a given year. For example, 80 Mt or 1.3% of 6500 million tonnes (Mt) Bauxite reserves were produced in 2013. Assuming 1.3% of estimated gallium reserves in bauxite were possible to extract that year, Australia's production potential is over 2.4 kilotonnes (kt), already several times that of global demand for that year (see Table 2.1). However, this represents only a portion of Australia's potential production for 2013, estimated to be over 5.3 kt gallium when considering all potential host commodities (e.g. lead-zinc-silver, iron, or coal) and deposit types (Yellishetty et al., 2017).

To examine the resource potential of critical minerals in Australia, it is necessary to first consider the metals hosting them. If Australia seeks to further develop its capacity for critical mineral production and supply to the world, a number of mineral systems and deposit types hosting these minerals could be considered (as outlined previously). The mineralising systems are, in many cases, already extensively mined for their major metals. Their widespread distribution suggests possible flexibility in the development of future infrastructure and supply chains for a number of them. The strong growth in demonstrated resources suggests growth also in Australia's endowment of extractable companion minerals, and increased host metal production suggests greater processing capacity for the by- or co-products.

5 AUSTRALIA'S METAL AND MINERAL PRODUCTION

5.1 Current Metals and Minerals Production, Exports and Imports

The Australian mining industry has a strong presence across most of the conventional metallic and mineral commodities, often making an important contribution to global metal and mineral production. A summary of Australia's 2017 mine production, exports, imports and financial value for various commodities is shown in Table 5.1. Iron ore is clearly dominant (59.7% of mine value), followed by gold (12.7%), base metals (copper, lead, zinc, nickel; 11.4%), bauxite-alumina (9.9%) and a range of other minor commodities.

Table 5.1 Conventional commodities—2017 Australian mine production, exports and imports (sorted by export value).

Commodity	Mine Production		Exports		Imports		Reference(s)
	Tonnes	$ million	Tonnes	$ million	Tonnes	$ million	
Iron Ore	883 356 738	73 244.0	827 185 688	63 101.9	344 454	26.2	[1]
Gold	292.27	15 625.7	318.39	16 890.5	104.74	5581.9	[1]
Copper metal	859 811	6897.7	354 123	7624.4	0	0	[1]
Copper conc.	3 278 461		1 774 686				
Alumina	20 485 770	8628.6	17 872 292	7527.8	10 594	14.1	[1]
Aluminium	1 487 324	3851.4	1 302 882	3373.8	50 700	137.8	[1]
Nickel	178 853	2408.9	204 381	2444.9	5672	76.4	[1]
Zinc metal	840 989	3220.6	435 246	1631.2	0	0	[1]
Zinc conc.	1 975 136		1 551 487	1799.7			
Iron & Steel	5 335 000	12 584.8	2 347 668	1739.7	2 306 222	2831.1	[1]
Lead metal	459 487	1390.4	345 636	1596.8	0	0	[1]
Lead conc.	708 382		154 767				
Bauxite	87 898 589	3551.5	27 199 111	1099.0	5789	2.6	[1]
Zircon conc.	345 075	343.4	687 359	684.0	nd	nd	[1] [2] [3] [8] [9]
Uranium	6301	501.8	7414	590.4	0	0	[1]
Diamonds	17 135 000	562.9	16 265 706	534.3	1 686 490	572.2	[1]
HMS-Synthetic Rutile	nd	nd	428 433	373.7	nd	nd	[1] [3]
Silver	1120.2	803.5	513.0	369.3	148.6	106.6	[1]
HMS-Rutile conc.	160 265	184.0	261 744	300.6	nd	nd	[1] [2] [3] [8] [9]
HMS-Ilmenite conc.	504 229	80.9	1 313 890	247.7	nd	nd	[1] [2] [3] [8] [9]
Tin	7402	195.3	6989	164.1	263	6.9	[1]
HMS-Leucoxene conc.	12 569	10.9	154 037	129.6	nd	nd	[1] [2] [3] [8] [9]
Antimony	3115	36.1	nd	nd	nd	nd	[6] [4]
Barite	8957	2.4	nd	nd	nd	nd	[2]
Cobalt	4971	375.6	nd	nd	nd	nd	[3]
HMS-Garnet	363 573	100.2	nd	nd	nd	nd	[3] [10]
Lithium	18 700	341.2	nd	nd	nd	nd	[4]
Manganese Ore	5 906 298	3407.9	nd	nd	nd	nd	[7] [3] [11]
Phosphate Rock	1 034 957	101.9	nd	nd	431 281	52.8	[1] [9]
Platinum+Palladium	765.2	25.5	nd	nd	nd	nd	[3]
REE & Yttrium	2000	565.9	nd	nd	nd	nd	[4]
Tungsten [A]	245 [A]	4.8 [A]	nd	nd	nd	nd	[5] [9]
Tantalum [B]	nd [B]	nd [B]	nd [B]	nd [B]	nd [B]	nd [B]	
	Total	$122 611.6		$112 223.4		$9270.7	

Notes: conc. = concentrates; nd = no data; HMS = heavy mineral sands; if local prices were not published, export prices were used to estimate local value; mine production was valued by multiplying metal production by market price (unless specific data had been published); [A] Data is mixed 2016 and 2017 data due to lack of available reporting; [B] Although tantalum is produced at Greenbushes (WA), no specific data are available (WA group tantalum with lithium and only report total value and not individual metal production data).

References: [1] Office of the Chief Economist (2018); [2] Lavingdale (2018); [3] Western Australian Department of Mines, Industry Regulation and Safety (2018); [4] United States Geological Survey (2018); [5] Tasmania Mines Ltd (var.); [6] Mandalay Resources Ltd (2018); [7] South32 Ltd (var.); [8] 2016/17 data (Earth Resources Regulation Victoria, 2018); [9] Queensland Department of Natural Resources & Mines (2017); [10] 2015 data (de Garis, 2017).

Table 5.2 shows 2017 data on locally produced concentrates and refined metals along with exports of concentrates (or intermediate products) and refined metals. About 80% of nickel concentrates are smelted or refined to intermediate or refined products locally; half of copper and lead concentrates are smelted and refined locally; one-quarter of zinc concentrates are refined locally; and no tin concentrates are smelted locally.

Table 5.2 Australian production and exports (2017) of metal concentrates and refined metals (all data Office of the Chief Economist, 2018).

Commodity	Local Production			Exports				
	Concentrates		Refined	Concentrates			Refined in Australia	
	Tonnes	Grade	t metal	Tonnes	Grade[A]	$ million	Tonnes	$ million
Copper	3 278 461	26.23% Cu	386 249	1 774 686	29.14% Cu	4782.4	354 123	2842.0
Lead	708 382	64.86% Pb	168 300	154 767	64.86% Pb [A]	442.2	345 636 [B]	1154.6 [B]
Zinc	1 975 136	42.58% Zn	462 095	1 551 487	42.58% Zn [A]	1799.7	435 246	1631.2
Nickel	1 166 683 [C]	15.33% Ni [C]	140 712 [D]	172 326	15.33% Ni [C]	274.7	173 364	2170.3
Tin	13 408 [E]	55.20% Sn [E]	-	12 661	55.20% Sn [E]	164.1	-	-

Notes: [A] If specific data is not reported, the grade of exported concentrates are assumed to be the same as those produced locally; [B] Combined lead bullion and refined lead; [C] Based on reported company data (including historical data); [D] Includes smelter intermediate products and class 1 & 2 refined nickel; [E] Australian tin concentrate data not reported, only data for exported tin concentrate—hence export concentrate grades are used to estimate local concentrate production based on reported mine production of 7402 t Sn.

5.2 Potential Critical Minerals Production

Based on current smelting and refining capacity (Table 5.2), it is possible to develop rough estimates of the potential critical minerals production in Australia. This report adopts typical concentrations found in base metal concentrates or host mineralisation (based on available technical literature or other data) and applies conservative recovery rates to estimate the potential annual production of various critical minerals, presented in Table 5.3. These estimates are largely theoretical, as the actual production of critical minerals as by-products may be limited by technical, social, economic and environmental factors that can vary for each mine or processing facility.

Table 5.3 Estimates of critical minerals potentially derived from current refineries of zinc, copper and alumina.

Commodity	Refined Zinc	Concentration	Basis	Reference
	Tonnes	mg/kg		
Zinc	462 095			
Indium	26.4	-	54.0 g In/t Zn recovered at refineries (~33% recovery)	USGS (2018)
Cadmium	1085	1500–3000	1 000 mg/kg recoverable Cd (~33% recovery)	Sinclair (2005)
Gallium	54.3	0–200	50 mg/kg recoverable Ga (~25% recovery)	Sinclair (2005)
Germanium	27.1	0–100	25 mg/kg recoverable Ge (~25% recovery)	Sinclair (2005)
Antimony	271	1000–1000	250 mg/kg recoverable Sb (~25% recovery)	Sinclair (2005)

Commodity	Refined Copper	Concentration	Basis	Reference
	Tonnes	mg/kg		
Copper	386 249			
Tellurium	2.3		6 g Te/t Cu recovered at refineries [A]	USGS (2018)
Selenium	1473	~1 000–3 000	1 000 mg/kg recoverable Se (~33% recovery)	Mudd data & estimates

Notes: [A] Tellurium data is only up to 2003, value assumed based on historical ratios.

Commodity	Refined Alumina	Basis	Reference
	Tonnes		
Alumina	20 485 770		
Gallium	410	20 mg/kg Ga recoverable in alumina	USGS (2018)

Australia could also derive additional value from critical minerals contained in exported concentrates and mineral products. Presented in Table 5.4 are the preliminary estimates developed of the potential critical minerals in currently exported volumes of mineral concentrates and processed mineral products.

There are additional opportunities that are not identified in this analysis that could be pursued, such as chromite, PGEs, vanadium, phosphate rock and tungsten. Some of these projects rely on new mines (e.g. Dubbo-Toongi, SCONI), which are under active assessment by owner companies, whilst some are now at pilot stage such as Browns Range which opened its pilot plant in July 2018 to begin producing a xenotime-based heavy REE concentrate product (especially dysprosium, terbium). Other critical mineral production could be secured through additional separation and marketing of products from existing mines (e.g. REE from monazite mined at existing heavy mineral sands mines, see Mudd & Jowitt, 2016, or new separation technology at Olympic Dam) or from smelters and refineries (e.g. indium, gallium and germanium from zinc refineries, gallium from alumina refineries). Any new sources of critical minerals would need to take account current market conditions (especially supply competitors), expected production costs (which are very poorly published externally by current producing companies), and link these to future trajectories for the numerous demands driven by the increasing use of many technologies (e.g. renewable energy, energy battery storage, consumer electronics, military applications, specialty alloys, chemicals, etc.).

Table 5.4 Estimates of critical minerals potentially derived from 2017 exports of zinc, copper and aluminium concentrates.

