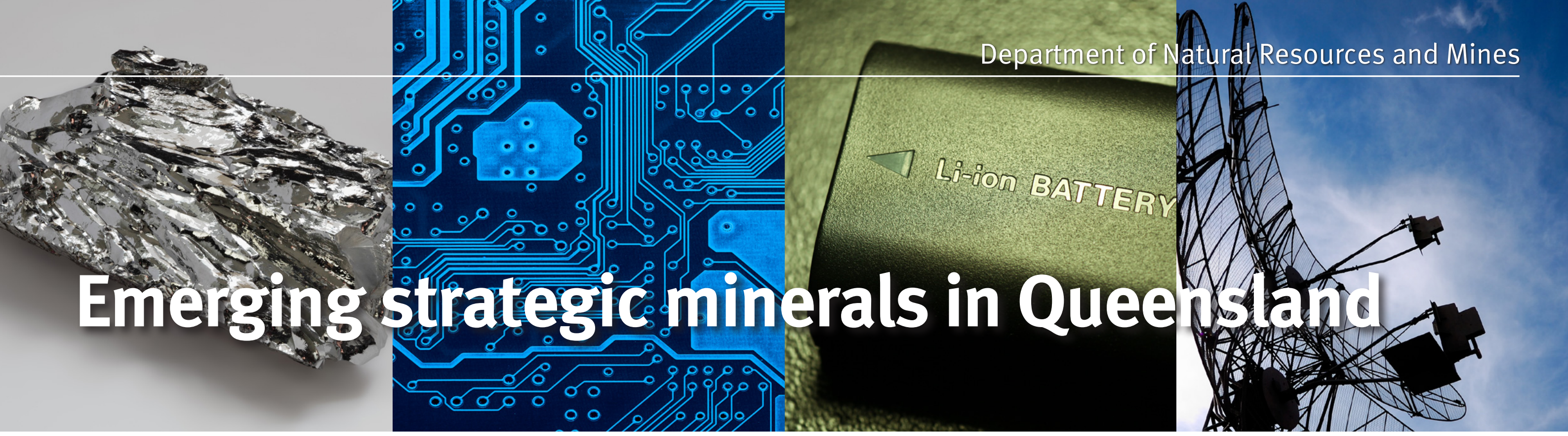
Department of Natural Resources and Mines



Emerging strategic minerals in Queensland

July 2017

Overview

New technologies being developed around the world require a different suite of elements from the traditional more commonly mined ores (Figure 1). Sourcing these new elements poses both challenges and opportunities for the mining industry and governments around the world. Queensland has resources of several of these elements and is well placed to support global demand.

Several emerging commodities are regarded as critical based on perceived supply issues, while some existing elements (such as tin) are also showing a resurgence due to increased demand from hi-tech industries. New technologies which use these critical elements include mobile phones, flat screen TVs, electric/hybrid vehicles, electric motors, wind turbine generators, high strength and high temperature alloys (military and civilian planes, space craft) and in catalytic converters in cars.

Critical commodities are strategic minerals for which the uses are both economically important and have a high risk of supply disruption. Based upon a compilation of reports defining commodities considered critical by Australia's major trading partners (United Kingdom, European Union, United States of America, Japan and Korea) a list of commodities considered critical was identified by Geoscience Australia (http://www.ga.gov.au/about/what-we-do/projects/minerals/current/critical-commodites).

Critical commodities include the Rare Earth Elements (REE), as well as gallium, indium, tungsten, and niobium. REE and associated element groups are sometimes referred to as 'spice elements' or 'vitamins for the new technologies'. Of particular importance in this group for Queensland are rhenium and scandium, for which the state has world class resources. Market economics for rare earths and other critical elements reflect the very low volumes required for the world's industrial consumption, however, the impact of these elements far outweighs their volume produced globally.

Government-industry collaborative drilling in the Diamantina region in south west Queensland also discovered rock and associated alteration conducive to hosting strategic minerals such as rare earths, platinoids and ferroalloys (Figure 2).

Figure 1: Periodic Table showing the position of the REE (Lanthanides) and other strategic elements

1A	2A	3B	4B	5B	6B	7B	8B	8B	8B	1B	2B	3A	4A	5A	6A	7A	8A
1 H 1.00794 Hydrogen																	2 He 4.002602 Helium
3 Li 6.941 Lithium	4 Be 9.012182 Beryllium											5 B 10.811 Boron	6 C 12.0107 Carbon	7 N 14.0067 Nitrogen	8 O 15.9994 Oxygen	9 F 18.9984032 Fluorine	10 Ne 20.1797 Neon
11 Na 22.989769 Sodium	12 Mg 24.3050 Magnesium											13 Al 26.9815386 Aluminum	14 Si 28.0855 Silicon	15 P 30.973762 Phosphorus	16 S 32.065 Sulfur	17 Cl 35.453 Chlorine	18 Ar 39.948 Argon
19 K 39.0983 Potassium	20 Ca 40.078 Calcium	21 Sc 44.955912 Scandium	22 Ti 47.867 Titanium	23 V 50.9415 Vanadium	24 Cr 51.9961 Chromium	25 Mn 54.938045 Manganese	26 Fe 55.845 Iron	27 Co 58.933195 Cobalt	28 Ni 58.6934 Nickel	29 Cu 63.546 Copper	30 Zn 65.38 Zinc	31 Ga 69.723 Gallium	32 Ge 72.64 Germanium	33 As 74.92160 Arsenic	34 Se 78.96 Selenium	35 Br 79.904 Bromine	36 Kr 83.798 Krypton
37 Rb 85.4678 Rubidium	38 Sr 87.62 Strontium	39 Y 88.90585 Yttrium	40 Zr 91.224 Zirconium	41 Nb 92.90638 Niobium	42 Mo 95.96 Molybdenum	43 Tc [98] Technetium	44 Ru 101.07 Ruthenium	45 Rh 102.90550 Rhodium	46 Pd 106.42 Palladium	47 Ag 107.8682 Silver	48 Cd 112.411 Cadmium	49 In 114.818 Indium	50 Sn 118.710 Tin	51 Sb 121.760 Antimony	52 Te 127.60 Tellurium	53 I 126.90447 Iodine	54 Xe 131.293 Xenon
55 Cs 132.9054519 Cesium	56 Ba 137.327 Barium	57-71 Lanthanides	72 Hf 178.49 Hafnium	73 Ta 180.94788 Tantalum	74 W 183.84 Tungsten	75 Re 186.207 Rhenium	76 Os 190.23 Osmium	77 Ir 192.217 Iridium	78 Pt 195.084 Platinum	79 Au 196.966569 Gold	80 Hg 200.59 Mercury	81 Tl 204.3833 Thallium	82 Pb 207.2 Lead	83 Bi 208.98040 Bismuth	84 Po [209] Polonium	85 At [210] Astatine	86 Rn [222] Radon
87 Fr [223] Francium	88 Ra [226] Radium	89-103 Actinides	104 Rf [267] Rutherfordium	105 Db [268] Dubnium	106 Sg [271] Seaborgium	107 Bh [272] Bohrium	108 Hs [270] Hassium	109 Mt [276] Meitnerium	110 Ds [281] Darmstadtium	111 Rg [280] Roentgenium	112 Cn [285] Copernicium	113 Uut [284] Ununtrium	114 Fl [289] Flerovium	115 Uup [288] Ununpentium	116 Lv [293] Livermorium	117 Uus [294] Ununseptium	118 Uuo [294] Ununoctium

