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Chapter 2

The Critical Metals: An Overview and Opportunities and Concerns for the Future

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Abstract

The critical metals are vital to modern life due to their use in a variety of domestic, green, and military high technology applications but have supplies that are inherently insecure. This study provides an overview of the concept of criticality as applied to the critical metals and outlines key issues around the resources and future supply of these metals. The methods used to quantify the criticality of critical metals have advanced over time, demonstrating that some metals are more strategically important than others, depending on the viewpoint of the organization considering criticality. However, global resources and reserves of a number of critical metals as well as their production statistics remain unclear. Methods exist to quantify the resources of critical metals with reasonable accuracy but these methods rely on information provided by the mining industry, indicating that better reporting practices would improve our knowledge of the global resources and cycling of these key commodities. Criticality can also be addressed in numerous ways, including the analysis of known mine supply chains to enable the economic extraction of critical metal by-products, the determination of the critical metal prospectivity of mining/mineral processing wastes (given a significant amount of critical metals currently deport to waste), increased amounts of recycling intermediates or end-use products containing critical metals, and the discovery of new and economic deposits of the critical metals. However, all of these approaches and the associated policy around them require more information in terms of mineral resource accounting, mineral economics, material flow analysis, mineral processing, as well as increased economic geology knowledge that would enable the making of future discoveries and increase the likelihood of critical metals being extracted as either primary or by-products. Without this information, significant parts of our knowledge base on the supply (and the security of this supply) of the critical metals will remain opaque.

Introduction

The critical metals are a group of commodities vital to modern life, but whose secure supply is at significant risk of restriction. These commodities are vital components in the manufacturing of modern (e.g., computers, smart phones, and touch screen technology) and green (e.g., wind turbines, solar panels, and large-scale batteries) technology and have a wide variety of military applications. The demand for these metals has grown significantly over recent decades for a number of reasons that are summarized in Table 1. However, it is also important to realize that there is currently no clear and uniform identification of critical and noncritical metals (as outlined by Graedel et al., 2014). The elements considered to be critical vary as a function of supply and demand and strategic considerations. These factors vary from country (or group of countries) to country, between different governmental departments, and from industry to industry, reflecting the viewpoints of the organization considering criticality and demonstrating that in general there is no objective consensus about critical metals. This is exemplified by a number of reports that assess the criticality of individual elements from the viewpoint of the organization that produced the report, such as the European Commission (2010, 2014), the U.S. Department of Energy (2010), Skirrow et al. (2013), the U.S. Department of Defense (2014), and the British Geological Survey (2015). However, even considering these necessarily subjective viewpoints (as criticality changes according to who is considering what is critical and when), it is common that the rare earth elements (REE), Ga, indium,[1] W, the platinum group elements (PGE), Co, Nb, Mg, Mo, Sb, Li, V, Ni, Ta, Te, Cr, and Mn (Table 2) are all considered to be critical and strategic commodities. They are vital for both modern technology and sustaining modern standards of living but have resources that are often dominated by a single or a small number of dominant suppliers based in one or two countries. The same situation could theoretically apply with supply dominated by one or two companies (i.e., oligopolies or monopolies), although country and company dominance often overlap, and a situation where a geographically diverse supply of a given critical metal is controlled by a single or very small number of companies has not eventuated to date.

The critical elements are also generally produced in relatively small amounts (compared to base metals, such as Cu, and bulk commodities, such as Fe; Fig. 1) or almost entirely as by-products of other metals (e.g., Graedel et al., 2014; Nassar et al., 2015b; Figs. 1, 2). The critical metals are also generally not recycled in significant quantities (e.g., Table 2), although this is dependent on both the characteristics of the metal in question and its associated end uses. For example, the REE are infrequently recycled (<1%; Binnemans et al., 2013; Jowitt et al., 2018) partly because (1) the amount of the REE used in end products ranges in magnitude from <milligrams to several kilograms, (2) these critical elements are generally used in complex physical configurations (e.g., in magnets and lasers) that require time-consuming and costly dismantling/separation processes,

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[1] We use indium rather than "In" to avoid confusion with the natural logarithm or the word "in."

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Table 1. Drivers of Increased Critical Metal Usage (critical metals are shown in bold; synthesized from Australia's Mineral Resource Assessment, 2013)

Driver of metal/material usage	Technology/product	Commodities used
Industrial production efficiency and infrastructure development	Steel, catalysts, ceramics, molds, flame retardants, cryogenics	Fe, Cr, V, **Mo**, Ni, **Co**, Mn, **PGE**, **Li**, **Ce**, Ti, **Zr**, **Sb**, He
Low-emissions energy production	Wind turbines, photovoltaics, nuclear reactors	**REE**, **In**, **Sb**, **Ga**, **Te**, Ag, Cu, **Se**, U, **Th**, **Zr**
Low-emissions energy storage and usage	Electric cars, conventional cars, batteries, wires	**REE**, **Li**, Ni, **Co**, Mn, **graphite**, **PGE**, **Sc**, Al, Mg, Ti, Cu
Communications and entertainment technologies	Microcapacitors, flat screen phosphors, semiconductors	**Te**, **Nb**, **Sb**, **In**, **Y**, **Ge**, **Ga**
Defence/security	Nuclear radiation detectors, armor and weapons, aerospace superalloys	He, **Be**, **W**, Cr, V, **Re**, **Nb**, Ni, **Mo**
Transport—fuel efficiency and performance	Light alloys and superalloys, high speed trains	Al, Mg, Ti, **Sc**, **Th**, **Re**, **Nb**, Ni, **Mo**, **Co**, **REE**
Water and food security	Water desalination, agricultural production, and fertilizers	**PGE**, Cr, Ti, P, Mg

Table 2. List of Critical Elements or Groups of Elements[1]

Element(s)	Who considers these critical?	Key mineral deposit types	Proportion recycled (%)
Rare earth elements (REE; or rare earth oxides, REO)	UK, EU, USDoD (Dy, Er, Tb, Tm), USDoE (La, Ce, Nd, Eu, Tb, Dy), Aus	Carbonatite, ionic clay, alkaline intrusion-related, laterite, heavy mineral sands, IOCG	<1
Tungsten	UK, EU, USDoD, Aus	Granite-related, placer	>10–25
Antimony	UK, EU, USDoD, Aus	Porphyry, epithermal, VMS, orogenic Au, and sediment-hosted base metal	1–10
Bismuth	UK, USDoD	Porphyry, epithermal, granite-related, VMS, orogenic Au, and sediment-hosted base metal	<1
Molybdenum	UK, Aus	Porphyry, epithermal, granite-related, IOCG	<25–50
Strontium	UK	Sediment-hosted base metal	<1
Mercury	UK	Porphyry, epithermal, granite-related, VMS, orogenic Au, and sediment-hosted base metal	1–10
Barite	UK, EU	Porphyry, epithermal, granite-related, and sediment-hosted base metal	<1
Graphite	UK, EU	Metamorphosed sedimentary rocks	no data
Beryllium	UK, EU, USDoD	Granite-related and pegmatite	<1
Germanium	UK, EU, USDoD	VMS, orogenic Au, and sediment-hosted base metal	<1
Niobium	UK, EU, Aus	Carbonatites, pegmatites	>50
Platinum Group Elements (PGE)	UK, EU, Aus	Mafic-ultramafic magmatic sulfide, alkaline intrusion-related, placer	Pd, Pt, Rh >50, Ir >25–50, Ru >10–25, Os <1
Cobalt	UK, EU, Aus	Mafic-ultramafic magmatic sulfide, sediment-hosted base metal, and laterite	
Thorium	UK	IOCG, alkaline intrusion-related, heavy mineral sands	no data
Indium	UK, EU, USDoE, Aus	VMS, orogenic Au, sediment-hosted base metal, secondary sources (e.g., slag)	<1
Gallium	UK, USDoD, Aus, EU	VMS, orogenic Au, sediment-hosted base metal, and bauxite	<1
Arsenic	UK, EU	Porphyry, epithermal, VMS, orogenic Au, and sediment-hosted base metal	<1
Rhenium	UK, EU	Porphyry, epithermal, IOCG	>50
Scandium	EU	Mafic-ultramafic orthomagmatic, laterite deposits, uranium deposits	<1
Tellurium	EU, Aus	Porphyry, epithermal, granite-related, mafic-ultramafic magmatic sulfide, IOCG, VMS, and orogenic Au	<1
Tantalum	UK, EU, Aus	Granite-related	<1
Lithium	UK, EU, Aus, USDoE	Pegmatites, Li brines, salar deposits	<1