Commodity	Zinc Concentrates	Concentration	Basis	Reference
	Tonnes	mg/kg		
Zinc	1 551 487			
Indium	35.7	-	54.0 g In/t Zn recovered at refineries	USGS (2018)
Cadmium	1085	1500–3000	1 000 mg/kg recoverable Cd (~33% recovery)	Sinclair (2005)
Gallium	77.6	0–200	50 mg/kg recoverable Ga (~25% recovery)	Sinclair (2005)
Germanium	38.8	0–100	25 mg/kg recoverable Ga (~25% recovery)	Sinclair (2005)
Antimony	388	1000–1000	250 mg/kg recoverable Sb (~25% recovery)	Sinclair (2005)

Commodity	Copper Concentrates	Concentration	Basis	Reference
	Tonnes	mg/kg		
Copper	1 774 686			
Tellurium	2.9		6 g Te/t Cu recovered at refineries [A]	USGS (2018)
Selenium	1775	~1000–3000	1 000 mg/kg recoverable Se (~33% recovery)	Mudd data & estimates

Notes: [A] Tellurium data is only up to 2003, value assumed based on historical ratios.

Commodity	Tonnes	Basis	Reference
Bauxite	27 199 111		
Alumina	17 872 292		
Bauxite-Gallium	544	20 mg/kg Ga recoverable in bauxite	USGS (2018)
Alumina-Gallium	357	20 mg/kg Ga recoverable in alumina	USGS (2018)

6 FUTURE RESEARCH NEEDS

This study has synthesised a wide array of data concerning primary metals and minerals production and discussed how this relates to the potential for generating additional value from critical minerals in Australia. This section summarises the key issues affecting the future of critical minerals in Australia, and outlines a range of areas that warrant further investigation.

Mining companies rarely report potential resources of critical minerals as they focus on their major commodities, which are material to their businesses, even in cases where they actually produce critical mineral by-products. This means that alternative methods are necessary to infer the potential grades of these by-products, using the available information reported in technical reports, annual reports or other company disclosures. Given the strong mineralogical relationships between base metals and their potential by-products, it is possible to identify relationships between base metal and by-product metal grades. For example, previous studies have shown that average indium grades can be inferred from Zn, Cu, and Sn in mineral deposits, or Ga grades from the presence of Zn and Al (Werner et al., 2017a). This approach of inferring critical minerals grades in mineral deposits can be further supported with data from geochemical databases, which provide a good basis for analysing the relationships between elements in different geological settings. As an example, Figure 6.1 illustrates the relationship between tin and indium. Similar relationships can be developed for critical mineral and core commodity pairs (e.g. rhenium and molybdenum, zinc and indium) thereby allowing the estimate of a critical minerals grade and potentially extractable resource.

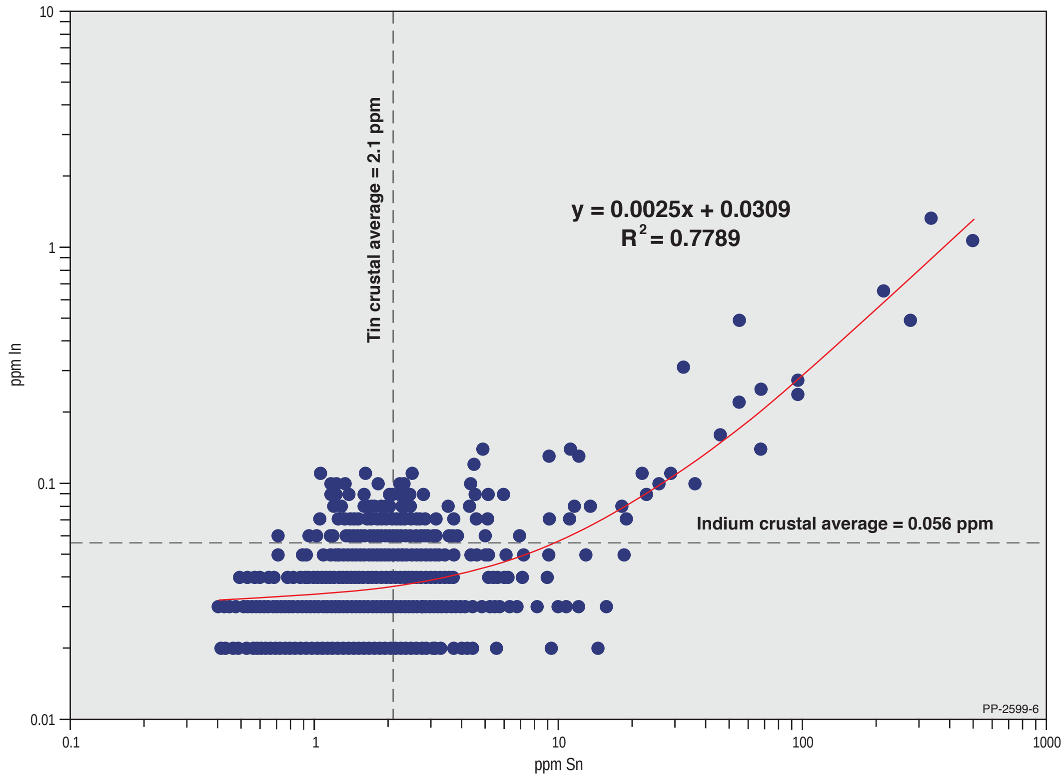

Figure 6.1 Example of the use of geochemical data and regression between primary metal (tin, or Sn) and critical metal (indium, or In) (Werner et al., 2017a).

Research on indium in Australia has shown that globally significant quantities of indium have accumulated in mining and mineral processing wastes in Australia (Werner et al., 2015, 2018). These studies relied extensively on Canadian data, which links critical minerals concentrations to major metal grades, to determine recovery rates during metallurgical processes (publicly available critical mineral behaviour in ore data and studies are extremely rare). It is sometimes possible to find useable data in company technical reports (for example those produced under the Canadian National Instrument NI 43-101 technical reports), however not all such reports provide critical mineral behaviour in ore information. Also, Australia does not have the same approach as Canada, with the JORC code not requiring the public release of technical reports and studies, which underpin reported mineral resources and mining operations. More research is needed to understand the complete ‘life cycle’ of the critical minerals from their behaviour within ores through mineral processing and extraction to waste products. Once this information becomes available, the potential volumes of critical minerals recoverable from ores, concentrates, wastes, will be quantifiable.

Based on the work to date, the following research is recommended in the short, medium and long-term to fully realise critical minerals opportunities in Australia.

Short Term (1–4 years)

- **Improve critical minerals knowledge base:** few data are available on critical mineral contents within Australia's mineral deposits and from mine products (ores, concentrates, tailings, etc.); deficiencies in this knowledge base could be addressed through a dedicated sampling and analysis program undertaken in consultation with industry.
- **Improve geochemical association models:** there is a need to extend statistical analyses of geochemical associations of critical minerals to major commodities in various ore deposit types in order to estimate critical mineral concentrations in ore resources; this information is crucial to inform potential value and supply options.
- **Improve estimation of production costs:** given the sparse extent of published information on the production costs of critical minerals (e.g. capital and operating costs), considerable research is required to establish likely costs for the numerous critical minerals in order to understanding the minimum size of viable critical mineral deposits and barriers to entry into this sector.
- **Undertake consumer and supplier mineral criticality assessments for Australia:** robust and updatable criticality assessments from the perspective of the Australian consumers and suppliers would improve Australia's ability to maximise future potential in the critical minerals global economy.

Medium Term (4–8 years)

- **Undertake critical mineral systems studies:** In order to maintain a pipeline of critical mineral projects for development it would be beneficial to undertake mineral systems studies. Mineral systems studies support exploration through better understanding of critical mineral potential, aimed at improving discovery of critical minerals in Australia to position industry to lead the world in critical mineral exploration.
- **Model supply scenarios:** at present there are no reliable scenarios for the supply potential of critical minerals that link actual mineral resource and mining data with growing technological demands (e.g. renewable energy, battery storage, electronics, alloys); there remains a crucial need to develop scenarios that link resources of critical minerals to the various economic opportunities created by demands for critical minerals; conversely examination of market collapse driven by oversupply or changing technologies is also needed (e.g. transition to electric cars could result in decrease demand for PGEs used in catalytic converters). This modelling will position the critical minerals sector into the future and improve responsiveness to changing markets.
- **Increase awareness of critical minerals opportunities for smelters/refineries:** as much of the production of critical minerals relies on smelters or refineries, there is an opportunity for Australian smelters and refineries to produce more critical minerals by-products; the proposed addition of a germanium and indium capability at the Risdon zinc refinery in Tasmania is one example.
- **Improve understanding of the metallurgical behaviour of critical minerals during ore processing:** there is very little research to understand the behaviour of almost all critical minerals during mineral processing, smelting and refining to improve recovery and value of critical minerals.
- **Develop methods to recover critical minerals from mine waste:** tailings, smelter and refinery slags or residues are a potential source of critical minerals but extraction methods from these mine wastes requires more research.
- **Improve processing technology:** new research into economically viable processing techniques by the Mining Equipment, Technology and Services (METS) sector for the extraction of diverse critical minerals would benefit Australia and position this sector as a global leader. This work is already underway for the emerging demand for battery metals and minerals.

Long Term (8+ years)

- **Conduct material flow analyses (MFA's):** detailed MFA studies on almost all critical minerals are needed to improve the robustness of criticality assessments; MFA's are also fundamental in understanding policy options for demand, supply, use and recycling.

7 SUMMARY

There are growing global technological demands and uses of critical minerals (e.g. in renewable energy, consumer electronics, energy storage, military hardware) and Australia has the potential to become a major global supplier. Some current barriers to reaching this potential in Australia are: insufficient knowledge of critical minerals in deposits and their behaviour during metallurgical processing due to limited reporting by industry; few geological studies dedicated to assessing and facilitating the discovery of critical mineral resources; the need for new mining technology and services to economically extract critical minerals; and gaps in capabilities of domestic smelters/refineries to process critical minerals.

This report recommends short, medium and long term research to support the full realisation of critical minerals opportunities in Australia. In the short term recommendations include: improving the critical minerals knowledge base, improving geochemical association models, improving estimation of production costs, and undertaking consumer and supplier mineral criticality assessments for Australia. In the medium term: undertaking critical mineral systems analysis, modelling supply scenarios, increasing awareness of critical minerals opportunities for smelters/refineries, improving understanding of the metallurgical behaviour of critical minerals during ore processing, develop methods to recover critical minerals from mine waste and improving processing technology. And in the long term: conducting material flow analyses.

By addressing these challenges, it is possible to add significant additional value to Australia's existing minerals industries, as well as Australia's mineral product exports and the mining equipment, technology and services sector. Australia is currently one of the world's principal producers of several key major mineral commodities (e.g. bauxite, coal, copper, lead, gold, ilmenite, iron ore, nickel, rutile, zircon, and zinc). Although some critical minerals are mined as primary products, many critical minerals are extracted as companion products from base or precious metal production. Considering Australia's leading expertise in mining and processing as well as extensive mineral resources likely to contain critical minerals, there is potential for Australia to develop into a supplier of critical minerals into the future.

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REFERENCES

Alkane Resources Ltd. 2017. Annual Report 2017. Alkane Resources Ltd, Perth, WA, 96 p.

British Geological Survey. 2015. Risk List 2015—Current Supply Risk for Chemical Elements or Element Groups Which Are of Economic Value. British Geological Survey, Nottingham, United Kingdom, 11 p.