Lanthanides series	57 La 138.90547 Lanthanum	58 Ce 140.116 Cerium	59 Pr 140.90765 Praseodymium	60 Nd 144.242 Neodymium	61 Pm [145] Promethium	62 Sm 150.36 Samarium	63 Eu 151.964 Europium	64 Gd 157.25 Gadolinium	65 Tb 158.92535 Terbium	66 Dy 162.500 Dysprosium	67 Ho 164.93032 Holmium	68 Er 167.259 Erbium	69 Tm 168.93421 Thulium	70 Yb 173.054 Ytterbium	71 Lu 174.9668 Lutetium
Actinides series	89 Ac [227] Actinium	90 Th 232.03806 Thorium	91 Pa 231.03588 Protactinium	92 U 238.02891 Uranium	93 Np [237] Neptunium	94 Pu [244] Plutonium	95 Am [243] Americium	96 Cm [247] Curium	97 Bk [247] Berkelium	98 Cf [251] Californium	99 Es [252] Einsteinium	100 Fm [257] Fermium	101 Md [258] Mendelevium	102 No [259] Nobelium	103 Lr [262] Lawrencium

Alkali Metals	Alkaline Earth	Transition Metal	Basic Metal	Semi Metal	Non Metal	Halogen	Noble Gas	Lanthanides	Actinides

Queensland AUSTRALIA

endless opportunities

Queensland Government

Rare Earth Elements

What are the REE?

The REE are a group of chemical elements that exhibit a range of special (some unique) properties which are used in many modern and green technologies. The International Union of Pure and Applied Chemistry defines the REE as the 15 lanthanides and yttrium and scandium.

The REE are subdivided into Light Rare Earth Elements (LREE) and Heavy Rare Earth Elements (HREE). Because all of the uses are in modern and green technologies, it is only in the last twenty years that the REEs have become such valuable commodities.

Heavy Rare Earth Elements

Why are HREE considered 'critical'?

The HREE include: terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu).

The HREE are considered critical because of their increasing importance in modern and green technologies. The HREE can be regarded as the 'vitamins' required for the shift from a carbon based economy to the new 21st century electron economy.

Foreign countries are increasingly exploring for REE in order to reduce the world's dependence on China and several deposits have been found (including the Mount Weld deposit in Western Australia). However, given the dependence of many new technologies on the REE and the reliance on China for their supply, the elements are listed at the top of the Critical Elements as defined by Geoscience Australia (http://www.ga.gov.au/about/what-we-do/ projects/minerals/current/critical-commodites).

It should be noted that, of the HREEs, dysprosium is considered the most critical over the next 5 years. While many of the HREE are not used in such large quantities than the LREE, they are rarer and not as abundant.

Where are HREE found in Queensland?

HREE are identified at several exploration locations in Queensland but are concentrated in northwest Queensland (such as the Milo Prospect). None are at the resource identification stage.

Yttrium is known from the Korella prospect associated with phosphate mineralisation in the Georgina Basin south of Mount Isa.

Light Rare Earth Elements

Authors disagree on which elements are included in the LREE group, but here are the following elements included in the LREE group: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), and gadolinium (Gd) – also known as the Cerium Group (Gschneidner, 1966).

Why are LREE considered 'critical'?

Like HREE, LREE are also considered critical because of their application in modern and green technologies.

Where are LREE found in Queensland?

LREE are known from many parts of Queensland but are concentrated in north west Queensland (Figure 2).

LREE occur in the tailings at the Mary Kathleen uranium mine east of Mount Isa. The deposit is hydrothermal, related to ~1540 million year (Ma) granites, and has a grade of 3% total REE. Although Mary Kathleen was a uranium mine, it was essentially a rare earths orebody containing uranium. The REE at Mary Kathleen comprise lanthanum, cerium and neodymium, with minor praseodymium.

Gallium

Why is gallium considered 'critical'?

Globally, most primary gallium is recovered as a byproduct of processing bauxite and zinc ores. As such, it is considered as critical because its supply is dependent on the prices of other commodities.