Notes: Adapted from Jowitt (2016) and Mudd and Jowitt (2017) with additional information from the European Commission (2010, 2014, 2017), U.S. Department of Energy (2010), Mudd et al. (2013), Skirrow et al. (2013), Weng et al. (2013, 2015), Hagelüken (2014), U.S. Department of Defense (2014), British Geological Survey (2015), Chakhmouradian et al. (2015); and Jowitt et al. (2018)

Abbreviations: Aus = Australia, EU = European Union, USDoD = U.S. Department of Defense, USDoe = U.S. Department of Energy

[1] Data indicates the countries that consider these elements critical, the key mineral deposit types that contain elevated concentrations of these critical metals, and the proportion of these elements that are recycled

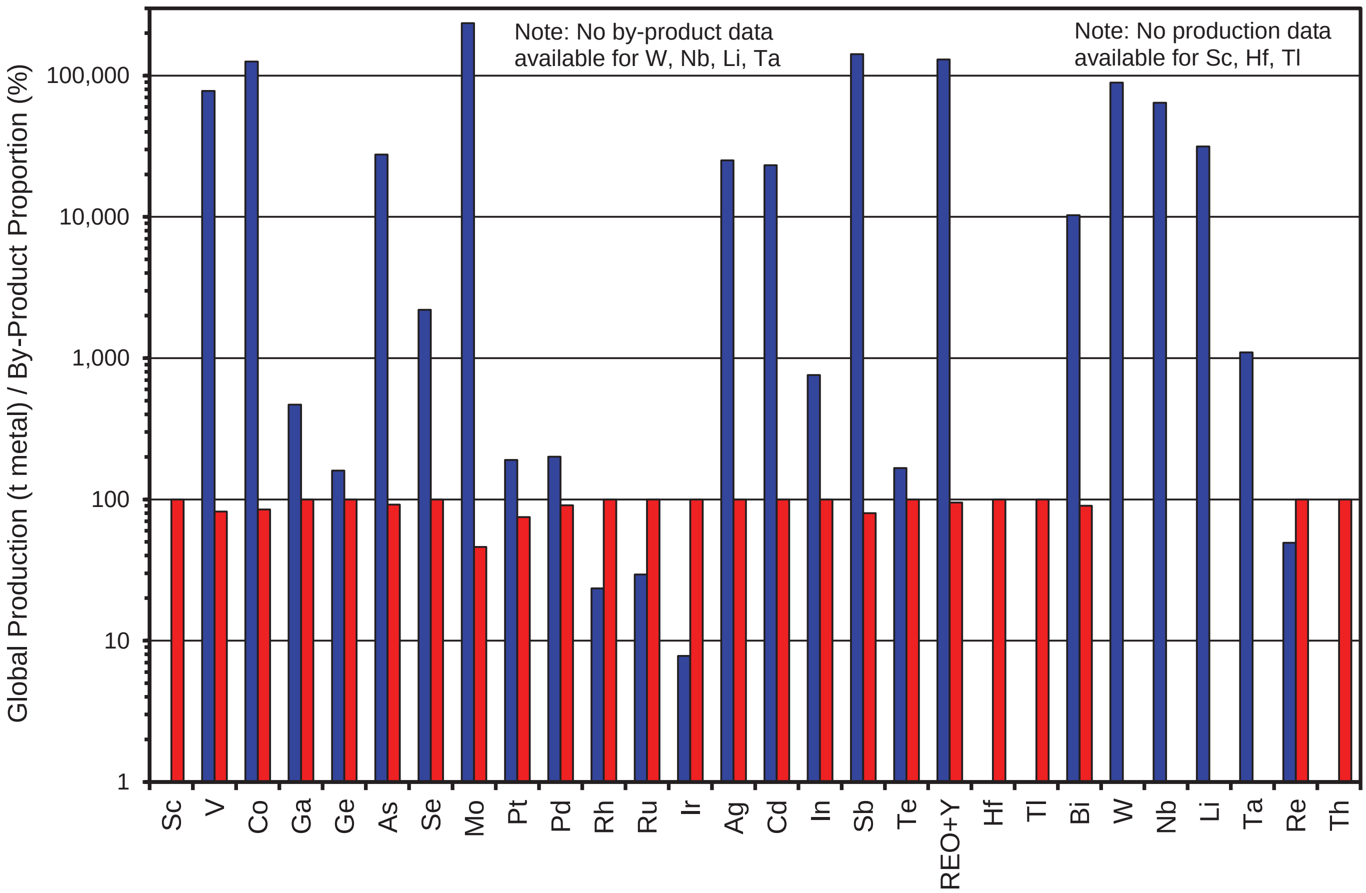

Fig. 1. Best estimates of global production of selected critical metals (blue bars) and proportion of given critical elements produced as a by-product of other metals (red bars; note that most are or very close to 100%) (data combined from Graedel and Nassar, 2013) and Tables 3, 4). REO = rare earth oxides.

(3) there is inherent difficulty in separating the individual REE from each other to yield pure single elements that can be used in a variety of end products rather than just re-used in the same way, (4) the long life of certain uses can delay the availability of these elements to recyclers (e.g., permanent magnets in electrical technologies; Binnemans et al., 2013), and (5) the relatively small volumes of the REE in current circulation impede the development of high-volume recycling.

All of the factors outlined in this introduction, namely a lack of clear and uniform identification of critical and noncritical metals, the fact that these elements are produced in relatively small amounts and usually as by-products of other metals and the fact that they are not recycled in significant quantities, all significantly increase the complexity of the economics of these critical metals. A lot of these elements also currently end up in waste material (e.g., Werner et al., 2015). This complexity is compounded by the interplay between the variables that control their economics and their potential price volatility (e.g., the REE; Weng et al., 2015), especially when compared to base and precious metals and bulk commodities. Our understanding of these issues, which are key to both sustaining our modern way of life and the somewhat nascent critical element minerals industry, is still somewhat in its infancy despite a growing body of research in this area. Here, we provide a comprehensive overview of the critical metals, the nature of criticality, global critical metals resources and production, and what we need to understand to ensure secure supplies of these metals into the future. This paper focuses on providing an overview of the state of knowledge of the critical metals and indicates areas where the knowledge that forms the basis of mineral exploration, economic geology, scientific research, policy, economic, strategic, exploration, environmental, and social decisions needs to be improved.