Ciacci, L., Nuss, P., Reck, B. K., Werner, T. T., & Graedel, T E. 2016. Metal Criticality Determination for Australia, the US, and the Planet - Comparing 2008 and 2012 Results. Resources, 5, 8.

de Garis, P. 2017. Engebø Rutile and Garnet Project—Prefeasibility Study. Prepared by Hatch (Africa) Pty Ltd for Nordic Mining ASA, Oslo, Norway, 30 Oct. 2017, 361 p.

Dewulf, J., Blengini, G. A., Pennington, D., Nuss, P., & Nassar, N. T., 2016. Criticality on the International Scene: Quo vadis? Resources Policy, 50, 169–176.

Duclos SJ. Testimony before the Subcommittee on Investigations and Oversight of the House Committee on Science and Technology. Feb 10, 2010. [accessed Nov, 2018]. 2010. [online]. Available: *https://science.house.gov/sites/republicans.science.house.gov/files/documents/hearings/031610_Duclos.pdf*.

Earth Resources Regulation Victoria, 2018, 2016–17 Statistical Report. Earth Resources Regulation, Victorian Department of Economic Development, Jobs, Transport & Resources, Melbourne, Victoria, 26 p.

European Commission, 2014, Critical Raw Materials for the EU - Report of the Ad-Hoc Working Group on Defining Critical Raw Materials. European Commission, Brussels, Belgium, May 2014, 41 p, http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/report-b_en.pdf, accessed 25/09/2015.

European Commission, 2015, Report on Critical Raw Materials for the EU: Critical Raw Materials Profiles. DG Enterprise & Industry, European Commission, Brussels, Belgium, Ref. Ares(2015)3396873 - 14/08/2015, 205 p.

European Commission, 2017, The 2017 List of Critical Raw Materials for the EU. DG Enterprise & Industry, European Commission, Brussels, Belgium, 8 p.

Fortier, S. M., Nassar, N. T., Lederer, G. W., Brainard, J., Gambogi, J., & McCullough, E. A.. 2018. Draft Critical Mineral List - Summary of Methodology and Background Information. United States Geological Survey Open-File Report 2018–1021, 15 p.

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., & Rebitzer, G. 2005. The Ecoinvent Database: Overview and Methodological Framework. International Journal of Life Cycle Assessment, 10, 3–9.

Goedkoop, M. J., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & Van Zelm, R. 2009. ReCiPe 2008: A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level—Report I: Characterisation. First Edition, 6 January 2009, http://www.lcia-recipe.net.

Graedel, T. E., Barr, R., Chandler, C., Chase, T., Choi, J., Christoffersen, L., Friedlander, E., Henly, C., Jun, C., Nassar, N. T., Schechner, D., Warren, S., Yang, M.-Y. & Zhu, C. 2012. Methodology of Metal Criticality Determination. Environmental Science & Technology, 46, 1063–1070.

Greenfield, A., & Graedel, T. E. 2013. The Omnivorous Diet of Modern Technology. Resources. Conservation & Recycling, 74, 1–7.

Gunn, G. (Ed.). 2014. Critical Metals Handbook, John Wiley & Sons, Chichester, West Sussex, United Kingdom, 454 p.

Harding, R. H. 1992. Wholeheartedly and At Once: A History of the First Operation of Mary Kathleen Uranium Ltd 1954–1964. CRA Ltd, Melbourne, Victoria, 205 p.

Huijbregts, M A, Steinmann, Z J N, Elshout, P M F, Stam, G, Verones, F, Vieira, M, Zijp, M, Hollander, A & van Zelm, R, 2017, ReCiPe2016: A Harmonised Life Cycle Impact Assessment Method at Midpoint and the Endpoint Level. International Journal of Life Cycle Assessment, 22 (2), 138–147.

Huston D. L., Brauhart, C. 2017. Critical commodities in Australia: an assessment of extraction potential from ores. Record 2017/14. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2017.014

International Resource Panel (ed.). 2017. Green Technology Choices: The Environmental and Resource Implications of Low-Carbon Technologies. International Resource Panel, United Nations Environment Programme, Nairobi, Kenya.

Johnson Matthey Plc. 2018. PGM Market Report February 2018. Johnson Matthey Plc, Hertfordshire, United Kingdom, February 2018, 40 p.

Lavingdale, M. 2018. South Australian Mineral Resource Production Statistic for the Six Months Ended 31st December 2017. Resources & Energy - Department of State Development, South Australia, Adelaide, Australia, Report Book 2017/00014, 8 p.

Mandalay Resources Ltd. 2018. Management's Discussion and Analysis for the year ended December 31, 2017. Mandalay Resources Ltd, Melbourne, Victoria, 29 March 2018.

Mudd, G. M. 2009. The Sustainability of Mining in Australia: Key Production Trends and Their Environmental Implications for the Future. Department of Civil Engineering, Monash University and Mineral Policy Institute, Melbourne, Victoria, October 2007; Revised April 2009, 277 p.

Mudd, G. M. 2010. The Environmental Sustainability of Mining in Australia: Key Mega-Trends and Looming Constraints. Resources Policy, 35, 98–115.

Mudd, G. M. 2014. The Future of Yellowcake: A Global Assessment of Uranium Resources and Mining. Science of the Total Environment, 472, 590–607.

Mudd, G. M., & Jowitt, S. M. 2016. Rare Earth Elements From Heavy Mineral Sands: Assessing the Potential of a Forgotten Resource. Applied Earth Science (Trans. Inst. Min. Metall. B), 125, 107–113.

Mudd, G. M., & Jowitt, S. M. 2018. Growing Global Copper Resources, Reserves and Production: Discovery is Not the Only Control on Supply. Economic Geology, In Press.

Mudd, G. M., Jowitt, S. M., & Werner, T. T. 2017. The World's By-Product and Critical Metal Resources Part I: Uncertainties, Current Reporting Practices, Implications and Grounds for Optimism. Ore Geology Reviews, 86, 924–938, doi:10.1016/j.oregeorev.2016.05.001.

Mudd, G. M., Jowitt, S. M., & Werner, T. T. 2018. Global Platinum Group Element Resources, Reserves and Mining - A Critical Assessment. Science of the Total Environment, 622–623, 614–625.

Mudd, G. M., Weng, Z., Jowitt, S. M., Turnbull, I. D. & Graedel, T. E., 2013, Quantifying the Recoverable Resources of By-Product Metals: The Case of Cobalt. Ore Geology Reviews, 55, 87–98.

Mudd, G. M., Yellishetty, M., Reck, B. K., & Graedel, T. E. 2014. Quantifying the Recoverable Resources of Companion Metals: A Preliminary Study of Australian Mineral Resources. Resources, 3, 657–671.

Nassar, N. T., Graedel, T. E., & Harper, E. M. 2015. By-Product Metals are Technologically Essential but Have Problematic Supply. Science Advances, 1, e1400180, 10 p,

Office of the Chief Economist. 2018. Resources and Energy Quarterly—June Quarter 2018. Office of the Chief Economist, Department of Industry, Innovation and Science, Australian Government, Canberra, ACT, 124 p.

Queensland Department of Natural Resources & Mines. 2017. Queensland's Metalliferous and Industrial Minerals 2016. Queensland Department of Natural Resources & Mines, Brisbane, Queensland, 98 p.

Sinclair, R. J. 2005. The Extractive Metallurgy of Zinc. Australasian Institute of Mining and Metallurgy, Spectrum Series Volume Number 13, Melbourne, Australia, 297 p.

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, Australia, 128 p.

South32 Ltd. var. Quarterly Reports to the Australian Securities Exchange. South32 Ltd, Melbourne, Victoria.

Tasmania Mines Ltd. var. Quarterly Reports to the Australian Securities Exchange. Tasmania Mines Ltd, Hobart, Tasmania.

United States Geological Survey, 2018. Mineral Commodity Summaries 2018. United States Geological Survey, Reston, Virginia, USA, 204 p, minerals.usgs.gov/minerals/pubs/mcs/.

United States National Research Council. 2008. Minerals, Critical Minerals and the US Economy. Committee on Critical Mineral Impacts on the U.S. Economy & Committee on Earth Resources, National Research Council of the National Academies, Washington DC, USA, 263 p.

Verplanck, P L & Hitzman, M W (Ed's), 2016, Rare Earths and Critical Elements in Ore Deposits. Reviews in Economic Geology, Society of Economic Geologists, Volume 18, Littleton, Colorado, USA, 372 p.

Western Australian Department of Mines, Industry Regulation and Safety. 2018. Western Australia Mineral and Petroleum Statistics Digest 2016/17. Western Australian Department of Mines, Industry Regulation and Safety, Perth, Western Australia, 65 p.

Weng, Z., Jowitt, S. M., Mudd, G. M., & Haque, N. 2015. A Detailed Assessment of Global Rare Earth Resources: Opportunities and Challenges. Economic Geology, 110, 1925–1952.

Werner, T. T., Ciacci, L., Mudd, G. M., Reck, B. K., & Northey, S. A. 2018. Looking Down Under for a Circular Economy of Indium. Environmental Science & Technology: doi: 10.1021/acs.est.7b05022.

Werner, T. T., Mudd, G. M., & Jowitt, S. M. 2015. Indium: Key Issues in Assessing Mineral Resources and Long Term Supply From Recycling. Applied Earth Science (Trans. Inst. Min. Metall. B), 124, 213–226.

Werner, T. T., Mudd, G. M., & Jowitt, S. M. 2017a. The World's By-Product and Critical Metal Resources Part II: A Method for Quantifying the Resources of Rarely Reported Metals. Ore Geology Reviews, 80, 658–675.

Werner, T. T., Mudd, G. M., & Jowitt, S. M. 2017b. The World's By-Product and Critical Metal Resources Part III: Indium. Ore Geology Reviews, 86, 939–956.

World Nuclear Association, 2018, World Uranium Mining Production. London, UK, Last Updated—July 2018, www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx (accessed 24 September 2018).

Yellishetty, M., Huston, D., Graedel, T. E., Werner, T. T., Reck, B. K., & Mudd, G. M. 2017. Quantifying the Potential for Recoverable Resources of Gallium, Germanium and Antimony as Companion Metals in Australia. Ore Geology Reviews, 82, 148-159.

APPENDICES

Source: Geoscience Australia (Britt, Hitchman and Skirrow), unpublished, 2018.