Because of the large power-handling capabilities, high-switching frequencies, and higher voltage capabilities of gallium nitride (GaN) technology, GaN-based products, which historically have been used in defence and military applications, are gaining acceptance in cable television transmission, commercial wireless infrastructure, power electronics, and satellite markets. The GaN power device market is forecast to increase at an average annual growth rate of nearly 29%. Together with a predicted growth in the use of gallium arsenide (GaAs) in semiconductors, the future usage of the metal is predicted to out strip supply. While the luminous flux of commercial LED retrofit lamps featuring silicon components is around 1000 lumen, researchers from the IAF have been successful in increasing this to 2090 lumen using GaN-based drivers. With 20% of energy consumption worldwide attributed to lighting, these savings are particularly worthwhile.

Driven by demand for electronics, particularly flat panel displays (FPD's) and smart phones, consumption of gallium has grown by an estimated 5–10% per annum over the last 10 years. Yet over the same period, the market price for 99.90% gallium has fallen roughly 30%.

Where is gallium found in Queensland?

Gallium is not produced in Queensland. Because it is not an element that is usually assayed for, its actual distribution is not known although it is commonly found in association with zinc mineralisation and bauxite. It is not separated from either commodity. Gallium is known to occur with antimony in quartz veins at the Missant deposit near Irvinebank, where the claim holder reported up to 5 parts per million (ppm) Ga. Potential for gallium mineralisation associated with other tin-gold deposits in Hodgkinson Province also exists (Figure 2).

Exploration potential in Queensland

Because gallium occurs with zinc and bauxite mineralisation both of which occur in Queensland, its abundance in these ores should be investigated as it is likely to become critical in the next few years.

Indium

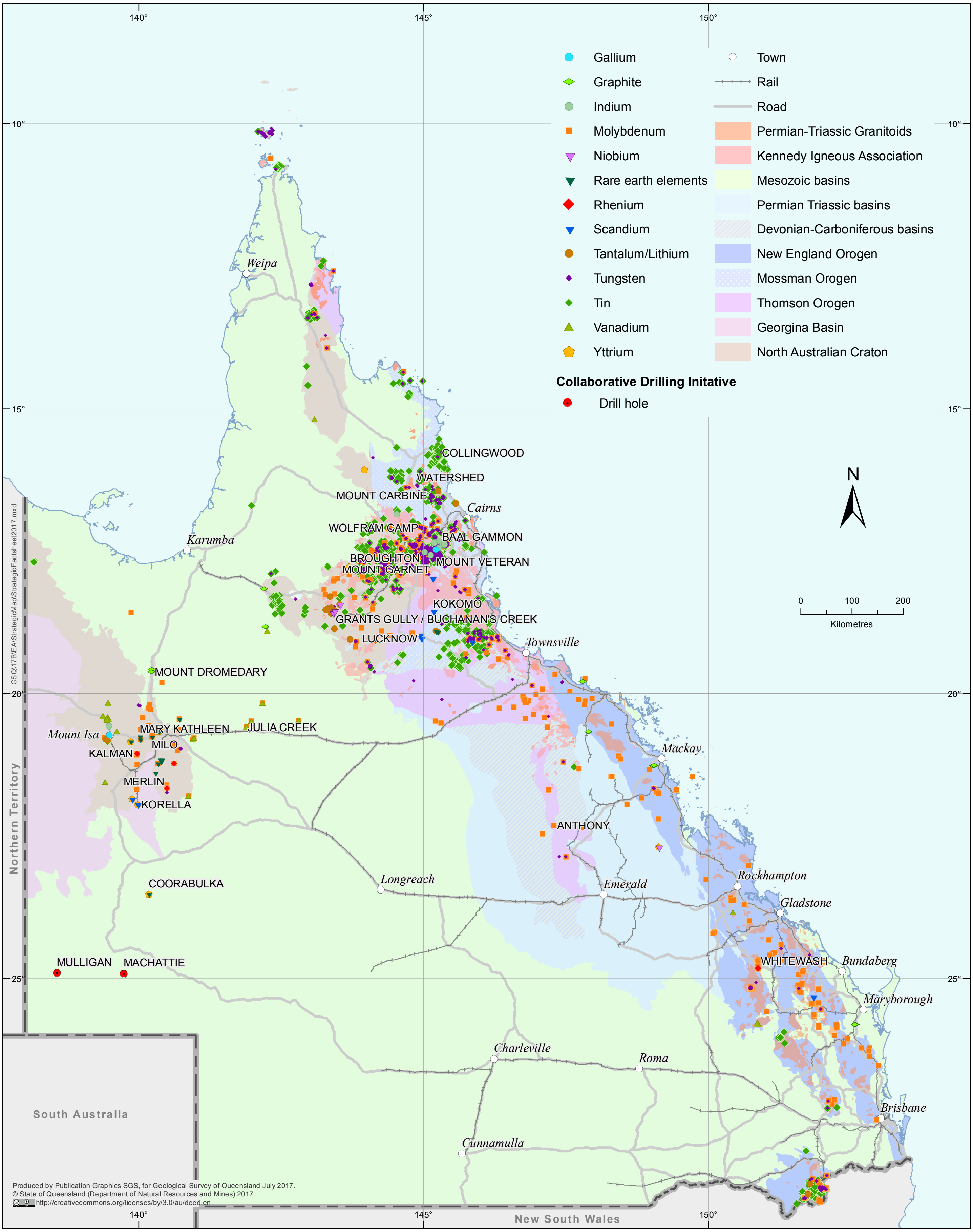
Why is indium considered 'critical'?

Indium is a rare, very soft, malleable and easily fusible heavy metal, chemically similar to gallium and thallium, and shows intermediate properties between these two. Globally, most primary indium is recovered as a by-product of processing zinc ores. As such, it is considered critical because its supply is dependent on prices of other commodities.