Criticality and the Concept of "Critical Metals"

Modern lifestyles are supported by the production of a wide range of minerals and metals, with the number of elements we consume increasing over time as a result of ever-increasing technological complexity. Modern high-technology devices such as smartphones, increased computing power, renewable and green energy, pollution controls, etc. all require increasing amounts of these critical metals. This has led to a range of elements being considered critical, although as discussed below, the precise definition of criticality differs according to the viewpoint of the organization and country dictating what they consider critical (e.g., Jowitt, 2015; Sykes et al., 2016). The initial discussions over critical metals or elements and criticality began with the 2008 publication of "Minerals, Critical Minerals, and the U.S. Economy" (U.S. National Research Council, 2008). This publication examined whether

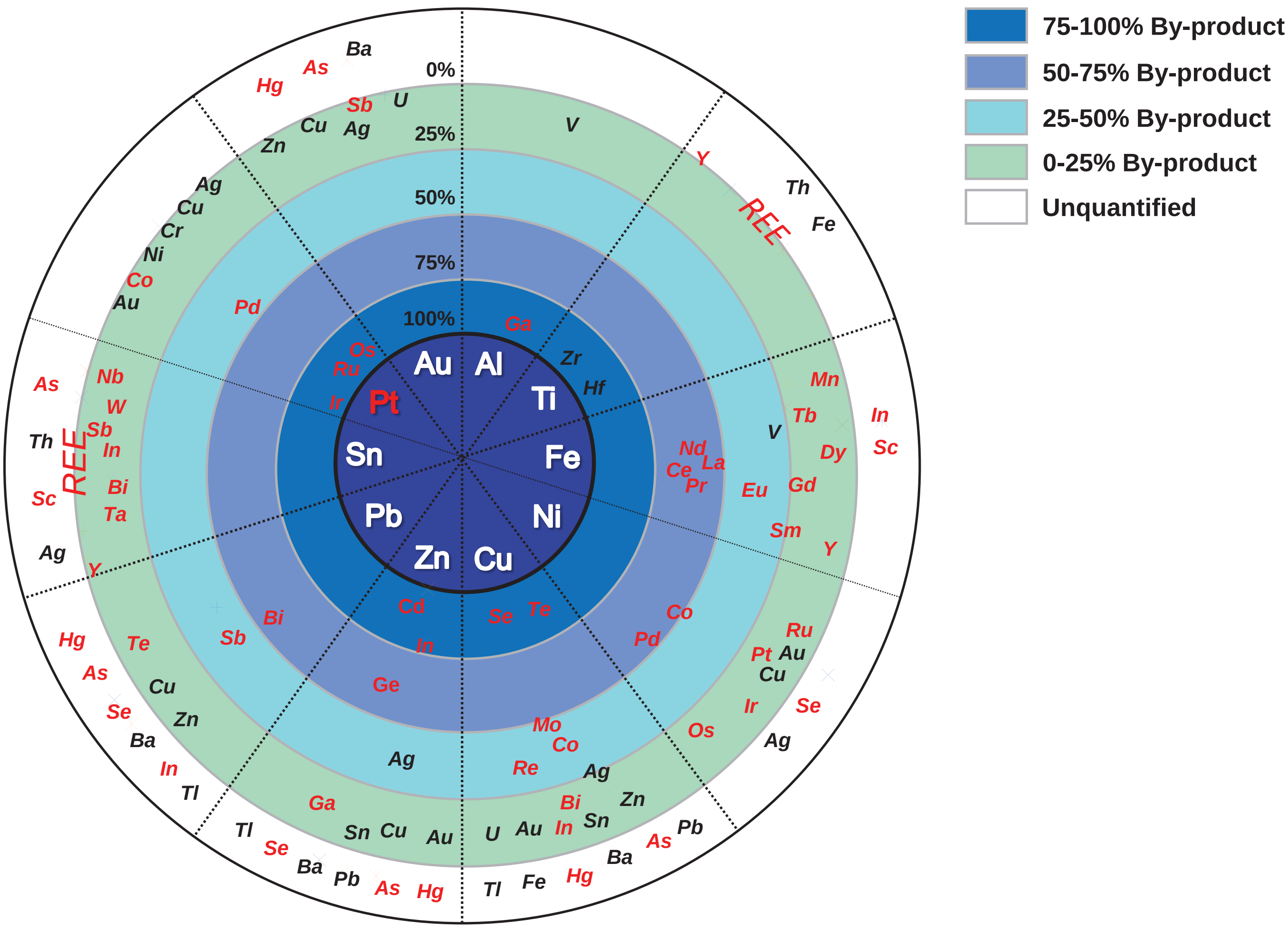

Fig. 2. The wheel of metal companionality (adapted from Nassar et al., 2015b). The diagram shows the relationship between primary metal (the central part of the wheel) and by- or co-product elements, indicating the percentage of the production of these elements that is associated with the metal at the center of the wheel. Critical metals are labeled red in this diagram, showing the reliance that the vast majority of these metals have on primary production of a small range of primary metals.

the security of supply of mineral and metal commodities was at risk of negatively affecting the United States economy by focusing on the importance of use and the availability of individual minerals or metals. More recent research (as summarized in Table 1) highlighted a list of elements that are considered critical by a range of different organizations, countries, and groups of countries, leading to uncertainty over which elements are considered critical. The uncertainty caused by these different viewpoints on criticality is compounded by a lack of understanding of how the mining and mineral industry operates, how this relates to resource and reserve reporting, and the opaqueness in the reporting of global and local critical metal resources relative to actual (and potential) production. What is certain is that there is a fundamental need to further our understanding of the nature of criticality, how that relates to the data made available by governments and the mining industry, and how these factors intersect.

What is criticality?

The degree to which a metal is considered critical is based on the following: geologic and economic factors, technological evolution, potential for substitutes, environmental impacts, and usages of the metal. An example of this is the Pt that is used in catalytic converters in vehicles for pollution control and during oil refining, which is generally sourced from mines within the Bushveld Complex of South Africa (Mudd et al., 2018). This has led to concerns about both the longevity of the Bushveld operations that supply this critical metal, the infrastructure required to support Pt and PGE production in South Africa, and major social and political concerns that have previously and could again also influence Bushveld production. A second example is the REE, which are used globally in military applications, high-technology consumer products such as smartphones and laptops, and green technology such as wind turbines but are dominantly supplied from China (e.g., Weng et al., 2015). The criticality of the REE was highlighted by the export restrictions that were imposed by China between 2006 and 2014, leading to a price spike and significant concerns over the security of supply of these key elements (Weng et al., 2015). The concerns over the security of supply of these critical elements were highlighted in the United States by Executive Order 13,817 (2017), which asserted that the United States is almost completely reliant on foreign sources for these critical metals and identified the need to determine the size and nature of potential domestic sources for these commodities.

Researchers have refined ways to quantify criticality in recent years to better understand criticality and inform decision making. The criticality of an element is measured as a function of the risk of supply restriction, the environmental implications of the production and usage of an element, and the vulnerability to supply restriction for that given element (Graedel et al., 2012). The supply risk of an element is determined by assessing three different sets of factors: (1) geological, technological, and economic factors; (2) social and regulatory factors; and (3) geopolitical factors. The first component measures supply availability of a given element and the other two factors assess the degree to which availability of supply may be constrained, all of which are assigned a numerical value between 1 and 100 to quantify the supply risk score (e.g., Graedel et al., 2012). These supply risks are very timescale dependent, indicating that no single approach is suitable for all timescales or all interested parties, leading to the scenario depicted in Table 2. The increased understanding of the environmental implications of mining must also be accounted for in forward-thinking metal supply models. These implications include the toxicity of metals, use of energy and water during extraction, management of mine tailings and waste rock and total emissions to air, water, and land. The social impacts of mining also need to be considered, such as social license to operate and considerations of sustainable development. Both environmental and social factors vary significantly depending on the type of mine/deposit and the location of the deposit (including social and political environments), as well as regulatory and socioeconomic contexts. The last aspect of criticality is the vulnerability to supply restriction, which varies depending on the observer and their organizational level because a single element may be vital to a given corporate entity but may be insignificant on a global level (e.g., Graedel et al., 2012). This is clearly demonstrated by the variations in criticality assessments between the national and multinational organizations depicted in Table 2. Here, we focus on vulnerability to supply restriction at a national and global levels. This aspect is based on two or three different components, with national vulnerability based on the importance of a given metal, how substitutable that metal is, and how susceptible a given country is to restrictions in supply. Global assessments of criticality clearly ignore the susceptibility aspect of the vulnerability of supply restriction.