APPENDIX A

A.1 US Import Reliance on Critical Minerals

Appendix Table A.1 US Import Reliance and Australian Geological Potential for Critical Minerals

Commodity	US Import Reliance (%)	Import Source
GALLIUM	100	China, Germany, United Kingdom, Ukraine
INDIUM	100	Canada, China, France, Republic of Korea
MANGANESE	100	South Africa, Gabon, Australia, Georgia
NIOBIUM (columbium)	100	Brazil, Canada, Russia
RARE EARTHS	100	China, Estonia, France, Japan
SCANDIUM	100	China
TANTALUM	100	Brazil, Rwanda, Australia, Canada
YTTRIUM	100	China, Estonia, Japan, Germany
TITANIUM MINERAL CONCENTRATES	91	South Africa, Australia, Canada, Mozambique
URANIUM (natural)	89	Canada, Kazakhstan, Australia, Russia
BAUXITE	>75	Jamaica, Brazil, Guinea, Guyana
COBALT	72	Norway, China, Japan, Finland
CHROMIUM	69	South Africa, Kazakhstan, Russia
PLATINUM (PGE)	68	South Africa, Germany, United Kingdom, Russi
ALUMINIUM	61	Canada, Russia, United Arab Emirates, China
TITANIUM (sponge)	53	Japan, China, Kazakhstan, Ukraine
GERMANIUM	>50	China, Belgium, Russia, Germany
HAFNIUM	<50	Germany, France, United Kingdom, China
LITHIUM	>50	Chile, Argentina, China
ZIRCONIUM MINERAL CONCENTRATES	<50	South Africa, Australia, Senegal
PALLADIUM (PGE)	45	South Africa, Russia, Italy, United Kingdom
ALUMINA	37	Australia, Suriname, Brazil, Jamaica
VANADIUM	100	Czechia, Austria, Canada, Republic of Korea
GRAPHITE (natural)	100	China, Mexico, Canada, Brazil
BISMUTH	96	China, Belgium, Peru
POTASH	92	Canada, Russia, Israel, Chile
ANTIMONY (oxide)	85	China, Belgium, Bolivia
RHENIUM	80	Chile, Belgium, Germany, Poland
TIN	75	Peru, Indonesia, Malaysia, Bolivia
TUNGSTEN	>50	China, Canada, Bolivia, Germany
MAGNESIUM COMPOUNDS	47	China, Canada, Australia, Brazil
BERYLLIUM	14	Kazakhstan, Japan, Brazil, United Kingdom
ARSENIC	100	Morocco, China, Belgium
CESIUM (RUBIDIUM)	100	Canada
FLUORSPAR	100	Mexico, China, South Africa, Vietnam
STRONTIUM	100	Mexico, Germany, China
TELLURIUM	>75	Canada, China, Belgium, Phillipines
BARITE	>75	China, India, Mexico, Morocco

Australian Geological Potential

- High
- Moderate
- Low

Notes:

1. Australian geological potential for discovery and supply of critical minerals has been ranked as high, moderate or low. These rankings are based on current understanding of known deposits, geology and potential for new discoveries, and build on the assessment by Geoscience Australia in Skirrow et al. (2013). Australia already supplies some critical minerals to the USA but has great potential to be a source of new critical minerals of strategic and economic interest.

Appendix Table A.2 US Import Reliance by Source of Critical Minerals

Source (2013–16)	# Critical Minerals	Imported Critical Minerals
China	21	ARSENIC (trioxide), FLUORSPAR, GALLIUM, GRAPHITE (natural), INDIUM, RARE EARTHS, SCANDIUM, STRONTIUM, YTTRIUM, BISMUTH, ANTIMONY (oxide), BARITE, COBALT, ALUMINUM, TITANIUM (sponge), GERMANIUM, LITHIUM, TUNGSTEN, MAGNESIUM COMPOUNDS, TELLURIUM, HAFNIUM
Canada	13	CESIUM, GRAPHITE (natural), INDIUM, NIOBIUM (columbium), TUNGSTEN, TELLURIUM, URANIUMTANTALUM, VANADIUM, POTASH, TITANIUM MINERAL CONCENTRATES, ALUMINUM, MAGNESIUM COMPOUNDS
Germany	8	GALLIUM, STRONTIUM, YTTRIUM, RHENIUM, PLATINUM, GERMANIUM, TUNGSTEN, HAFNIUM
Russia	8	NIOBIUM (columbium), POTASH, CHROMIUM, PLATINUM, ALUMINUM, GERMANIUM, PALLADIUM, URANIUM
Australia	7	MANGANESE, TANTALUM, TITANIUM MINERAL CONCENTRATES, ZIRCONIUM MINERAL CONCENTRATES, MAGNESIUM COMPOUNDS, ALUMINA, URANIUM
Brazil	7	GRAPHITE (natural), NIOBIUM (columbium), TANTALUM, BAUXITE, MAGNESIUM COMPOUNDS, ALUMINA, BERYLLIUM
South Africa	7	FLUORSPAR, MANGANESE, TITANIUM MINERAL CONCENTRATES, CHROMIUM, PALLADIUM, PLATINUM, ZIRCONIUM MINERAL CONCENTRATES
Belgium	6	ARSENIC (trioxide), BISMUTH, ANTIMONY (oxide), RHENIUM, GERMANIUM, TELLURIUM
Japan	5	RARE EARTHS, YTTRIUM, COBALT, TITANIUM (sponge), BERYLLIUM
United Kingdom	5	GALLIUM, PLATINUM, PALLADIUM, BERYLLIUM, HAFNIUM
Mexico	4	FLUORSPAR, GRAPHITE (natural), STRONTIUM, BARITE
Kazakhstan	4	CHROMIUM, TITANIUM (sponge), BERYLLIUM, URANIUM
Bolivia	3	ANTIMONY (oxide), TIN, TUNGSTEN
Chile	3	POTASH, RHENIUM, LITHIUM
France	3	INDIUM, RARE EARTHS, HAFNIUM
Estonia	2	RARE EARTHS, YTTRIUM
Jamaica	2	BAUXITE, ALUMINA
Morocco	2	ARSENIC (trioxide), BARITE
Peru	2	BISMUTH, TIN
Republic of Korea	2	INDIUM, VANADIUM
Ukraine	2	GALLIUM, TITANIUM (sponge)
Suriname	1	ALUMINA
Argentina	1	LITHIUM
Poland	1	RHENIUM
Austria	1	VANADIUM
Czechia	1	VANADIUM
Finland	1	COBALT
Gabon	1	MANGANESE
Georgia	1	MANGANESE
Guinea	1	BAUXITE
Guyana	1	BAUXITE
India	1	BARITE
Indonesia	1	TIN
Israel	1	POTASH
Rwanda	1	TANTALUM
Italy	1	PALLADIUM
Malaysia	1	TIN
Mozambique	1	TITANIUM MINERAL CONCENTRATES
Norway	1	COBALT
Senegal	1	ZIRCONIUM MINERAL CONCENTRATES
United Arab Emirates	1	ALUMINUM
Vietnam	1	FLUORSPAR
Phillipines	1	TELLURIUM

A.2 Use for each Critical Mineral in the United States

Antimony

In 2017, the United States consumed 25 kt of antimony, 85% of which was imported. Non-metal products such as ceramics, glass, paint, enamels and rubber accounted for 31% of consumption, flame retardants for another 31% and metal products such as ammunition and antimonial lead, which is used to make lead-acid batteries, accounted for the remaining 38%.

Arsenic

In 2017, the United States consumed 7.3 kt of arsenic, was 100% import reliant, with an estimated value of approximately $6.9 million. In 2017, arsenic trioxide was primarily used for treatments to preserve lumber. Arsenic metal was used to strengthen the grids of lead-acid batteries and by the U.S. military for hardening ammunition. Arsenic metal was also used as an antifriction additive for bearings, to harden lead shot, and in clip-on wheel weights. Arsenic compounds were used in herbicides and insecticides. High-purity arsenic was used to produce gallium-arsenide semiconductors for solar cells, space research, and telecommunications. Arsenic also was used for germanium-arsenide-selenide specialty optical materials. Indium-gallium-arsenide was used for short-wave infrared technology.

Barite

In 2016, the United States consumed 1450 kt of barite (2017 data withheld) of which more than 75% was imported. More than 90% was used as a weighting agent in fluids for drilling oil and natural gas wells. Barite is also used as a filler, extender, or weighting agent in paints, plastics, and rubber. Because barite significantly blocks x-ray and gamma-ray emissions, it is used as aggregate in high-density concrete for radiation shielding around x-ray units in hospitals, nuclear power plants, and university nuclear research facilities. Ultrapure barite is used as a contrast medium in x-ray and computed tomography examinations of the gastrointestinal tract.

Bauxite, Alumina, Aluminium

In 2017, the United States consumed 4.2 Mt of bauxite with an estimated value of about $130 million. More than 90% of the bauxite was refined into alumina, and the remainder went to products such as abrasives, cement, chemicals, proppants, refractories, and as a slag adjuster in steel mills. The United States consumed 2400 kt of alumina in 2017, of which 37% was imported. This market is estimated to have a value of approximately $1.08 billion with 60% of the alumina used for aluminium production and the remainder in non-metallurgical products, such as abrasives, ceramics, chemicals, and refractories. The aluminium market in the United States was worth almost $13 billion in 2017 with the country consuming an apparent 5980 kt of metal of which 61% was imported. Transportation applications accounted for an estimated 41% of domestic consumption followed by packaging (20%), building (14%), electrical (8%), machinery (7%), consumer durables (7%) and other (3%).

Beryllium

In 2017, the United States consumed 200 t of beryllium, of which only 14% was imported. Approximately 21% of beryllium products were used in consumer electronics, 19% in industrial components, 14% in automotive electronics, 11% in defence applications, 9% in telecommunications infrastructure, 6% in energy applications, 2% in medical applications, and 18% in other applications. Beryllium alloy strip and bulk products, the most common forms of processed beryllium, were used in all application areas. The majority of unalloyed beryllium metal and beryllium composite products were used in defence and scientific applications.

Bismuth

In 2017, the United States consumed 2080 t of bismuth, was 96% import reliant, with an estimated value of approximately $22 million. About two-thirds of bismuth consumption was for chemicals used in cosmetic, industrial, laboratory, and pharmaceutical applications. Bismuth use in pharmaceuticals includes over-the-counter stomach remedies and burn, intestinal and stomach ulcer treatments. Bismuth has a wide variety of metallurgical applications, including use as a non-toxic replacement for lead in pipe fittings, fixtures, and water meters. Bismuth is used as a triggering mechanism for fire sprinklers and in the manufacture of semiconductor devices.

Cesium

There is no current data on cesium consumption in the United States but it is thought to be only a few thousand kg each year and the country is 100% reliant on imports. Cesium is primarily used for high-pressure, high-temperature oil and gas well drilling. It is also used in the pyrotechnic industry, nuclear medicine, agricultural applications, photoelectrical cells, solar cells, fuel cells, atomic clocks, geophysical instruments and chemical applications.

Chromium

In 2017, the United States consumed 510 kt of chromium, was 69% import reliant, with an estimated value of approximately $679 million. The United States consumes around 6% of world chromite ore production in various forms of imported materials, such as chromite ore, chromium chemicals, chromium ferroalloys, chromium metal, and stainless steel. Stainless steels and superalloys require chromium and stainless-steel and heat-resisting-steel producers were the leading consumers of ferrochromium. Imported chromite ore was also used to produce chromium chemicals and chromium metal.

Cobalt

In 2017, the United States consumed 9830 t of cobalt, was 72% import reliant, with an estimated value of approximately $575 million. About 45% of the cobalt consumed in the United States was used in superalloys, mainly in aircraft gas turbine engines; 7% in cemented carbides for cutting and wear-resistant applications; 17% in various other metallic applications; and 31% in a variety of chemical applications.