Global secondary indium production increased significantly during the past several years and now accounts for a greater share of indium production than primary. This trend is expected to continue in the future. In the past, the indium market has been in deficit as demand for the metal, supported largely by indium tin oxide (ITO) demand, continued to outpace supply.

However, increased manufacturing efficiency and recycling (especially in Japan) are being developed to maintain a balance between demand and supply. Demand increased as the use of the metal in LCDs and televisions increased, and supply decreased when Chinese mining concerns stopped extracting indium from their zinc tailings. In 2002, the price was US$94 per kilogram (kg). Recent changes in demand and supply have resulted in high and fluctuating prices of indium, which from 2006 to 2009 ranged from US$382/kg to US$918/kg, and in 2017 was US$720/kg (http://www.mineralprices.com).

Figure 2: Deposits containing strategic minerals in Queensland



Where is indium found?

Trace amounts of indium occur in base metal sulfides—particularly chalcopyrite, sphalerite and stannite—by ionic substitution. Indium is most commonly recovered from the zinc-sulphide ore mineral sphalerite. The average indium content of zinc deposits from which it is recovered, ranges from less than 1 ppm to 100 ppm. Although the geochemical properties of indium are such that it occurs with other base metals — copper, lead and tin and to a lesser extent with bismuth, cadmium and silver, most deposits of these metals are sub-economic for indium.

Vein stockwork deposits of tin and tungsten host the highest known concentrations of indium. However, the indium from this type of deposit is usually difficult to process economically. Other major geologic hosts for indium mineralisation include volcanic-hosted massive sulphide deposits, sediment-hosted exhalative massive sulphide deposits, polymetallic vein-type deposits, epithermal deposits, active magmatic systems, porphyry copper deposits and skarn deposits.

Where is indium found in Queensland?

Indium occurs associated with zinc mineralisation and Queensland is a global supplier of zinc. In 2015–16, Queensland produced ~5% of global zinc (Office of the Chief Economist, 2017; USGS, 2017), making it a potential large scale producer of Indium. Indium is known to occur with tin–base metal mineralisation in vein deposits in the Irvinebank–Herberton and Mount Garnet areas (for example, Arbouin, Black Sparkle, Isabel, Orient Camp, Weinert, Baal Gammon, Khartoum) within the Hodgkinson Province (Figure 2).

Queensland's known indium resources and reserves total 114 392 tonnes (t), but because it is not an element that is usually assayed for, its full distribution is not known.

Polymetallic sulphide-tin deposits of the Hodgkinson Province represent the most important indium resources in Australia. The Baal Gammon deposit has total reindicated and inferred resources of 2.8 Mt of ore at 0.996% Cu, 0.199% tin, 40 grams per tonne (g/t) silver and 38 g/t indium. All of these metals are expected to report in the concentrate. These indium grades are amongst the highest in the world.

Exploration potential in Queensland

The Hodgkinson Province in Queensland has the potential to be one of the world's leading indium resource areas.

Tin

Why is tin considered 'critical'?

Tin is present in almost all continents, and of the 19 countries in which tin was mined in 2016, the top 6 accounted for 90% of the total world tin production of 280 000 t. China was the leading producer (35% of world output), followed by Indonesia (19%), Burma (12%), Brazil (9%), Bolivia (7%) and Peru (7%) (USGS, 2017).

Worldwide demand for primary tin was expected to increase at moderate annual rates. The rate of increase, however, could increase in a few years if new applications continue to find acceptance in the marketplace, especially in the electronics field where tin solder is needed. Higher tin prices that have prevailed in recent years, however, discourage use in new applications.

During the next decade, technological changes will likely affect tin consumption in its main applications of electronics, solder, and tinplate. Miniaturization, new assembly technologies, and lower coating weights could reduce consumption, but offsetting this were prospects for new applications for tin chemicals, energy-related technologies such as lithium-ion batteries, and steel alloys.

Another possible use for tin is in sodium ion batteries. While these batteries lag behind lithium ion batteries at present, they are cheaper to produce. They are however, heavier and at present, have inferior cycling performance to lithium ion batteries.

Where is tin found?

The only mineral of commercial importance as a source of tin is cassiterite (SnO_2), although small quantities of tin are recovered from complex sulfides such as stanite, cylindrite, frankeite, canfieldite and teallite.

Most of the world's tin is produced from placers, secondary deposits found downstream from the primary deposits. Primary deposits or lodes can occur within granite or within pegmatite or aplite (dyke like rocks) or greisens associated with the granite. Greisens are formed by alteration of granite during the cooling stages of emplacement by fluids formed as the last highly gas- and water-rich phases. This fluid is forced into the interstitial spaces of the granite and pools at the upper margins, where boiling and alteration occur. Primary tin deposits also occur also in rocks surrounding the margins of the intrusive rocks as veins, disseminations, skarns or carbonate replacements generated by tin bearing fluids derived from the granite magmas.

Where is tin found in Queensland?

- **Collingwood:** The Collingwood underground tin mine, 35 km south of Cooktown, was commissioned in late 2005 by Bluestone Tin (renamed Metals X Limited) (Figure 2). The first commercial shipment of concentrates was produced early in 2006, but the mine was closed in May 2008. The identified mineral resources are currently 643 000 t at 1.19% tin. The project is currently on hold.
- **Mount Garnet area:** The Mount Garnet tin project is largely based on the Gillian, Pinnacles and Deadmans Gully/ Windermere tin and fluorite-bearing wrigglite magnetite skarns. The main Gillian deposit is 7 km west south-west of Mount Garnet, and the Pinnacles project and Deadmans Gully/ Windermere prospect are 7 km and 24 km east north-east of Mount Garnet respectively. The skarn deposits contain fine cassiterite closely associated with iron oxides that have historically presented challenges to recovery methods developed for coarse tin ore. Gillian will be the first deposit to be mined at the Mount Garnet project. Mount Veteran, 13 km north east of Mount Garnet, consists of several tin deposits.
- **Herberton area:** The Baal Gammon deposit, a polymetallic resource containing copper, silver, tin and indium, forms part of Monto Minerals Limited larger Herberton tin project, centred on the historic tin mining region around, and to the west of, Herberton (Figure 2). Several other deposits occur in the Herberton area including the Confederation copper-tin prospect, contiguous with the existing Baal Gammon mining leases and within 800 metres of the Baal Gammon mine, as well as the Alexandra and Dargo prospects at Mount Ormonde about 7 km south west of Baal Gammon.