The economic geology of the critical metals

Understanding the criticality of the critical metals requires an understanding of their geologic context and the nature of the primary sources of these metals. As discussed elsewhere, the majority of the critical metals are derived as by-products of the mining of other primary commodities, although these by-products can be concentrated to potentially economic levels within a variety of different mineralizing systems (Table 2). The simplest way to visualize the relationships between critical metals and mineralizing systems is to use the approach of Skirrow et al. (2013), who divided mineralizing systems into a total of nine mineral systems families; this section is adapted from this comprehensive overview of critical metals-related systems:

1. Porphyry-epithermal magmatic-hydrothermal mineralizing systems typically associated with the generation of Cu-Au-Mo dominated porphyry, Au-Ag-Zn-Cu-Pb epithermal, and Cu-Au-Zn-Pb-Ag skarn deposits, usually within magmatic arc-type convergent tectonic settings (e.g., Sillitoe, 2010). These systems are associated with enrichments in critical elements such as Mo, Re, W, Sn, As, Bi, Li, Se, Te, Pt, and Pd (but not the other PGE), Sb, Bi, Ga, In, Ge, Mn, and Cd, although not all to economic levels (e.g., John and Taylor, 2016; Kelley and Spry, 2016). These deposits dominate global Mo, Re, and Se production and also generate significant amounts of Te.
2. Granite-related mineralizing systems associated with often generally reduced felsic magmatism in broad convergent margin-type settings, although the magmatism and associated mineralization can be either orogenic or postorogenic. This group of mineral deposits includes granite-related Sn-W-F (and associated skarn; e.g., Dostal, 2016), pegmatitic Ta-Nb-Cs-Li-Be-F (Černý, 1991; London, 2008), porphyry-type Mo (e.g., John and Taylor, 2016), and intrusion-related gold systems. These mineral systems are associated with enrichments in Sn, W, Mo, Re, U, Be, the REE, Nb, Ta, As, Bi, In, F, Ga, In, Ge, Mn, Cd, Be, Li, and Cs, although again not all of these are present at economic concentrations and the commodities present vary significantly as a function of the subtype of granite-related mineralizing system being considered.
3. Iron oxide-copper-gold (IOCG) mineralizing systems, as exemplified by Olympic Dam and the associated IOCG deposits of the Gawler craton, Australia, as well as a number of other districts globally. In general, IOCG deposits are enriched in Cu and Au, as well as a range of other elements, including U, the REE, As, Ba, Bi, Cd, Co, Cr, F, In, Mo, Nb, Re, Sb, Se, Sn, Sr, Te, V, W, Y, and Zn, although very few of these are extracted in any significant amounts (e.g., Williams et al., 2005).
4. Mafic-ultramafic-related mineralizing systems where commodities of interest are concentrated as a result of orthomagmatic processes that form sulfides or oxides or alloys that are preferentially enriched in Ni, Cu, and a number of critical metals, including the PGE, Cr, Ti, V, and Co, all of which are economically extracted from these types of mineral deposits (e.g., Arndt et al., 2005; Barnes and Lightfoot, 2005). These systems also have minor enrichments in elements such as Mo, Se, Te, Co, and Sc, although these elements are infrequently extracted from these systems.
5. Volcanogenic massive sulfide-type mineralizing systems associated with hydrothermal vents located in ancient and rarely modern (e.g., the Solwara deposit offshore of Papua New Guinea) generally extensional seafloor environments, such as back-arc basins and rifted arcs. These deposits contain significant amounts of Cu, Zn, Pb, Au, and Ag, depending on the interactions between the mineralization systems and the type of environment and host rock. In terms of critical metals, they are also variably enriched in Cd, Sb, Te, Hg, As, Ga, In, Ge, Mn, Mo, Re, Se, Bi, Sn, some of which are already extracted

during processing and refining of these types of ores (e.g., Monecke et al., 2016).

6. Orogenic mineralizing systems, including orogenic Au systems, form during continent-continent and continent-oceanic collisional events and are generally hosted by granite-greenstone or turbidite-dominated sedimentary environments. They produce Au, Ag, Sb, Zn, Pb, and W, and are also enriched in critical elements such as Te, Bi, As, Cd, Mo, and Hg (e.g., Goldfarb et al., 2016).
7. Sedimentary basin-hosted mineralizing systems, including sediment-hosted Pb-Zb-Ag-Sb-Cd-Hg-Ba, Cu-Co-Ag, U-Cu-PGE-Au, and phosphate-related Sr-V-U-Cd-Mo-Se deposits. These deposits form in sedimentary basin environments as a result of hydrothermal fluid flow within these systems. They are important sources of Cu, Zn, Pb, Co, Ag, and U, and are enriched in Cd, Ga, Ge, In, Hg, Bi, Sb, As, Pd, and Pt (but not the other PGE), V, Se, and Mo, although these enrichments vary according to the mineralizing systems being considered (e.g., Marsh et al., 2016). For example, sediment-hosted Pb-Zn deposits may be enriched in Cd and In, but sediment-hosted Cu-Co deposits are unlikely to be enriched in these commodities. Sedimentary phosphate deposits are also enriched in Sr, the REE, Cr, V, Mn, U, Ni, Cd, Mo, Co, Se, Te, As, Th, and Sb, although none of these are currently recovered (e.g., Emsbo et al., 2016).
8. Alkaline intrusion-related mineralizing systems, including mineralization associated with carbonatites, kimberlites, and other alkaline systems (Dostal, 2016; Verplanck et al., 2016). These deposits produce diamonds, the REE, Cu, Nb, Y, Zr, Ta, U, Fe, Ti, and P, and are the world's most important source of the REE (e.g. the Bayan Obo carbonatite) and Nb (e.g., the Araxa carbonatite, Brazil), among other critical elements.
9. Surficial mineralizing systems where commodities of interest are concentrated as a result of surface processes such as weathering-related supergene enrichment or the concentration and deposition of minerals in economic quantities as a result of sedimentary processes (e.g., Ernst and Jowitt, 2013; Mudd and Jowitt, 2016; Munk et al., 2016; Sanematsu and Watanabe, 2016; Sengupta and Van Gosen, 2016; Verplanck et al., 2016). These deposits include Ni-Co-Sc laterite, Al bauxite, Zr-Ti-REE-Y-Th heavy mineral sands, calcrete-hosted U-V, brine-hosted Li-B-K, marine Mn, placer Au-Sn-Ta, and supergene-enrichment zones associated with Au-Ag-Pb-Cu mineralization. This wide variety of surficial process-related deposits are variably enriched in critical elements, some of which form primary products (e.g., within heavy mineral sands operations). These include Mn, Cr, Co, Sc, Zr, Ti, the REE, Y, Th, U, V, Li, Sn, Ta, Nb, Ba, Sr, Ga, Ge, As, Mo, the PGE, W, Hg, and Sb, although the specific enrichments present vary as a function of the protolith undergoing weathering or erosion to generate these surficial deposits.

This demonstrates that current knowledge of the economic geology of the critical metals is certainly more than sufficient to understand which broad mineralizing processes can concentrate specific critical metals. However, this also highlights some of the knowledge gaps in our understanding of critical elements and their geologic context. For example, although we know that IOCG systems can concentrate the REE, the deportment of the REE within these systems (i.e., which minerals host the REE and whether these minerals can be processed) is still relatively unknown. This lack of understanding hampers the assessment of whether the extraction of these critical elements could improve (or would detract) from the economics of a given operation.