Fluorspar

In 2017, the United States consumed 450 kt of fluorspar, was 100% import reliant, with an estimated value of $122 million. Fluorspar is used for producing hydrofluoric acid, which is the primary feedstock for the manufacture of nearly all fluorine-bearing chemicals and is a key ingredient in the processing of aluminium and uranium. Fluorspar was also used in cement production, in enamels, as a flux in steelmaking, in glass manufacture, in iron and steel casting, in welding rod coatings and for water fluoridation.

Gallium

In 2017, the United States consumed 24 t of gallium, was 100% import reliant, with an estimated value of approximately $5 million. Gallium is used in the manufacture of integrated circuits (70% of consumption), including defence applications, high-performance computers, and telecommunications. Optoelectronic devices, such as laser diodes, light-emitting diodes (LEDs), photodetectors, and solar cells, account for around 30% of consumption and are used in aerospace applications, consumer goods, industrial equipment, medical equipment, and telecommunications equipment.

Germanium

In 2017, the United States consumed 30 t of gallium, more than 50% imported, with an estimated value of approximately $41 million. The United States used germanium for fibre optics, infrared optics, electronics and solar applications including solar cells for satellites.

Graphite

In 2017, the United States consumed 24 kt of natural graphite, was 100% import reliant, with an estimated value of approximately $43 million. The major uses of natural graphite in 2017 were brake linings, lubricants, powdered metals, refractory applications, and steelmaking. Future uses are expected to include use in lithium-ion electric vehicle batteries and advances in thermal technology and acid-leaching techniques that enable the production of higher purity graphite powders are likely to lead to development of new applications for graphite in high-technology fields.

Hafnium

Data for hafnium consumption in the United States for 2017 has been withheld but based on the assumption that the 160 t of hafnium imported was consumed then value of the market is approximately $146 million. Hafnium occurs within zirconium so it is also assumed that the United States is less than 50% import reliant, thus the domestic market could be greater. The leading use of hafnium metal is in superalloys. It is also used in the control rods of nuclear reactors, in for removing trave gases from vacuum tubes.

Helium

In 2017, the United States consumed 43 million cubic metres of helium gas worth approximately $660 million. The USA is not reliant on imports and is actually the world's leading helium producer. The primary uses of Grade-A helium in the United States was for magnetic resonance imaging (30%), lifting gas (17%), analytical and laboratory applications (14%), welding (9%), engineering and scientific applications (6%), leak detection (5%), semiconductor manufacturing (5%) and various other minor applications (14%).

Indium

In 2017, the United States consumed 120 t of indium, was 100% import reliant, with an estimated value of approximately $26 million. Production of indium tin oxide (ITO) continued to account for most of global indium consumption. ITO thin-film coatings were primarily used for electrical conductive purposes in a variety of flat-panel displays—most commonly liquid crystal displays (LCDs). Other indium end uses included alloys and solders, compounds, electrical components and semiconductors, and research.

Lithium

In 2017, the United States consumed an estimated 3 kt of lithium and was more than 50% import reliant. Data scarcity makes market value is difficult to estimate but it is thought to be at least $42 million and perhaps as much as $200 million. Most lithium is used in battery production but also for ceramics and glass, lubricating greases, polymer production and air treatment. Lithium consumption for batteries has increased significantly in recent years owing to the growing market for portable electronic devices, electric tools, electric vehicles and grid storage applications for power.

Magnesium

In 2017, the United States consumed 620 kt of magnesium compounds, was 47% import reliant, with an estimated value of approximately $250 million. Magnesium compounds were used in the USA for agricultural, chemical, construction, environmental, and industrial applications (60%) with the remaining 40% used for refractories in the form of dead-burned magnesia, fused magnesia, and olivine.

Manganese

In 2017, the United States consumed 660 kt of manganese, was 100% import reliant, with an estimated value of approximately $940 million. Steel production accounted for most ore consumption as pig iron or ferroalloy manufacture. Manganese was also used for non-metallurgical purposes such as the production of dry cell batteries, in fertilizers and animal feed, and as a brick colourant.

Niobium

In 2017, the United States consumed 9.8 kt of niobium, was 100% import reliant, with an estimated value of approximately $290 million. The steel industry used ferroniobium for enhancing the strength of steel, such as that used in gas pipelines (76%) and the aerospace industry consumed niobium alloys and metal (24%).

Platinum Group Elements (PGEs)

Consumption data for PGEs in the United States in 2017 is unavailable but is estimated to be 165.9 t for platinum and 55 t for palladium, the two main elements. The PGE market in the USA is thought to be worth approximately

$6.5 billion and the country is 68% reliant on platinum imports and 45% on palladium imports. The leading use for PGEs was in catalytic converters to decrease harmful emissions from automobiles. They were also used in catalysts for bulk-chemical production and petroleum refining, in computer hard disks, multilayer ceramic capacitors, hybridized integrated circuits, jewellery, glass manufacturing, laboratory equipment and dental restoratives. Platinum, palladium, and rhodium are also used as a store of value, similarly to gold investments, as exchange-traded products and individual holdings of bars and coins.

Potash

In 2017, the United States consumed 6.1 Mt of potash, was 92% import reliant, with an estimated value of approximately $4.8 billion. Potash denotes a variety of mined and manufactured salts, which contain the element potassium in water-soluble form, necessary for the growth of certain crops. In agriculture, the term potash refers to potassic fertilizers and the fertilizer industry used about 85% of US potash sales. The remainder was used for chemical and industrial applications.

Rare Earth Elements (REEs)

In 2017, the United States consumed 11 kt of REEs, was 100% import reliant, with an estimated value exceeding $150 million. Rare earths have a wide variety of applications particularly for modern, high-end technological applications such as mobile phones and computers. In the USA, REEs were used in catalysts (55%), ceramics and glass (15%), metallurgical applications and alloys (10%), polishing (5%) with the remaining15% going into other applications.

Rhenium

In 2017, the United States consumed 42.6 t of rhenium, was 80% import reliant, with an estimated value exceeding $80 million. The major uses of rhenium were in superalloys used in high-temperature turbine engine components (80%) and in petroleum-reforming catalysts (15%). Rhenium was also used in the production of lead-free gasoline and high-temperature nickel-base superalloys. Rhenium alloys were used in crucibles, electrical contacts, electromagnets, electron tubes and targets, heating elements, ionization gauges, mass spectrographs, metallic coatings, semiconductors, temperature controls, thermocouples and vacuum tubes.

Scandium

Data for scandium consumption in the United States for 2017 is not available and only 10 to 15 tonnes is consumed globally each year. The USA is 100% reliant on imports but the value of the market is thought to be very small. The principal uses for scandium in 2017 were in alloys (sporting goods, aerospace and other high-end applications) and solid oxide fuel cells. Other uses for scandium included ceramics, electronics, lasers (defence and dentistry applications), lighting, and radioactive isotopes.

Strontium

In 2017, the United States consumed 17.2 kt of strontium, 100% imported as celestite and strontium compounds. The value of the US market is unknown but based on celestite prices it might be around $1 million. Celestite is used in the United States as an additive for drilling fluids in the oil and gas industries. Strontium compounds are used in pyrotechnics, signals, magnets, alloys, pigments, fillers, zinc production and glass.

Tantalum

In 2017, the United States consumed 660 t of tantalum, was 100% import reliant, with an estimated value exceeding $240 million. Tantalum was used for the production of tantalum alloys, capacitors, compounds and metal. Major end uses for tantalum capacitors include automotive electronics, mobile phones, and personal computers. Tantalum oxide is used in glass lenses and tantalum carbide is used in cutting tools.

Tellurium

Data for tellurium consumption in the United States for 2017 has been withheld. It is known that USA is more than 75% reliant on imports and the domestic market value is likely in excess of $4 million. Tellurium's main use in the USA is in solar cells. It is also used in steel, lead and copper alloys and in cast iron. The chemical industry uses it for processing rubber and synthetic fibre production. It is used in photoreceptor and thermoelectric applications, in blasting caps and as a pigment for glass and ceramics.

Tin

In 2017, the United States consumed 40.9 kt of tin, was 75% import reliant, with an estimated value of approximately $816 million. The major uses for tin in the United States were chemicals (21%), babbitt, bronze, brass, tinning and other alloys (20%), tinplate (18%), solder (17%), and other (24%).

Titanium

In 2017, the United States consumed 1.1 Mt of titanium mineral concentrates (ilmenite and rutile) and 37 kt of titanium sponge (metal). These markets are valued at $561 million and $318 million, respectively, and the USA is 91% reliant on imports of titanium mineral concentrates and 53% reliant on titanium sponge imports. About 90% of titanium mineral concentrates were consumed by titanium dioxide pigment producers. The remainder was used in welding-rod coatings and for manufacturing carbides, chemicals, and metal. Around 80% of titanium metal was used in aerospace applications. The remaining 20% was used in armour, chemical processing, marine hardware, medical implants, power generation, and consumer and other applications.

Tungsten

Data for tungsten consumption in the United States for 2017 has been withheld. It is known that USA is more than 50% reliant on imports and the domestic market is valued at approximately $500 million. About 55% of the tungsten used in the United States was used in cemented carbide parts for cutting and wear-resistant applications, primarily in the construction, metalworking, mining, and oil and gas drilling industries. Tungsten was used to make various alloys and specialty steels; electrodes, filaments, wires, and other components for electrical, electronic, heating, lighting, and welding applications; and chemicals for various applications.

Uranium

In 2017, the United States consumed 19.5 kt of uranium, was 89% import reliant, with an estimated value of approximately $1.7 billion. The primary use for uranium was for power generation. Uranium is also used in nuclear weapons and as a colourant.

Vanadium

In 2017, the United States consumed 7.9 kt of vanadium, was 100% import reliant, with an estimated value exceeding $91 million. Vanadium is primarily used as an alloying agent for iron and steel, accounted for about 94% of US vanadium consumption in 2017. The major non-metallurgical use was for catalysts to produce maleic anhydride and sulfuric acid.

Yttrium

In 2017, the United States consumed 300 t of yttrium, was 100% import reliant, with an estimated value of approximately $1.2 million. The leading uses of yttrium were in ceramics (abrasives, jet engine coatings, oxygen sensors in cars, corrosion resistant cutting tools), metallurgy (superalloys, high-temperature superconductors), electronics (microwave radar, dental and surgical procedures, digital communications, industrial cutting and welding, photochemistry, distance and temperature sensing) and phosphors (flat-panel displays).

Zirconium

In 2017, the United States consumed 50 kt of zirconium, less than 50% of which was imported, with an estimated value of approximately $48 million. Ceramics, foundry sand, opacifiers and refractories are the leading end uses for zircon. Other end uses of zircon include abrasives, chemicals, metal alloys, and welding rod coatings. The leading consumers of zirconium metal are the chemical process and nuclear energy industries.

References:

United States Mineral Commodity Summaries 2018.

United States Mineral Commodity Summaries 2017.

US Energy Information Administration 2017 Data.

APPENDIX B

B.1 UK and EU Import Reliance on Critical Minerals

Data from the UK Government on critical minerals, import reliance and source countries is sparse. However, one of the most important criteria for criticality is risk of supply. The British Geological Survey has published the assessment listed in Table B.1. A cut-off value of 7.0 applied to the British Geological Survey assessment, results in a list of 23 minerals (platinum and palladium are grouped under PGEs) that have high to very high risk for disrupted supply (Table B.2). This criterion alone does not make that mineral 'critical' but of these minerals the UK is 100% import reliant for all but barium. The EU, conversely, has published extensively on critical minerals in recent years with the European Commission's Critical Mineral Factsheets underpinning this assessment.