Exploration potential in Queensland

Queensland has several tin bearing provinces, particularly the Carboniferous–Permian Kennedy Igneous Province in north Queensland. If tin prices continue to increase, the increased exploration is expected to unearth new tin resources in this region.

Tantalum and niobium

Why is tantalum considered 'critical'?

Australia historically has been the world's largest producer of tantalite concentrates from two mines—Greenbushes and Wodgina in Western Australia. More recently there has been production from the now closed Mount Cattlin lithium mine, also in Western Australia. Currently the Congo and Rwanda produce 68% of global tantalum (USGS, 2017). The United States, a major user of tantalum, must import all of its source materials for processing.

The large-scale producers of niobium are in Brazil and Canada, and the ore there also yields a small percentage of tantalum. Some other countries such as China, Ethiopia, and Mozambique

Table 1: Resource projects containing strategic elements

Project	Commodity	Location	Company
Baal Gammon	Copper, tin silver, indium	7 km west of Herberton	Baal Gammon Copper Pty Ltd
Kalman	Copper, molybdenum, gold, rhenium	60 km south east of Mount Isa	Hammer Metals Limited
Merlin	Molybdenum, rhenium, copper	100 km south of Cloncurry	Chinova Resources Limited
Anthony	Molybdenum	67 km north north-west of Clermont	Zamia Metals Limited
Whitewash	Molybdenum, copper	30 km west of Monto	Aeon Metals Limited
Julia Creek	Vanadium, molybdenum (oil shale)	North east of Julia Creek and north west of Richmond	Intermin Resources Limited
Wolfram Camp	Tungsten, molybdenum, bismuth	16 km north of Dimbulah	Almonty Industries Inc
Watershed Scheelite	Tungsten	140 km north west of Cairns	Vital Metals Limited
Mount Carbine	Tungsten	90 km north west of Cairns	Carbine Tungsten Limited
Mount Veteran	Tin	13 km north east of Mount Garnet	MGT Resources Limited
Mount Garnet	Tin	Mount Garnet	Consolidated Tin Mines Limited
SCONI	Scandium, nickel, cobalt	30 km south of Mount Garnet	Metallica Minerals Limited
Milo	Rare earth elements, yttrium oxide, copper, phosphate, minor molybdenum, gold silver and uranium	20 km west of Cloncurry	GBM Resources Limited
Mary Kathleen	Rare earth elements, uranium	57 km east of Mount Isa	–
Mary Kathleen shear zone	Copper, gold, rare earth elements, uranium	6 km south of Mary Kathleen	Hammer Metals Limited
Broughton Creek	Copper, gold, heavy rare earths, light rare earths, yttrium oxide	50 km south east of Mount Isa	Orion Metals Limited
Korella	Rare earth elements, yttrium	145 km south of Mount Isa	
Urquhart Point Mineral Sands	Zircon, rutile, ilmenite	3 km south west of Weipa	Oresome Australia Pty Ltd
Grants Gully / Buchanan's Creek	Tantalum, lithium, niobium, gold	Georgetown area	Strategic Metals Australia Pty Ltd
Mount Dromedary flake graphite deposit	Graphite	125 km north of Cloncurry	Graphitecorp Limited
Esmeralda	Graphite	70 km south of Croydon	Metallica Minerals Ltd

mine ores with a higher percentage of tantalum, and they produce a significant percentage of the world's output. Tantalum is also produced in Thailand and Malaysia as a by-product of the tin mining there.

The Democratic Republic of Congo has also been a major producer of tantalum, but internal issues has resulted in limited supply and a consequential price increase.

With the closure of Wodgina and Mt Cattlin and the increasing depth of mining at Greenbushes (combined with low grades) Australia's production is likely to taper so new sources are required.

Where are tantalum and niobium found in Queensland?

Anomalous tantalum and niobium are known in pegmatites in the Buchanan's Creek and Grant's Gully areas, in the Georgetown-Forsayth area. Tantalum has been reported from some gold mines in the Georgetown area, for example, Cumberland. Tantalite (and columbite) has been found in alluvial deposits in the same areas and at Gilberton.

Tantalum also occurs associated with tin-tungsten pegmatite mineralisation in the Hodgkinson Province in north Queensland and with pegmatite at Mica Creek, south of Mount Isa.

Because tantalum and niobium are not usually assayed for, their actual distribution is poorly known.

Tungsten

Why is tungsten considered 'critical'?

Most of the global output of tungsten comes from China which is also the world's leading tungsten consumer. In 2016, 82% of global production or about 71 000 t came from China (USGS, 2017).

Much of the remainder comes from Russia and Canada. Such limited supply means that tungsten is considered to have a high risk of supply disruption. Tungsten is an important component of many industrial and military applications, in which its hardness and high melting point make it critical.

Where and how is tungsten found in Queensland?

Tungsten occurs naturally in two minerals, wolframite ($[Fe,Mn]WO_4$), and scheelite ($CaWO_4$). Both minerals occur in granite pegmatites in contact metamorphic aureoles, and in high temperature hydrothermal veins associated with granitic rocks.