Criticality issues

One of the key issues in global critical metal accounting, or determining global resources and reserves of the critical metals, is the way the mining industry reports ore reserves and mineral resources. For bulk commodities and the majority of major metals and minerals, reporting reserves and resources is routine and is guided by a series of formal codes and guidelines, such as the Australian JORC and Canadian NI43-101 instruments. However, the vast majority of critical metals are by-products of primary metal mining and processing (Figs. 1, 2). This means that the grades of these metals are not always reported in resource and reserve statements, even if they are recovered at some point during mineral processing. This is exemplified by indium, a metal critical to liquid crystal display, solar panel, and touch screen technology (Schwarz-Schampera, 2014; Tolcin, 2014; Werner et al., 2015, 2017a, b). Indium is typically present in recoverable concentrations in Zn deposits and is associated with sphalerite and therefore typically deports to Zn concentrates during mineral processing (e.g., Mudd et al., 2017a). However, the amount of indium within Zn concentrates may be relatively small and therefore does not contribute much to the economic value of the concentrate despite their relatively high unit values. This is primarily a result of the ratio of primary to (potential, i.e., critical metal) by-products within ores being currently mined and the resulting concentrates and the small size of critical metals markets compared to other base and precious metals (e.g., Sykes et al., 2016; Fig. 3). The primary to by-product ratio within ores and concentrates reflects the geology of the ore deposits being mined. For example, it would be possible to explore for Co-Cu deposits instead of Cu-Co deposits, but this has not been undertaken in the past because of the relative sizes and values of the Cu and Co markets; thus exploration has focused on the commodities we now mine as primary products, rather than those we mine as by-products (in the main including the critical elements). In other words, critical metals are often by-products rather than primary products for economic reasons not geologic reasons, suggesting that economic geology could provide some solutions to the criticality issues surrounding some critical metals.

This has two major implications for assessing global resources of critical metals and the criticality of any given element. First, the potentially low concentrations of critical metals within a given mineral deposit may not even be determined based on the assumption that these commodities are of insignificant value. This means that a significant number of critical metals are unreported or are ignored at the mineral resource reporting stage. This issue is compounded if other resource accounting by geological surveys and other organizations takes the available data and calculates global resources by assuming a typical critical metal to primary product ratio

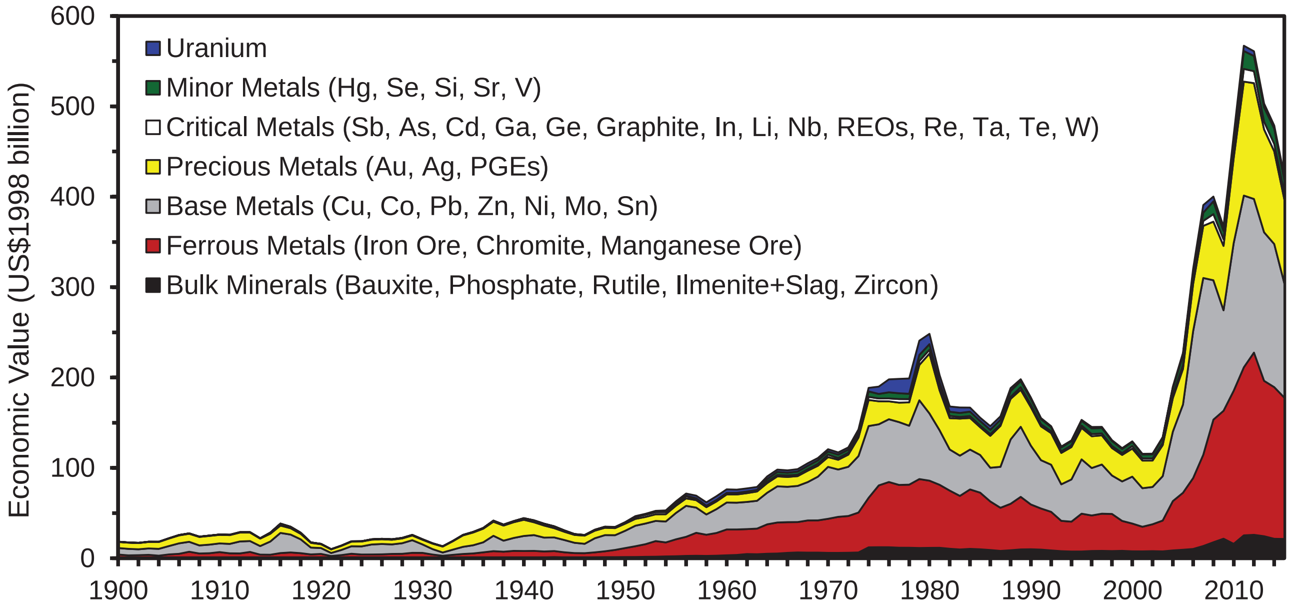

Fig. 3. Market value of major groups of metals and minerals over time in US$1998. Data synthesized from British Geological Survey (1913–2016), Schmitz (1979), Mohr et al. (2012), and Kelly et al. (2017). REOs = rare earth oxides.

based on these available but inherently biased data. Second, the fact that the dominant value of the concentrate is the contained primary metals (e.g., Zn in the case of indium), rather than by-products such as the critical metals, means that this concentrate will be processed at the smelter or refinery that provides the best economic return for these primary metals, rather than being preferentially directed to a refinery equipped with a critical metals (e.g., indium) recovery circuit, but at potentially less attractive economics.

Mining companies logically focus on the most dominant economically valuable commodities (e.g., Cu, Ni, Zn) in a mine or exploration program, meaning that commodities such as the critical metals that have small (including the critical metals; Fig. 3) or volatile markets or that are difficult to extract are often ignored. Jaireth et al. (2014) and Weng et al. (2015) highlight Olympic Dam as one example of this, where the REE contained within the deposit are estimated to be of equivalent value to the Cu, U, Au, and Ag within reported reserves and resources. However, BHP Billiton, the owner and operator of the mine, has not considered REE production from Olympic Dam as "the technology available to recover these is not economically viable at this point in time" (BHP Billiton Ltd., 2011, p. 81). Laterite-hosted Ni deposits provide another example, where the companies exploiting these deposits focus on Ni and may ignore potential Co or Sc production as a result of the mineral processing configuration chosen for specific projects (e.g., Mudd et al., 2013). These scenarios are applicable to a wide range of critical metals (e.g., Ga, Te, Ge, Se, Cd, Co, Hf, Re, and others; Figs. 1, 2), indicating that the supply of these elements is intrinsically linked with the economics and mineral processing characteristics of other commodities.

One other important consideration is that many by-product metals have increased price volatility relative to their primary metal hosts (e.g., Co; Mudd et al., 2013), reflecting the small market size of the majority of the critical metals. This suggests that the same incident (e.g., a temporary closure of a critical metal-producing mine) would have a bigger impact on a smaller market than a large one). This volatility causes mining companies to often ignore by-products such as the critical metals. This is exemplified by a scenario where a reduction in demand for a primary metal coincident with an increase in the demand for a by-product could limit the supply of the latter. This is particularly challenging in cases where the critical metals in question are only produced as a by-product of a specific primary metal production, such as Te and Se production from Cu (Fig. 2).

Another aspect of uncertainty in critical metals is the lack of quality of production data. Global and country production figures are available and are undoubtedly fairly accurate for certain critical elements, such as the REE (Fig. 1; although some uncertainties remain over unreported smuggled production of the REE from China) and the PGE (Fig. 1). However, production data are either not available, are based on data of unclear or uncertain provenance, or contain significant uncertainties for a range of other critical elements (e.g., Table 2). These uncertainties are exemplified by the data for Te and Se, which have a range of critical uses in modern and strategic technology (Table 1). Global metal production data are regularly reported by both the U.S. Geological Survey and the British Geological Survey, with both organizations having excellent reputations for providing accurate data. However, the data available for these critical metals varies depending on the reporting organization; for example, Figure 4 shows significant disparities between global production statistics for Se and Te from these two organizations. Other metals do not have any reliable global production statistics, making the markets for these metals very opaque (Fig. 1). All of this indicates that precisely and accurately determining the criticality of given elements is difficult. This lack of data can be misunderstood or misinterpreted, such as the case when only a small number of reported resources of a given critical metal do not