Appendix Table B.1 British Geological Survey Risk List 2015

Element or element group	Symbol	Relative supply risk index	Leading producer	Top reserve holder
rare earth elements	REE	9.5	China	China
antimony	Sb	9.0	China	China
bismuth	Bi	8.8	China	China
germanium	Ge	8.6	China	
vanadium	V	8.6	China	China
gallium	Ga	8.6	China	
strontium	Sr	8.3	China	China
tungsten	W	8.1	China	China
molybdenum	Mo	8.1	China	China
cobalt	Co	8.1	DRC	DRC
indium	In	8.1	China	
arsenic	As	7.9	China	
magnesium	Mg	7.6	China	Russia
platinum group elements	PGE	7.6	South Africa	South Africa
lithium	Li	7.6	Australia	Chile
barium	Ba	7.6	China	China
carbon (graphite)	C	7.4	China	China
beryllium	Be	7.1	USA	
silver	Ag	7.1	Mexico	Peru
cadmium	Cd	7.1	China	
tantalum	Ta	7.1	Rwanda	Australia
rhenium	Re	7.1	Chile	Chile
selenium	Se	6.9	Japan	China
mercury	Hg	6.9	China	
fluorine	F	6.9	China	South Africa
niobium	Nb	6.7	Brazil	Brazil
zirconium	Zr	6.4	Australia	Australia
chromium	Cr	6.2	South Africa	Kazakhstan
tin	Sn	6.0	China	China
manganese	Mn	5.7	China	South Africa
nickel	Ni	5.7	Indonesia	Australia
thorium	Th	5.7		USA
uranium	U	5.5	Kazakhstan	Australia
lead	Pb	5.5	China	Australia
iron	Fe	5.2	China	Australia
carbon (diamond)	C	5.2	Russia	Australia
titanium	Ti	4.8	Canada	China
copper	Cu	4.8	Chile	Chile
zinc	Zn	4.8	China	Australia
aluminium	Al	4.8	Australia	Guinea
gold	Au	4.5	China	Australia

Supply risk index runs from 1 (green—very low risk) to 10 (red—very high risk)

Appendix Table B.2 UK Import Reliance and Australian Geological Potential for Critical Minerals

Commodity	UK Import Reliance (%)		Import Source
CADMIUM	100	High	Netherlands, Mexico, Belgium, Peru, South Korea
COBALT	100	High	United States, Germany, Netherlands, Poland, France
GALLIUM	100	High	data unavailable
GERMANIUM	100	High	data unavailable
INDIUM	100	High	data unavailable
LITHIUM	100	High	data unavailable
MOLYBDENUM	100	High	United States, Netherlands, Mexico, China, Austria
PALLADIUM (processed)	100	High	Switzerland, South Africa, United States, Canada, Belgium
PLATINUM (processed)	100	High	Switzerland, South Africa, United States, Belgium, Italy
RARE EARTHS	100	High	Italy, United States, Austria, Japan, France
SILVER	100	High	Switzerland, South Africa, Germany, Poland, United States
TANTALUM	100	High	China, United States, Austria, Germany, Japan
VANADIUM	100	High	data unavailable
ANTIMONY	100	Moderate	Vietnam, China, Netherlands, United States, Canada
BERYLLIUM	100	Moderate	data unavailable
BISMUTH	100	Moderate	Belgium, Netherlands, France, United States, Germany
GRAPHITE (natural)	100	Moderate	Austria, China, Hong Kong, Germany, India
MAGNESIUM	100	Moderate	China, United States, Germany, Israel, Czech Republic
RHENIUM	100	Moderate	data unavailable
TUNGSTEN	100	Moderate	Germany, China, South Africa, South Korea, Austria
ARSENIC	100	Low	data unavailable
STONTIUM	100	Low	data unavailable
BARIUM	69	Low	data unavailable

Australian Geological Potential

- High
- Moderate
- Low

Notes:

1. Australian geological potential for discovery and supply of critical minerals has been ranked as high, moderate or low. These rankings are based on current understanding of known deposits, geology and potential for new discoveries, and build on the assessment by Geoscience Australia in Skirrow et al. (2013). Australia does not currently supply critical minerals to the EU but it is possible that Australia supplies some of the precursor ores and concentrates directly to the UK or to intermediate countries (data unavailable). Australia has great potential to be a source of new critical minerals of strategic and economic interest to the EU and UK.
2. Import reliance is assumed to be 100% for those minerals for which the UK has no mine production regardless of whether the UK is a net exporter or not. It is assumed that minor minerals are being processed as by-products from imported ores, metals and concentrates, some of which may be then exported.
3. PGE—Platinum Group Elements. Platinum and palladium are the two main elements in a broader suite that also comprises osmium, iridium, ruthenium and rhodium.
4. Rare Earths or Rare Earth Elements (REEs) comprise the 15 lanthanide elements—*cerium*, *dysprosium*, *erbium*, *europium*, *gadolinium*, *holmium*, *lanthanum*, *lutetium*, *neodymium*, *praseodymium*, *promethium*, *samarium*, *terbium*, *thulium*, *ytterbium*—as well as *scandium* and *yttrium*.
5. Barium data is based on the annual average from 2010–14.

Appendix Table B.3 EU Import Reliance and Australian Geological Potential for Critical Minerals

Commodity	EU Import Reliance (%)	Import Source
BORON (borates)	100	Turkey
NIOBIUM (ferroniobium)	100	Brazil, Canada
PALLADIUM (PGE)	100	Russia, Switzerland, South Africa, USA
RARE EARTHS	100	China, USA, Russia
SCANDIUM	100	Russia, Kazakhstan
TANTALUM	100	Nigeria, Rwanda, China
YTTRIUM	100	China, USA, Russia
PLATINUM (PGE)	98	Switzerland, South Africa, USA, Russia
GERMANIUM	64	China, Russia, USA
GALLIUM	34	China, USA, Ukraine, South Korea
COBALT	32	Russia, Dem. Rep. Congo, USA
HAFNIUM (zircon)	9	Canada, China
ANTIMONY	100	China, Vietnam, Kyrgyzstan
BERYLLIUM	100	USA, Kazakhstan, Japan
BISMUTH	100	China, USA, Peru, South Korea
MAGNESIUM	100	China, Israel
VANADIUM	100	Russia, China, South Africa
WHITE PHOSPHORUS	100	Kazakhstan, China, Vietnam
GRAPHITE (natural)	99	China, Brazil, Norway, Ukraine
HELIUM	96	USA, Algeria, Qatar, Russia
PHOSPHATE ROCK	88	Morocco, Russia, Syria, Algeria
SILICON METAL	64	Norway, Brazil, China, Russia
TUNGSTEN	44	Russia, Bolivia, Vietnam
BARITE	80	China, Morocco, Turkey
FLUORSPAR	70	Mexico, China, South Aftica, Namibia

Australian Geological Potential

- High
- Moderate
- Low

Notes:

1. Australian geological potential for discovery and supply of critical minerals has been ranked as high, moderate or low. These rankings are based on current understanding of known deposits, geology and potential for new discoveries, and build on the assessment by Geoscience Australia in Skirrow et al. (2013). Australia does not currently supply critical minerals to the EU but it is possible that Australia supplies some of the precursor ores and concentrates directly to the UK or to intermediate countries (data unavailable). Australia has great potential to be a source of new critical minerals of strategic and economic interest to the EU and UK.
2. Data is based on the annual average from 2010–14.
3. Hafnium always occurs with zirconium in nature and the main source for both elements is zircon (mineral sand). The EU does not mine zircon sand and is thus 100% import reliant on zirconium and by implication also hafnium. Data is not available for the source of importation; however Australia is the world's largest producer and is known to have exported to France in the past. Other large producers are South Africa, Indonesia and China.
4. PGE—Platinum Group Elements. Platinum and palladium are the two main elements in a broader suite that also comprises osmium, iridium, ruthenium and rhodium.
5. Rare Earths or Rare Earth Elements (REEs) comprise the 15 lanthanide elements—*cerium*, *dysprosium*, *erbium*, *europium*, *gadolinium*, *holmium*, *lanthanum*, *lutetium*, *neodymium*, *praseodymium*, *promethium*, *samarium*, *terbium*, *thulium*, *ytterbium*—as well as *scandium* and *yttrium*.

Appendix Table B.4 UK Import Reliance by Source of Critical Minerals (2010–14)

Commodity	UK Net Import Reliance (%)	Major Import Sources (2010-2014)
ANTIMONY	100	Vietnam, China, Netherlands, United States, Canada
ARSENIC	100	data unavailable
BERYLLIUM	100	data unavailable
BISMUTH	100	Belgium, Netherlands, France, United States, Germany
CADMIUM	100	Netherlands, Mexico, Belgium, Peru, South Korea
COBALT	100	United States, Germany, Netherlands, Poland, France
GALLIUM	100	data unavailable
GERMANIUM	100	data unavailable
GRAPHITE	100	Austria, China, Hong Kong, Germany, India
INDIUM	<100	data unavailable
LITHIUM	100	data unavailable
MAGNESIUM	100	China, United States, Germany, Israel, Czech Republic
MOLYBDENUM	100	United States, Netherlands, Mexico, China, Austria
PALLADIUM (processed)	100	Switzerland, South Africa, United States, Canada, Belgium
PLATINUM (processed)	100	Switzerland, South Africa, United States, Belgium, Italy
RARE EARTHS	100	Italy, United States, Austria, Japan, France
RHENIUM	100	data unavailable
SILVER	100	Switzerland, South Africa, Germany, Poland, United States
STRONTIUM	100	data unavailable
TANTALUM	100	China, United States, Austria, Germany, Japan
TUNGSTEN	100	Germany, China, South Africa, South Korea, Austria
VANADIUM	100	data unavailable
BARITE	69	data unavailable

Appendix Table B.5 EU Import Reliance by Source of Critical Minerals (2010–14)

Commodity	EU Net Import Reliance (%)	Major import sources (2010–14)
ANTIMONY	100	China, Vietnam, Kyrgyzstan
BERYLLIUM	100	USA, Kazakhstan, Japan
BISMUTH	100	China, USA, Peru, South Korea
BORON (borates)	100	Turkey
MAGNESIUM	100	China, Israel
NIOBIUM (ferroniobium)	100	Brazil, Canada
PALLADIUM (processed)	100	Russia, Switzerland, South Africa, USA
RARE EARTHS	100	China, USA, Russia
SCANDIUM	100	Russia, Kazakhstan
TANTALUM	100	Nigeria, Rwanda, China
VANADIUM	100	Russia, China, South Africa
WHITE PHOSPHORUS	100	Kazakhstan, China, Vietnam
YTTRIUM	100	China, USA, Russia
GRAPHITE (natural)	99	China, Brazil, Norway, Ukraine
PLATINUM (processed)	98	Switzerland, South Africa, USA, Russia
HELIUM	96	USA, Algeria, Qatar, Russia
PHOSPHATE ROCK	88	Morocco, Russia, Syria, Algeria
BARITE	80	China, Morocco, Turkey
FLUORSPAR	70	Mexico, China, South Africa, Namibia
GERMANIUM	64	China, Russia, USA
SILICON METAL	64	Norway, Brazil, China, Russia
TUNGSTEN	44	Russia, Bolivia, Vietnam
GALLIUM	34	China, USA, Ukraine, South Korea
COBALT (ore and concentrate)	32	Russia, Dem. Rep. Congo, USA
HAFNIUM (zircon)	9	Canada, China
INDIUM	0	China, Kazakhstan, South Korea, Canada

B.2 Use for each Critical Mineral in the EU (inclusive of the United Kingdom)

Antimony

From 2010–14, EU member states consumed 18 kt of unwrought antimony metal, 90% of which was imported from China. The EU also imported 5.9 kt of antimony trioxide (ATO) from China (65% of its needs) and 1.6 kt of ores and concentrates during this period. The EU is also a significant producer of ATO, mainly in Belgium, France, Spain and Italy, and is reliant on metal imports for source material. The main antimony applications in the EU are flame retardants in the form of ATO (43%), lead-acid batteries (32%), lead alloys (14%), plastics (6%) and glass and ceramics (5%). The recycling rate for antimony is unclear but thought to be between 1 and 28% and is largely dependent on lead (battery) recycling.