Tungsten mineralisation is widespread in eastern Queensland, generally in association with tin-bearing granites, copper-molybdenum porphyries and their associated skarn deposits. Significant mineralisation has been found in the Stanthorpe, Kangaroo Hills, Herberton-Mount Garnet and Cooktown areas (Figure 2).

The Kennedy Igneous Association in North Queensland is an attractive area for tungsten exploration because of the presence of abundant granites, some of which are associated with operating mines and defined resources of tungsten. All of the main tungsten deposits in Queensland occur where granites of the Kennedy Igneous Association intrude the Hodgkinson Province (Figure 2).

There are two operating mines, one granted mining lease and two prospects for tungsten in Queensland.

- **Mount Carbine** (Carbine Tungsten Limited): The Mount Carbine mine was an operating mine prior to 2017, and is about 75 km north west of Cairns in north Queensland. The deposit is in an outlier of thermal metamorphism related to the S-type Mount Carbine Granite.
- **Wolfram Camp** (Almonty Industries Inc): The Wolfram Camp deposit is 80 km west of Cairns and was discovered in 1888. It comprises predominantly glassy to white quartz with shoots containing coarse-grained wolframite, molybdenite and bismuthinite. Mineralisation occurs in greisen within the roof zone of a highly fractionated granite of Carboniferous age.
- **Watershed Scheelite project** (Vital Metals Limited): The Watershed Scheelite deposit occurs as stratabound replacement lenses in calc-silicate rocks of the Devonian Hodgkinson Formation, and in dyke-like bodies of albitised granite associated with Carboniferous granite intrusions. Mineralisation is exclusively scheelite over a strike length of 3 km. The deposit is approximately 150 km north west of Cairns and mineralisation is exposed on a north-trending ridge

Rhenium

Why is rhenium considered critical?

Rhenium is one of several strategic elements that have not been exploited in significant quantities, but which are now attracting new interest because of likely new sources and their potential use in new technologies. Regarded as one of the rarest elements in the Earth's crust, rhenium is highly ductile with the third highest melting point behind carbon and tungsten.

Rhenium is one of a group of refractory metals, including niobium, molybdenum, tantalum and wolfram, which have very high resistance to heat and wear. Rhenium is probably not found free in nature, but only in the mineral molybdenite which is the major commercial ore. Chile has the world's largest rhenium reserves in molybdenite as a minor constituent in its porphyry copper deposits.

Where is rhenium found in Queensland?

The Merlin deposit is the world's highest grade molybdenum and rhenium deposit and is hosted by the metasedimentary rocks of the Kuridala Group in the Mount Isa Eastern Succession (Figure 2). Very high-grade molybdenum mineralisation close to the surface also occurs at its southern end in the subsidiary Little Wizard deposit. The origin of the mineralisation is unclear, but there are closely related copper–gold deposits in the region, which are classified as iron-oxide–copper–gold (IOCG) and are probably related to Proterozoic granitoids. The molybdenum–rhenium mineralisation is overlain by discrete copper and zinc-rich polymetallic sulphide zones of the Mount Dore ore body (http://www.australianminesatlas.gov.au). Published probable reserves at Merlin are 7.1 Mt at 1.1% molybdenum and 18.1 g/t rhenium for a contained 78 000 t molybdenum and 129 t rhenium.

Chinova Resources commenced construction of a decline at Merlin in late 2010 and reported that phase 1 was completed in early 2012. Phase 2 of the decline development is awaiting project approval (http://www. australianminesatlas.gov.au).

Rhenium is also present at the Kalman copper–gold–molybdenum deposit 62 km south east of Mount Isa. This molybdenum also contains high concentrations of rhenium. The deposit is still being explored. The deposit has inferred resources of 60.8 Mt at 0.05% molybdenum, 1.19 g/t rhenium, 0.32% copper and 0.15 g/t gold, with a contained 30 400 t of molybdenum (http://www. australianminesatlas.gov.au).

Molybdenum

Why is molybdenum considered 'critical'?

Molybdenum is used mainly for the production of alloy steels (stainless steel) and superalloys.

It is used in high strength steel in skyscrapers. Alternative high strength steels would be more costly and in some instances, the increased weight would render construction unmanageable or impossible. There is little substitution for molybdenum in its major application as an alloy in steels. Due to the supply and versatility of molybdenum, current research seeks to develop new materials

Global molybdenum reserves are focused in China (~56%), USA (~18%) and Chile (~12%) (USGS, 2017). Even though there are sufficient reserves globally, over 60% of molybdenum is produced as a by-product of the mining of low-grade porphyry copper deposits. This means that the supply of molybdenum is closely related to the economics of copper mining. A drop in the price of copper could lead to a shortage of molybdenum.

Because of its strength and high melting point, molybdenum is an important component of many industrial and military applications.

Currently molybdenum is used in:

- **Alloy steels:** About two thirds of all molybdenum usage is in steel alloys and superalloys. Because of its high melting point, molybdenum alloyed with steel produces a hard, high-temperature steel. Stainless steels, produced using molybdenum, are used where high quality is required.
- **Defence:** Because of its strength and ability to withstand extreme temperatures without softening or expanding, molybdenum steels are used in armour, aircraft parts and industrial motors.
- **Lubricant:** Molybdenum is also used as a lubricant, particularly under high pressures. Either as a dry powder, or mixed with grease, it is able to withstand high pressures and high temperatures (Gray, 2009).
- **Medical uses:** Isotopes of molybdenum decay to Technetium-99m, a short lived isotope used in medical imaging (Gray 2009).

Where does molybdenum occur?

Molybdenum mostly occurs in deposits related to granitoid bodies in a class of deposits known as 'porphyry copper' deposits. As such, most of the world's molybdenum is mined as a by-product of copper mining. In the United States, a style of deposits known as 'Climax type' have molybdenum as a primary mineral but none of these are known in Australia.

Where is molybdenum found in Queensland?