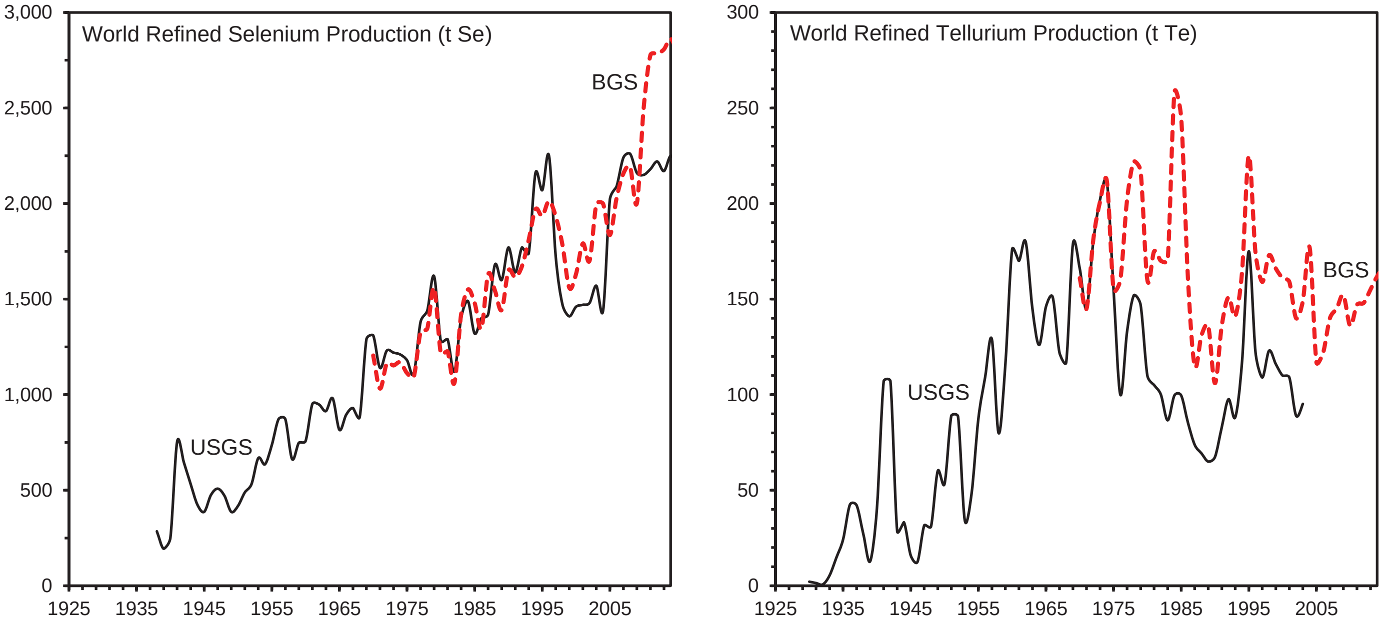

Fig. 4. Comparison of global selenium and tellurium production figures from the U.S. Bureau of Mines (1933–1993) and the U.S. Geological Survey (1994–2014; both compiled as USGS) and from the British Geological Survey (1913–2016).

include global production from unreported sources such as Se from porphyry Cu systems (e.g., John and Taylor, 2016).

These uncertainties are compounded by a number of publications (e.g., Cohen, 2007; Moyer, 2010; Ragnarsdóttir and Sverdrup, 2015) that assert that we only have a certain (i.e., low) number of years of given key commodities remaining. Cohen's (2007) estimate that only four to 13 years of indium remain to be extracted is one example of this type of prediction, although to date the world certainly has not run out of indium. For example, Werner et al. (2017a, b; 2018) indicate that known resources would meet current demand (including increased demand) to 2060, some 40 years more than the estimate of Cohen (2007). The suggestions of Ragnarsdóttir and Sverdrup (2015) and, to a point, those of Nickless et al. (2014) that we may have already reached peak production of all metals, materials, and fossil fuels are also somewhat misleading. The problems with these assumptions are neatly summarized by Tilton (1996) and later by Meinert et al. (2016), both of whom outline that these and earlier studies are based on current reported reserves without considering that reserves and resources can grow over time due to exploration success (e.g., Jowitt et al., 2013), that new technologies can improve recovery and the grades of ore that can be economically exploited, and many other considerations. Furthermore, Nickless et al. (2014) and Meinert et al. (2016) assert that the overall economics of mining and mineral exploration as well as the way mineral exploration operates is generally poorly understood by both scientists and the general public, an issue that urgently needs to be addressed.

Overall, it is clear that there are significant uncertainties in quantifying criticality and its various aspects. However, even if accurately estimated, the interpretations of how one responds to these perceived risks can vary considerably. In many cases, this is appropriate, as strategies to manage criticality should reflect a country's or company's contexts. For example, low rates of recycling of an element alone do not suggest that recycling is the best option to achieve its supply security. In the case of indium in Australia, significantly greater gains can be made through increased focus on adaptations made during mining, smelting, or refining processes than through increased recycling.

Global Critical Metals Resources: What We Know, and What We Need to Know

What we know about global critical metals resources

A significant amount of publicly available and robustly reported information (e.g., as a minimum resource and reserve data as well as more robust country and global resource assessments) is available for some critical metals. This information is primarily available for elements that are produced as primary rather than co- or by-products (e.g., the PGE and the REE), or for those elements that have significant market sizes (e.g., cobalt; Mudd et al., 2013). These data are highlighted in Tables 3 and 4, although key information is still missing from these databases (e.g., Fig. 1).

Understanding where future supplies of critical metals will come from requires knowledge of current resources of these critical metals. However, as outlined above and exemplified by Table 2, significant knowledge gaps are present in current global critical metals assessments. One example of this is resource data for Re that are reported annually by the U.S. Geological Survey but have largely remained unchanged for over 20 years, raising questions as to the accuracy of this information. Critical metal assessments may also significantly underestimate critical metals resources due to either not fully understanding resource reporting or assumptions that the critical metals outlined in resource and reserve reporting represent all critical metals abundances. This assumption ignores the fact that critical metals are known

Table 3. Economic Aspects of Selected Primary Commodity Production, Unit Prices, and Approximate Market Values (year 2015; sorted by market value)

Primary metal	Relative supply risk [1]	World production [2]	Lead-producing country (%) [2]	Price (US$/t) [2]	Market value (US$M)	World reserves [3]	Lead reserves country (%) [3]	Our reserves/resources
Iron ore	5.2	2,280 t saleable ore	Australia (35.8)	81.19	185,113	186,000 t saleable ore	Australia (29.2)	no data
Gold	4.5	3,100 t Au	China (14.5)	37,395,498	115,926	56,000 t Au	Australia (16.3)	54,026 /195,897 t Au [4]
Copper	4.8	19.1 Mt Cu	Chile (30.2)	5,500	105,059	720 Mt Cu	Chile (29.2)	631.2 /3,021.3 Mt Cu [5]
Nickel	5.7	2.28 Mt Ni	Philippines (24.3)	11,831	26,975	79 Mt Ni	Australia (24.1)	?/296.2 Mt Ni [6]
Zinc	4.8	12.8 Mt Zn	China (33.6)	1,931	24,720	200 Mt Zn	Australia (31.5)	?/610.3 Mt Zn [7]
Silver	7.1	25,100 t Ag	Mexico (21.4)	505,496	12,687	570,000 t Ag	Peru (21.1)	?/~1,500,000 t Ag [8]
Manganese	5.7	53.2 Mt Mn conc. [9]	South Africa (33.7)	213 [10]	11,353	~1,375 Mt Mn conc. [11]	South Africa (32.3)	no data
Lead	5.5	4.95 Mt Pb	China (47.3)	1,786	8,839	89 Mt Pb	Australia (39.3)	?/226.1 Mt Pb [7]
Bauxite	-	293 Mt bauxite	Australia (27.6)	26	7,618	28,000 Mt bauxite	Guinea (26.4)	no data
Chromium	6.2	30.4 Mt Cr	South Africa (46.1)	217	6,597	>480 Mt Cr	Kazakhstan (~47.9)	no data
Uranium	5.5	71.3 kt U_3O_8 [12]	Kazakhstan (39.3)	80,374	5,733	6,911 kt U_3O_8 [12]	Australia (29.1)	11,043 kt U_3O_8 [13]
Tin	6.0	289 kt Sn	China (38.1)	16,072	4,645	4,800 kt Sn	China (31.3)	no data
Molybdenum	8.1	235 kt Mo	China (35.3)	15,010	3,527	11,000 kt Mo	China (39.1)	10,168/73,679 kt Mo
Zircon	6.4	1.52 Mt zircon	Australia (37.3)	1,061	1,613	78 Mt zircon	Australia (65.4)	no data
Vanadium	8.6	77.8 kt V	China (54.0)	9,171	714	15,000 kt V	China (33.3)	no data
Ilmenite	4.8 [15]	6.19 Mt TiO_2 [16]	South Africa (20.7)	110	681	740 Mt TiO_2 [16]	Australia (27.0)	no data
Rutile	4.8 [15]	0.76 Mt TiO_2 [16]	Australia (50.0)	840	638	54 Mt TiO_2 [16]	Australia (40.7)	no data