Barite

Between 2010 and 2014, the EU imported around 535 kt of barite per year, mainly from China (53%), Morocco (37%) and Turkey (7%). The EU was also a producer (around 117 kt a year over the same period—Germany 49%, UK 30%, Slovakia 17%, Bulgaria 4%) and exporter of barite. Net EU 2010–14 barite consumption was 575 kt per year, used as a weighting agent in oil and gas well drilling fluids (60%), filler in rubbers, plastics, paints and paper (30%) and the chemical industry (10%).

Beryllium

While there appears to be no data about EU beryllium reserves and resources, the consensus is there are no reserves and only a few dozen tonnes of resources. The EU does not import beryllium ore as it has no capacity to process it. Instead it imports around 50 t per year of refined beryllium in the form of alloys and master alloys (80%) as well as metal and oxides which it uses to produce high-performance, lightweight electronic and telecommunications equipment (40%), automotive electronics (16%), automotive components (16%), aerospace components (10%) and other industrial, energy and medical components (18%) that use beryllium's superior chemical, mechanical and thermal properties. The main EU suppliers are the US (60%), Kazakhstan (23%) and Japan (17%).

Bismuth

The EU was a 100% reliant net importer of refined bismuth in the period 2010–14, importing an average 560 t per year from China (84%), Peru (3%), South Korea (3%), US (3%) and other origins (7%). Bismuth is a by-product of lead and tungsten production and primary product is mainly supplied by China and refined in Europe, North America and Southeast Asia. Domestic supply from Bulgaria accounts for around 0.1% of EU needs. As an 'eco-friendly' material, key uses include anti-ulcer, nuclear medicine, anti-cancer, anti-tumour and anti-microbial applications in the pharmaceutical sector, as a replacement for more harmful metals (e.g. lead in solders) and in coatings, pigments and electronics in the industrial sector, and in the animal feed industry.

Boron (borates)

The European Commission estimates that from 2010–14 its member states consumed approximately 285 kt of borates, 83% of which was imported from Turkey as refined borates with the USA supplying 7%. Boron was primarily used in the EU for glass and fibreglass applications (49%), frits and ceramics (15%), fertilisers (13%), wood preservatives, chemicals and metals (4% each), and other applications accounting for the remaining 11%.

Cobalt

Between 2010–14, the EU (Finland), contributed 1% of global cobalt mine production and (Finland, Belgium and Norway) 22% of refined cobalt production. Notwithstanding this domestic production, the EU imported the majority of its required cobalt ores, concentrates and other forms over this period. Major suppliers of cobalt ores and concentrate were Russia (91%), Democratic Republic of Congo (7%) and the US (2%) but it is worth noting that imports decreased drastically from around 9 kt in 2010 to 2 kt in 2014. Imports of cobalt in other forms (oxides, hydroxide, chlorides, mattes, intermediate products, unwrought metal and powders) remained steady at around 20 kt over the same period. Major suppliers were Democratic Republic of Congo (49%), US (8%, Russia (7%). Cobalt uses include in battery chemicals (42%), in superalloys and alloys (23%), in hard materials such as carbides and diamond tools (10%), catalysts (7%), ceramics and pigments (5%), magnets (5%) and tyre adhesives and paint dryers (4%).

Fluorspar

Fluorspar is the commercial name for fluorite (CaF_2) and is the principal source of fluorine, an essential ingredient in many industrial processes. The EU was 70% import reliant on fluorspar for the 2010–14 period, importing an average 586 kt per year predominantly from Mexico (38%), China (17%), South Africa (15%) and Namibia (12%), the last of which ceased supply in 2014. Domestic production amounted to some 290 kt (acid-grade only) and occurred in the UK, Spain, Germany and Bulgaria (although Bulgaria ceased production in 2016). In the EU, fluorspar is primarily used in the metallurgical, ceramics and chemical industries, mostly in the production of hydrofluoric acid (HF) and aluminium fluoride (AlF_3). Fluorspar is used as a flux in steelmaking and in iron and steel casting (33%), refrigerants (17%), primary aluminium production (14%), polymers for cookware coating and cable insulation (10%), fluorochemicals (9)%, nuclear fuel (6%) and also in glass manufacture, welding rod coatings, cement production, optical applications, cut gems and ornaments.

Gallium

The EU was 34% reliant on gallium imports for the 2010–14 period, importing an average 65 t per year predominantly from China (53%), the USA (11%), Ukraine (9%) and South Korea (8%). Domestic capacity for primary gallium production from aluminium smelters in Hungary and Germany is 50 t, however this production ceased in 2013 owing to high operating costs and oversupply from Chinese sources. Gallium is primarily used for the production of semiconductors which, in turn, are mainly used in the manufacture of integrated circuits (70%), which are critical components in mobile phones and military applications such as radar, satellites and night vision. Gallium is also used for lighting applications (25%), mainly light-emitting diodes (LEDs) but also laser diodes and photodetectors and in photovoltaic technology (5%).

Germanium

In 2010–14, the EU imported an average of 34 t per year of germanium in refined products and was 64% reliant on imports. Germanium is mainly extracted from zinc ore and coal ashes but only 12% of germanium mined outside of China and Russia is refined, leading to supply risk. The EU's domestic production came from Finnish refining of Congolese cobalt concentrates. China accounted for 60% of imports followed by Russia (17%) and the USA (16%). In the EU, the main uses for germanium are for infrared optics (47%), fibre-optics (39%) and solar cells (13%). Minor uses include gamma-ray detectors and organic chemistry, phosphor, metallurgical and chemotherapy applications.

Graphite

From 2010–14, the EU was 99% import reliant on natural graphite, importing an average 95 kt per annum. There was very small production in the EU from Austria and Germany. The major import sources were China (66%), Brazil (13%) and Norway (7%). Natural graphite is used in the EU by the refractory sector for steel making (40%) followed by the foundry sector for non-metallic products such as flat glass (20%). Graphite is also used for lubricants, friction products, flame retardants, sealing products, pencils, batteries and other products.

Hafnium

During the 2010–14 period, the EU import reliance for hafnium was only 9% as France is a major global producer. However, this figure does not tell the true story because, in nature, hafnium always occurs with zirconium, with both metals derived from zircon (mineral sand). Without zircon imports, France is unable to produce hafnium. In addition, the EU imported 12 kt of hafnium from Canada (67%) and China (33%). The leading use of hafnium metal is in superalloys such as those used in the aerospace and industrial gas industries for turbine blades (45%). It is also used in the control rods of nuclear reactors and nuclear submarines (26%). Other uses include refractory ceramics, electronics, optics, chemicals and microchips.

Helium

The EU was 96% import reliant on helium for the 2010–14 period, importing an average 25.5 million cubic metre per year, predominantly from the USA (53%), Algeria (29%), Qatar (8%) and Russia (8%). The only EU producer was Poland, responsible for 1% of global supply. Primary uses for helium in the EU are cryogenics, controlled atmospheres, arc welding, pressurisation and purging, leak detection, semiconductors, optical fibres, lifting gas and analytical applications.

Indium

The EU was a net exporter of indium in 2010–14. Member states imported 544 t of indium metal from China (41%), Kazakhstan (19%) and South Korea (11%) and exported 672 t. The EU also produced 239 t of refined indium—France from imported zinc concentrates and Belgium as a by-product of lead-copper processing. Primary domestic sources include zinc concentrates from Portugal but it is not known if the indium was actually extracted. Indium tin oxide (ITO) thin-film coatings act as a transparent conductor and are used in a variety of flat-panel displays—most commonly liquid crystal displays (56%). Refined indium was also used in the EU for solders (10%), photovoltaics (8%), thermal applications (6%), batteries (5%), alloys (4%), semiconductors and LEDs (3%) and other uses (8%).

Magnesium

During 2010–14, the EU was 100% import reliant on magnesium with China providing 94% of imports and Israel 3%. The EU does not extract or produce pure magnesium metal but does produce magnesium alloys from imports. In addition, magnesium recycling from plants in Austria, the Czech Republic, Germany, Hungary, Romania and the UK provided significant secondary supply to the market. In the EU, the major end uses of magnesium were in the automotive industry, civil and military aerospace applications, steel making, aluminium alloys, and medical, sport, chemical and electrochemical applications.

Niobium

The EU had 100% net import reliance in 2010–14 for niobium, which is not imported by member states as primary ore and concentrates but only as processed products (e.g. ferroniobium and niobium metal). Most EU imports of ferroniobium came from Brazil (71%) and Canada (13%). The EU did, however, produce specialist niobium-based alloys and chemicals from the niobium imports. The majority of niobium (as ferroniobium) was used for making high-strength, low-alloy steel used in the automotive, gas, rail and shipping industries. Niobium is also used in the nuclear and space industries and in superconducting magnets such as those in magnetic resonance imaging (MRI) scanners.

Platinum Group Elements (PGEs)

In the period 2010–14, the EU was a producer, importer and exporter of PGEs, primarily platinum (Pt) and palladium (Pd), with a net import reliance of about 100%. Known domestic resources are in Greenland (Pt), Sweden (Pd), Finland (Pt+Pd) and Poland (Pt+Pd). In 2014, Finland produced 1.06 t Pt and 0.81 t Pd as by-products of nickel and copper mining and Poland 0.1 t Pt+Pd from copper refining. PGEs are also sourced from recycled materials such as chemical industry catalysts and glass industry equipment. The international PGE fabrication industry has a strong presence in Europe where four of the five biggest companies have operations. In 2014, around 178 t of PGEs in unwrought, powder and semi-manufactured form were imported with Switzerland (34%), South Africa (31%), the US (21%) and Russia (8%) the main suppliers. The dominant application for Pt and Pd (8090% in Europe) is in catalytic converters for cars. Far smaller uses include bulk-chemical production and petroleum refining, electronic components, jewellery, glass manufacturing, laboratory equipment and dental restoratives.