There are currently no operating molybdenum mines in Queensland, but the world's highest grade deposit, which occurs at Merlin, south of Cloncurry, is undergoing development (Figure 2). This deposit represents one of the few molybdenum-dominant deposits in the world and also has high rhenium.

There are many molybdenum-bearing deposits elsewhere in Queensland which are undergoing exploration (Figure 2). In these deposits, molybdenum is associated as an accessory phase with porphyry-style mineralisation, intrusive-related tin and tungsten deposits, uranium deposits, some copper–gold deposits in north-west Queensland and in oil shales.

- **Merlin and Kalman:** For details on these molybdenum-rhenium deposits, refer to the section dealing with rhenium.
- **Greater Whitewash:** A series of molybdenum–copper–silver deposits, related to a porphyry copper–molybdenum system, have been discovered near Monto in central Queensland by Aeon Metals Ltd. The deposits have a total JORC Code compliant resource of 242 Mt grading 258 ppm molybdenum, 1173 ppm copper and 1.54 ppm silver, including indicated resources of 185 Mt grading 263 ppm molybdenum, 1189 ppm copper and 1.55 ppm silver with a contained 48 500 t of molybdenum.

- **Wolfram Camp:** The Wolfram Camp tungsten–molybdenum mine, 90 km west of Cairns, produces molybdenum as a byproduct of tungsten—its primary product. The deposit has an inferred and indicated resource of 1.42 Mt at 0.6% WO_3 and 0.12% molybdenum.
- **Anthony prospect:** Zamia Metals Limited completed a scoping study on the Anthony molybdenum project 67 km north north-west of Clermont. Mineralisation is related to a porphyry molybdenum copper system. Zamia has reported an inferred sulphide resource of 250 Mt at 0.039% molybdenum in sulphide ore body (0.02% Mo cut-off grade). It is estimated it has a contained metal resource of 121 940 t.
- **Julia Creek:** Potentially significant molybdenum resources occur within the oxidised part of the Julia Creek oil shale deposits in the Eromanga Basin in north west Queensland. Intermin Resources Limited has estimated that the oil shales contain molybdenum of slightly more than 900 000 t.

Exploration potential in Queensland

In addition to the deposits described above, resources are at Anduramba in south east Queensland, Ben Lomond East near Townsville, Maureen near Georgetown and Monument near Monto (Figure 2). Ben Lomond is one of the highest grade per tonne uranium resources in Australia with a substantial molybdenum credit at an average grade of 0.15%. Auzex Resources Limited has intersected significant molybdenum mineralisation during drilling at the Galala Range tungsten prospect west of Cairns. There is potential for the delineation of significant molybdenum resources at the Mungana and Red Dome porphyry and skarn copper-gold deposits near Chillagoe.

Scandium

Why is scandium considered critical?

The lack of production has restricted scandium's usefulness, but likely future increased production will lead to more research and more uses will emerge. Regular supply, such as that predicted to come from Queensland will see the scandium use increase and become more common.

The main current uses for scandium are:

- **Bicycle frames and golf clubs:** In scandium–aluminium alloys a small amount of scandium significantly increases the strength and corrosion resistance of the alloy. Such light, high strength alloys are currently mainly used in high performance sporting goods such as baseball bats, bicycle frames or golf clubs.
- **Advanced fuel cell technology:** In the manufacture of solid oxide fuel cells which chemically convert natural gas (or other fuels) into electricity, scandium oxide produces the most efficient cells at lower temperatures. These cells provide more efficient on-site electricity and heating and produce less carbon dioxide than conventional fuel cell technology.
- **Lighting for film and television:** High intensity discharge lamps use scandium iodide to create a light that is similar to daylight. Scandium lights are used on film sets or sporting arenas to improve television pictures because of the light quality and because they are more efficient than other high intensity lights. The USA uses 20 kg of scandium a year to create high intensity lights.
- **Fighter jets and hand guns:** Scandium alloy is also used to make high strength hand gun frames for the same reason it is used in sporting goods—it is light and strong. Russia uses the scandium–aluminium alloy in the frames of its MiG fighter airframes. This use is likely to be more common as supplies of scandium increase.
- **Defence and dentistry:** Laser crystals of gadolinium scandium (or gallium garnets) are used in strategic defence applications and in dental lasers.

Where is scandium found?

Scandium is found in the minerals thortveitite, euxenite, and gadolinite, which are rare and are believed to be magmatic in origin and occur in association with fluorite-bearing granitic pegmatite.

Scandium is often concentrated in laterite profiles in humid tropical environments. Absorption on clay minerals is a primary source for enrichment. The element is generally associated with siderophile elements like iron, chromium, and cobalt.

Where is scandium found in Queensland?

Globally significant scandium resources are located in north Queensland (Figure 2). Metallica Minerals Limited reported at the Mining 2011 Conference, that the SCONI deposits (previously NORNICO) at their Lucknow deposit south of Greenvale contains 6.24 Mt of ore at 169 g/t scandium for 1580 t of scandium oxide (Sc_2O_3) and their Kokomo deposit further north has 8.9 Mt of ore at 109 g/t scandium for 1500 t of Sc_2O_3. The deposits are lateritised serpentines and also contain nickel and cobalt resources. Currently scandium deposits are being developed in New South Wales. The price of Sc_2O_3 in 2017 was US$15 000/kg (http://www.mineralprices.com).

Exploration potential in Queensland

The distribution of scandium in Queensland stream sediment samples was tested during a national drainage geochemical survey (Tang and Brown, 2011). The survey shows several drainage systems in Queensland with anomalous scandium concentrations in the sediments. At this stage there has been no testing to determine the source of the scandium. One possible scenario is the streams sampled drain laterite anomalies which can concentrate scandium. These data suggest there is potential for more discoveries in Queensland if the predicted surge in demand eventuates. Because scandium is also concentrated along with other REE, exploration for these commodities could go hand in hand.