Notes: [1] British Geological Survey (2015); [2] U.S. Geological Survey (2017) (unless otherwise noted); [3] U.S. Geological Survey (2016); [4] data updated from Jowitt and Mudd (2014); [5] Mudd and Jowitt (in review); [6] Mudd and Jowitt (2014); [7] Mudd et al. (2017b); [8] Silver resources extracted from Cu resource data (exclusive of Pb-Zn deposits, see [5]), Pb-Zn resources data (exclusive of Cu deposits, see [7]) and Au resources data (exclusive of Cu and Pb-Zn deposits, see [4]); [9] Brown et al. (2017); [10] Office of Chief Economist (2017); [11] assumes 620 Mt Mn from USGS reserves data (see [3]) and 45% Mn grade in saleable concentrates; [12] OECD-NEA and IAEA (2016); [13] data for year 2011 from Mudd (2014); [15] no specific risk index given for rutile or ilmenite, value for titanium used instead; [16] reported as titanium dioxide content of ilmenite or rutile

Table 4. Economic Aspects of Critical Metals Production, Unit Prices, and Approximate Market Values (year 2015; sorted by market value)

Primary metal	Relative supply risk [1]	World production [2]	Lead-producing country (%) [2]	Price (US$/t) [2]	Market value (US$M)	World reserves (USGS) [3]	Lead reserves country (%) [3]	Our reserves/resources
Platinum group elements (PGE)	7.6	451.2 t PGEs [4]	South Africa (60.9) [4]	26,214,070 [5]	11,785	66,000 t PGE	South Africa (95.5)	16,775/105,682 t PGE [6]
Cobalt	8.1	126 kt Co	DRC (50.0)	28,439	3,583	7,100 kt Co	DRC (47.9)	?/26,793 kt Co [7]
Tungsten	8.1	89.4 kt W	China (81.7)	23,948	2,141	3,300 kt W	China (57.6)	-
Rare earth oxides (REO)	9.5	0.13 Mt REOs	China (80.7)	15,776 [8]	2,051	130 Mt REO	China (42.3)	?/619.5 Mt REO [9]
Niobium	6.7	64.3 kt Nb	Brazil (90.2)	24,000	1,543	>4,300 t Nb	Brazil (~95.3)	-
Antimony	9.0	142 kt Sb	China (77.5)	7,209	1,024	2,000 kt Sb	China (47.5)	-
Indium	8.1	759 t In	China (46.1)	410,000	311	no data	no data	?/356,000 t In [10]
Lithium	7.6	31.5 kt Li	Australia (44.8)	6,500	205	14,000	Chile (53.6)	?/23,600 kt Li [11]
Tantalum	7.1	1,100 t Ta	Rwanda (37.3)	158,061	174	>100,000 t Ta	Australia (~67.0)	-
Germanium	8.6	>160 t Ge	China (~71.9)	1,000,000	160	no data	no data	-
Gallium	8.6	469 t Ga	China (93.2) [a]	317,000	149	>1,000,000 t Ga	no data	-
Bismuth	8.8	10.3 kt Bi	China (72.8)	14,176	146	370 kt Bi	China (64.9)	-
Rhenium	7.1	49.4 t Re	Chile (52.6)	2,750,000	136	2,500 t Re	Chile (52.0)	?/~135,000 t Re [12]
Selenium	6.9	2,200 t Se	Japan (35.1)	48,700	107	120,000 t Se	China (21.7)	-
Cadmium	7.1	23.2 kt Cd	China (32.8)	1,470	34.1	no data	no data	-
Arsenic	7.9	27.6 kt As	China (71.2)	845	23.3	no data	no data	-
Tellurium	-	~167 t Te [13]	USA (30.0) [13]	77,000	12.9	25,000 t Te	Peru (14.4)	-

Notes: [1] British Geological Survey (2015); [2] U.S. Geological Survey (2017) (unless otherwise noted); [3] U.S. Geological Survey (2016); [4] Johnson Matthey (2016); [5] production-weighted average PGE price data synthesized from [2] and [4]; [6] Mudd et al. (2018); [7] Mudd et al. (2013); [8] data combined from [1] and [9]; [9] Weng et al. (2015); [10] Werner et al. (2017b); [11] Mohr et al. (2012); [12] Werner et al. (2018); [13] Brown et al. (2017); - = no data to be produced from deposits where no critical metals are reported within resources or reserves determined using Committee for Mineral Reserves International Reporting Standards (CRIRSCO) reporting codes. For example, Freeport-McMoRan does not report Re in their reserves or resources for the Sierrita mine, United States, a mine that is known to produce Re, or for that matter at any of their other Re-producing sites. It is therefore sometimes even unclear which mines actually produced the critical metals that end up in circulation. This means that other methods of assessing critical metals resources are required, outlining a key difference between these often co- and by-products and more typical base and precious metals.

There are a number of ways of dealing with the uncertainties present in global critical metal resource assessments. The first is the use of proxies and statistical modeling to estimate the amount of a given critical metal that is typically present in a given type of mineral deposit (e.g., Frenzel et al., 2015; Werner et al., 2017a, b). These proxies include the relationship between critical metal concentrations and the concentrations of metals that are more typically determined during resource and reserve assessments. For example, the abundances of elements such as Se, Te, and indium relate to the ability of these metals to substitute into the lattices of minerals such as chalcopyrite and sphalerite. This indicates that the relationship between grades of these commonly reported metals and the grades of critical metals in the comparatively few deposits that report them can be used as a proxy for the concentrations of critical metals in the same types of mineral deposits that do not report any information on critical metals concentrations (e.g., Frenzel et al., 2015; Werner et al., 2017a, b). This approach relies on the fact that the processes that cause the concentration and precipitation of base and critical metals are similar within given types of mineral deposits (although clearly these processes may vary between mineral deposits). Other possible proxies include the relationships between base and critical metals in large whole-rock or surficial sample databases (e.g., Werner et al., 2017a, b), although these proxies may be considered less reflective of the processes that operate in mineralizing environments. A final proxy is the use of an average value, either an overall average concentration of a given critical element in certain (or all) mineral deposits, or the average concentration of a given critical element relative to the concentration of a base or precious metal (e.g., Werner et al., 2017a, b). However, as Figure 5 shows, the average ratio of critical metals to base metals can vary significantly, adding extra uncertainty to both this proxy and the first proxy based on individual mineral deposit types outlined above.