Phosphate Rock and White Phosphorus

The EU imported over 6 Mt per year on average of phosphate rock during 2010–14. Morocco was the source for 31% of imports with Russia (16%), Syria (11%) and Algeria (10%) also contributing. The EU supplied 12% of its own phosphate rock from Finland. Phosphate rock is overwhelmingly (95%) used in agricultural applications such as fertiliser and animal feed additives as it is one of the elements essential for life and has no substitute. The remainder is used for a variety of applications including lubricants, detergents, oil additives, agrochemicals, pyrotechnics, plastic additives, nickel plating, catalysts, cobalt and other metal extraction.

White phosphorus (P4) is a refinery product and the EU is 100% import reliant. The EU imported an average of 46.215 kt per year of white phosphorus from 2010–14. Kazakhstan was the source of 77% of all imports even though China is the world's largest producer of white phosphorus (58% of global production). It is used in a wide variety of chemical applications (90%) including flame retardants, oil additives, water treatment, phosphatic acids and synthetic detergents, as well as metal products (5%) and microelectronics (5%).

Rare Earth Elements (REEs)

The EU is 100% reliant on REE imports, in 2010–14 importing around 8 kt/year, mainly from China (40%), US (34%) and Russia (25%). Primary uses include as catalysts (42%), additives for glass (18%), in metallurgy (12%), polishing (7%), ceramics (6%) and in magnets (3%). Typical end uses are modern, high-end technological applications such as mobile phones and computers.

Scandium

In 2010–14, the EU was 100% import reliant on scandium primarily sourced from Russia (67%) and Kazakhstan (33%), mainly as scandium oxide. Reliable data for end use in the EU is scarce but scandium is thought to be mainly used in R&D projects and other small markets such as scandium-aluminium alloys for sports equipment. Solid oxide fuel cells are expected to be a major user of scandium as this technology matures.

Silicon Metal

Silicon metal is not actually a metal but is technically a metalloid, having properties of both metals and non-metals. It is an inert element extracted from the mineral quartz (SiO4). Silicon metal is produced from high-purity quartz in Spain, Germany and France but, overall, the EU is 64% net import reliant. External sources are dominated by Norway (35% of imports), Brazil and China (18% each). The major uses for silicon metal in the EU are in chemical applications such as plastic, rubber, paint, varnish, ink, detergent and polishing manufacture (54%), aluminium alloys (38%), solar cells (6%) and electronic components (2%).

Tantalum

In 2010–14, the EU was 100% reliant on imports of tantalum ores and concentrates, mainly from Nigeria (81%), Rwanda (14%) and China (5%). In addition, the EU imported processed (oxides, salts and alloys) and end-product tantalum but data on quantities are unavailable. In the EU, superalloys using tantalum are important for the aerospace sector but the largest use of tantalum globally is for the manufacture of capacitors used in all electronic devices. Minor uses include mill, mining, chemical and medical applications.

Tungsten

In 2010–14, the EU was only 44% reliant on imports of tungsten ores and concentrates, with production from Spain, Portugal and Austria amounting to some 2.2 kt per annum. The remaining tungsten requirements were mainly imported from Russia (84%), Bolivia and Vietnam (5% each). Tungsten in the EU was used primarily for the manufacture of mining, construction, milling and cutting tools (69%), steel applications (7%), catalysts and pigments (7%), lighting and electronics (6%), aeronautics and energy (5%). Other uses accounted for 6%.

Vanadium

The EU was 100% reliant on imports of vanadium ores and concentrates from 2010–14 but did produce 1650 t of vanadium oxides in Belgium, the UK, the Netherlands and Germany. Imports were primarily from Russia (71%), China and South Africa (13% each). Vanadium is primarily used as an alloying agent for iron and steel, but is also used as a catalyst for maleic anhydride and sulfuric acid production as well as ceramic manufacture and glass tinting.

Yttrium

The EU was 100% import reliant on yttrium during 2010–14 with China supplying 40% of yttrium in mixed rare-earth oxides and compounds, followed by the USA (34%) and Russia (25%). An average of 786 t of yttrium was imported into the EU over this period where it was used mainly for lighting (46%) and ceramics (35%) and also for aluminium and magnesium alloys (7%), camera glass (4%) and other uses such as electronics and oxygen sensors.

References:

Study on the review of the list of Critical Raw Materials. Critical Materials Factsheets. European Commission. Publications Office of the European Union, 2017. doi:10.2873/398823

N. E. Idoine, T. Bide, T. J. Brown and E. R. Raycraft. 2016. United Kingdom Minerals Yearbook 2015. British Geological Survey Open Report, OR/16/021. 79pp.

British Geological Survey. Risk List 2015. An Update to the supply risk index for elements or element groups that are of economic value. 11pp.

Word Bank. World Integrated Trade Solution. *wits.worldbank.org.*

APPENDIX C

C.1 China Import Reliance on Critical Minerals

Appendix Table C.1 China Import Reliance and Australian Geological Potential for Critical Minerals

Commodity	China Net Import Reliance	Major Import Sources
NIOBIUM	100%	data unavailable
CHROMITE	98%	South Africa, Turkey, Albania, Iran, Pakistan
RHODIUM (PGE)	95%	South Africa, UK, Belgium, Russian Federation, Japan
TANTALUM	91%	Israel, Japan, Thailand, USA, Germany
COBALT-MINE	89%	D.R. Congo, Cuba, South Africa, USA, Zambia
ZIRCONIUM-CONCENTRATES	84%	Australia, South Africa, Indonesia, Madagascar, Mozambique
PALLADIUM (PGE)	84%	UK, Japan, South Africa, Russia, USA
LITHIUM	83%	data unavailable
SELENIUM	80%	data unavailable
PLATINUM (PGE)	78%	South Africa, Japan, Switzerland, Russia, UK
BORON	74%	Turkey, Bolivia, Chile, Peru, USA
MANGANESE-MINE	65%	Australia, South Africa, Gabon, Ghana, Brazil
GALLIUM-HIGH PURITY	65%	data unavailable
COPPER-MINE	60%	Chile, Peru, Mongolia, Australia, Mexico
IRON ORE	60%	Australia, Brazil, South Africa, Iran, Sierra Leone
CADMIUM	58%	South Korea, Kazakhstan, Japan, Canada, Mexico
TITANIUM	56%	Australia, India, Mozambique, Vietnam, Kenya
SILVER	45%	Peru, Mexico, Australia, Bolivia, USA
SULFUR	35%	Saudi Arabia, Iran, Kazakhstan, Japan, South Korea
ZINC-MINE	16%	Australia, Peru, Mongolia, Ireland, Kazakhstan
LEAD-MINE	15%	USA, Australia, Russia, Peru, Mexico
COPPER-REFINERY	12%	data unavailable
ALUMINA	10%	Australia, Brazil, India, Vietnam, Venezuela
ZINC-SMELTER	7%	data unavailable
LEAD-REFINERY	4%	data unavailable
BERYLLIUM-MINE	69%	Kazakhstan, USA, Japan,Singapore, Australia
RHENIUM	53%	data unavailable
ANTIMONY	19%	Vietnam, Germany, USA, Japan, Honduras

Notes:

1. Australian geological potential for discovery and supply of critical minerals has been ranked as high, moderate or low. These rankings are based on current understanding of known deposits, geology and potential for new discoveries, and builds on the assessment by Geoscience Australia in Skirrow et al. (2013). Australia already supplies many minerals that are essential to the Chinese economy but has great potential to be a source of new critical minerals of strategic and economic interest.
2. Data sourced from 'China, the United States, and competition for resources that enable emerging technologies'. Proceedings of the National Academy of Sciences of the United States of America, April 2018. *http://www.pnas.org/content/suppl/2018/03/28/1717152115.DCSupplemental.*
3. PGE—Platinum Group Elements. Platinum and palladium are the two main elements in a broader suite that also comprises osmium, iridium, ruthenium and rhodium.

Appendix Table C.2 China Import Reliance by Source of Critical Minerals

Source	# Critical Minerals	Imported Critical Minerals
Japan	14	RHODIUM, TANTALUM, PALLADIUM, PLATINUM, BERYLLIUM, CADMIUM, SULFUR, ANTIMONY, BISMUTH, COBALT, MAGNESIUM, POTASH, RARE EARTHS, TIN
United States	14	TANTALUM, COBALT-MINE, PALLADIUM, BORON, BERYLLIUM, SILVER, ANTIMONY, LEAD, BISMUTH, COBALT, MAGNESIUM, MOLYBDENUM, POTASH, RARE EARTHS
Australia	11	ZIRCONIUM, BERYLLIUM, MANGANESE, COPPER, IRON ORE, TITANIUM, SILVER, ZINC, LEAD, ALUMINA, ALUMINIUM
South Africa	8	CHROMITE, RHODIUM, COBALT-MINE, ZIRCONIUM, PALLADIUM, PLATINUM, MANGANESE, IRON ORE
Peru	6	BORON, COPPER, SILVER, ZINC, LEAD, MOLYBDENUM
Germany	5	TANTALUM, ANTIMONY, COBALT, MAGNESIUM, POTASH
Kazakhstan	5	BERYLLIUM, CADMIUM, SULFUR, ZINC, BISMUTH
Mexico	5	COPPER, CADMIUM, SILVER, LEAD, BISMUTH
Russian Federation	5	RHODIUM, PALLADIUM, PLATINUM, LEAD, MAGNESIUM
South Korea	5	CADMIUM, SULFUR, BISMUTH, POTASH, TIN
Malaysia	4	ALUMINIUM, COBALT, RARE EARTHS, TIN
Bolivia	3	BORON, SILVER, TIN
Brazil	3	MANGANESE, IRON ORE, ALUMINA
Chile	3	BORON, COPPER, MOLYBDENUM
India	3	TITANIUM, ALUMINA, ALUMINIUM
Indonesia	3	ZIRCONIUM, ALUMINIUM, TIN
Iran	3	CHROMITE, IRON ORE, SULFUR
Mongolia	3	COPPER, ZINC, MOLYBDENUM
Turkey	3	CHROMITE, BORON, MOLYBDENUM
United Kingdom	3	RHODIUM, PALLADIUM, PLATINUM
Vietnam	3	TITANIUM, ANTIMONY, ALUMINA
Canada	2	CADMIUM, RARE EARTHS
Mozambique	2	ZIRCONIUM, TITANIUM
Albania	1	CHROMITE
Austria	1	MAGNESIUM
Belgium	1	RHODIUM
Cuba	1	COBALT-MINE
D.R. Congo	1	COBALT-MINE
Dominican Republic	1	ALUMINIUM
France	1	COBALT
Gabon	1	MANGANESE
Ghana	1	MANGANESE
Honduras	1	ANTIMONY
Ireland	1	ZINC
Israel	1	TANTALUM
Kenya	1	TITANIUM
Madagascar	1	ZIRCONIUM
Pakistan	1	CHROMITE
Philippines	1	RARE EARTHS
Saudi Arabia	1	SULFUR
Sierra Leone	1	IRON ORE
Singapore	1	BERYLLIUM
Sweden	1	POTASH
Switzerland	1	PLATINUM
Thailand	1	TANTALUM
Venezuela	1	ALUMINA
Zambia	1	COBALT-MINE

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