Lithium

Why is lithium considered 'critical'?

A major application for lithium is for production of ceramics and glasses, including heat-resistant glass and ceramics such as those used in oven wear and cook tops. It is also used in fluxes and glazes. Lithium is also used in alloys to increase strength to weight ratios, taking advantage of lithium's strength and light weight (low-density) characteristics. Aluminium-lithium alloys, for example, are used in the aerospace and motorsport industries.

Lithium is used in the manufacture of computers, communication devices and electronics, as well as medical applications, lubricants, fuel cells and nuclear technology.

In the last 12–18 months, Lithium-ion batteries have undergone dramatically increased production due to their use in electric/hybrid vehicles and also in home storage. This has led to increased price for lithium and increased exploration.

New Scientist reports that lithium-ion batteries are critical to the development of electric cars in order to make them competitive with petrol engine vehicles. They predict an increase in production of lithium carbonate (the compound used in lithium-ion batteries) from 129 000 t in 2011 to 499 000 t in 2025 (The Tesla electric car being developed in the US is predicted to require 40 kg of lithium).

Lithium is a light metal with abundant charge-carrying ions for its weight making it ideal for charge storage in batteries.

While new battery technologies are being developed, they are unlikely to be commercially available in the short term making lithium ion batteries the most advanced currently available.

Where is lithium found?

Globally, lithium is not particularly rare with low cost abundant lithium occuring in salt flats in Chile and Bolivia. In 2016, Australia and Chile were responsible for 75% of global production (USGS, 2017). Brines are also known from China and the USA. Extraction of lithium from brines is in the form of lithium chloride then needs to be converted to lithium carbonate for use in batteries – an energy intensive process.

In Australia, lithium is mostly recovered from lithium minerals, specifically the mineral spodumene ($LiAlSi_2O_6$), mostly in several deposits associated with pegmatites in Western Australia. The largest deposit is the Greenbushes deposit south of Perth.

Recent technological advances have identified a process for the low cost extraction of lithium from the mineral lepidolite, which occurs in pegmatites. This process extracts the lithium as lithium carbonate which is used directly in lithium-ion batteries. Globally, the mineral lepidolite has not been readily recorded making the resources of the mineral uncertain.

Where is there potential for lithium resources in Queensland?

The mineral lepidolite has been known in Queensland for some time but its distribution has been uncertain. Recently lepidolite has been the focus of exploration in the Georgetown region in north Queensland. Significant quantities have been found at Buchanan's Creek and the adjacent Grant's Gully south of Georgetown. Exploration of this deposit is continuing and drilling to define a resource is expected later this year.

Recently, lepidolite has been identified at Gingeralla west of Mount Garnet south west of Cairns.

Graphite

Why is graphite considered 'critical'?

Graphite has a number of traditional uses, including refractory applications (foundry facings, crucibles, retort linings), brushes in electric motors, dry cells, "lead" pencils, and as an additive in paints, lubricants and stove polishes.

The automotive industry has also adopted graphite for use in brake linings, gaskets, clutch materials and dry lubricants, while elsewhere it's been adopted for use in fire retardants and reinforcements in plastics. Graphite is now also being used in nuclear reactors to control the speed of the nuclear fission reaction.

More recently, the market for graphite has begun to expand incrementally reflecting its use in a number of green technologies including lithium ion batteries, fuel cells, flow batteries and the expansion of nuclear power development. Many of these applications have the potential to consume more graphite than all present uses combined. The proliferation of batteries used in the development of electric cars will further drive increased graphite demand in the future. Battery grade graphite involves production of a new form of graphite – spherical graphite. The manufacture of spherical graphite requires chemical modification of flake graphite and at present is mainly performed in China. However other parts of the world are seeking to manufacture the product.

A new carbon-based compound, graphene, has also been developed from flake graphite. Graphene is a 2 dimensional hexagonal lattice of pure graphite one atom thick which is very strong and efficiently conducts heat. It is 100 times as strong as steel and has exciting uses in areas such as battery technology and conductive coatings.

Where and how is graphite found in Queensland?

More recently, Graphitecorp Limited explored the Mount Dromedary flake graphite deposit located 125 km north of Cloncurry. The deposit is hosted in schist and slate and outcrops over a 3 km strike length. A preliminary drilling program over a small portion of the deposit has outlined an inferred resource. Flake sizes are in the range of 27% jumbo, 18% coarse, 6% medium, 23% fine and 26% very fine. The flake size and grade increases with depth.

Further east at a location 70 km south of Croydon, Metallica Minerals Limited encountered significant graphite mineralisation at their Esmeralda Project near Prospect Station. Their 2015 drilling program in the area targeted graphite associated with the Esmeralda Granite, based on their previous exploration for massive sulphide mineralisation in the area. The granite-hosted graphite may be formed from assimilation of highly carbonaceous metasedimentary rocks or may be formed from hydrothermal sources. The latter deposit types are typically of very high purity graphite in either flake or crystalline form, forming the basis for high grade, high value resources.

References

Gray, T., 2009: The Elements – A visual exploration of every known atom in the Universe. Black Dog & Leventahl Publishers, Inc.

Gschneidner, K.A., Jr, 1966: Rare Earths – The Fraternal Fifteen. Washington, DC, US atomic Energy Commission, Divisions of Technical Information.

Office of the Chief Economist, 2017: Resources and Energy Quarterly Report, June 2017.

United States Geological Survey, 2017: Mineral Commodity Summaries, 2017.

For further information contact

Manager, Mineral Geoscience
Geological Survey of Queensland
Department of Natural Resources and Mines
PO Box 15216, City East, Queensland 4002
Email: geological_info@dnrm.qld.gov.au

www.dnrm.qld.gov.au

CS7176 07/17