The controls on these variations are unclear as they may reflect either natural geologic variability (meaning it is vital to split proxies up by, for example, mineralizing processes) or increasing demand, knowledge, and/or value of critical metals. This is clearly shown by Figure 5, where the ratio of indium to zinc in global metal production is matched by an increase in global indium production. This suggests that the increasing value and demand for indium has led zinc producers to increase indium production, primarily by sending concentrates to refineries with indium extraction capabilities. However, this does not solve the problem of which indium to zinc ratio should be used to estimate global indium resources (assuming a version of this proxy is used) as these statistics are economically or logistically based, rather than reflecting the geologic processes that concentrate indium within zinc-bearing minerals such as sphalerite. Using the maximum indium to zinc ratio (e.g., Werner et al., 2017b) would most likely (but not definitively) still yield an underestimate of global potentially recoverable indium resources, given that certainly not all indium is recovered (despite the increase in both indium production and indium to zinc production ratios). To summarize, it remains unclear which of these proxies is the most accurate, as exemplified by the application of all of these to the case of indium (Werner et al., 2017a, b), an approach that yielded

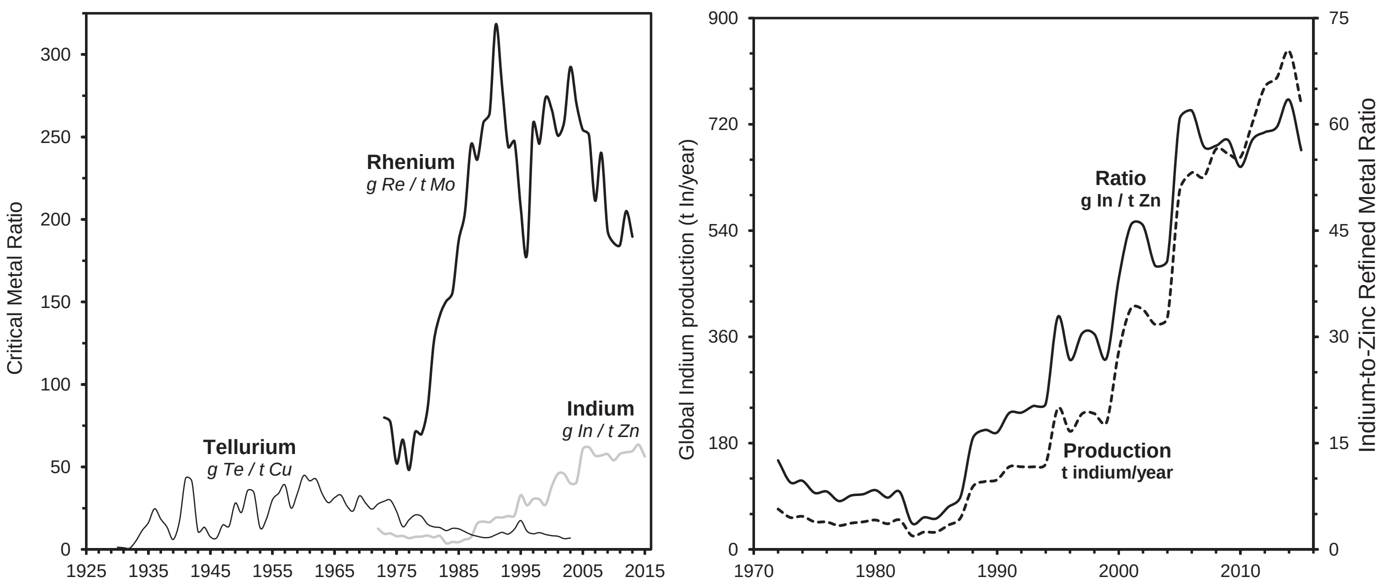

Fig. 5. Graph showing ratios of key critical element production to the base metals they are most commonly associated with (left) and correlation between increasing refined indium-to-zinc ratios and the resulting global increase in indium production (right). Data from the U.S. Bureau of Mines (1933–1993) and the U.S. Geological Survey (1994–2014).

a significant range of values that exemplifies the uncertainty involved in estimating unreported critical metal resources.

A vital step in increasing the accuracy of global critical metals assessments is understanding the recoveries and economics of the critical metals. The value given to a mining project by the presence of a critical metal or metals is often unclear as described above. Processing approaches designed to extract base or precious metals may also not be amenable to the economical extraction of associated critical metals (as discussed above for the REE at Olympic Dam and Co and Sc in Ni laterites). This has the benefit of the production of mining waste that may contain significant amounts of critical metals, although clearly extracting these metals during initial processing may well be easier than extracting critical metals from slag, tailings, or other processing waste. All of this indicates that furthering our understanding of the controls on the distribution of critical metals in mineralizing systems, in terms of understanding the concentrations and deportment of critical metals into ore and gangue minerals within these systems and hence whether these critical metals can be processed and extracted at a profit, is vital. A significant amount of research has been undertaken in this area (e.g., Cook et al., 2009; Murakami and Ishihara, 2013), but this knowledge has still to be fully applied to global estimates of critical metal resources as well as processing approaches.

Securing Future Supplies of the Critical Metals

The key to securing future supplies of the critical metals is to understand the distribution of these commodities in mineralizing systems and the application of this knowledge during resource and reserve assessments and mining operations. The increased consideration of critical metal deportment and mineral processing streams could increase the economic value of the mineral deposits in question by adding critical metals production with the added bonus of ensuring that these critical commodities are extracted where possible rather than deporting to waste. However, although a significant amount of research has been undertaken in this area, still more is required. The lack of knowledge of critical metal grades in mineral deposits known to contain these critical metals is one of the main reasons for the uncertainty in global critical metal resources outlined above (Fig. 1). Of equal or higher importance is the economics of critical metal extraction, as the grades of these metals may not be high enough to consider extraction. However, the lack of knowledge of the value of critical metals causes the majority of companies to not even consider the potential economic contribution of critical metal extraction during resource estimation, focusing instead on primary and significant by-products.

In terms of primary production, furthering our understanding of the economic geology of the critical metals is an essential step in understanding the critical metal potential of mineral deposits that are already being exploited. Research by both academia and industry on the processes that control the deportment of critical metals within the mineralizing systems outlined above could provide pathways to enhanced critical metal recovery as well as potentially improving the economics of operating mines. Understanding these processes and the variations in critical metal contents of key ore minerals within different deposit types could not only enable the extraction of these critical metals but could also inform research into exploiting secondary sources of the critical metals, such as mine waste and tailings.

Primary production of critical metals is not the only way to meet demand. Increasing amounts of recycling of the critical metals could alleviate rising demand for these critical commodities. However, in general and as discussed above, the vast majority of the critical metals are recycled in low to very low proportions (e.g., Table 1; Binnemans et al., 2011; Jowitt et al., 2018). Notable exceptions include critical metals used in alloys, such as Co or Re, or in certain types of catalysts, such as the PGE, all of which are recycled at rates >50%. This is certainly not the case for the majority of the critical elements, especially those that are used in small amounts within specialized technological end products (e.g., Jowitt et al., 2018). The combination of the relatively small amounts of these critical elements used in end products, with the difficulty of the collection, extraction, and recovery of the constituent materials within these end products (such as e-waste), means that critical metal recycling rates are generally very low (e.g., Binnemans et al., 2013). This is being addressed through research and development in e-waste reprocessing (e.g., Rombach and Friedrich, 2014) or by landfill mining (e.g., Enhanced Landfill Mining Consortium, 2012; Richards, 2014). However, significant developments need to be made to turn these theoretical approaches into reality. The other issue here is that the recycling of all of a given critical metal in circulation cannot meet an increase in demand; alternative sources such as mining will also be required. For example, analyses of the indium usage in Australia and Europe revealed that a country might require at most 2.3 g indium per person (Werner et al., 2018). Taking recycling losses into account, collecting and processing the entire planet's in-use stocks of solar panels, LCD screens, smartphones, laptops, and all other devices containing indium would provide about 3,450 t of indium. This value is smaller than single mineral deposits already known to exist in Portugal, Bolivia, and China and would also be very impractical to recover (Ciacci et al., 2018; Werner et al., 2018).

The development of other secondary sources of the critical metals in addition to recycling may be more fruitful and may also have other additional benefits. For example, road dust is known to contain significant amounts of the PGE that are removed from catalytic converters in modern road vehicles, suggesting that this may be another viable secondary source of these elements (e.g., Prichard and Fisher, 2012). More importantly, significant amounts of the critical metals are known to reside in mine waste, with the latter also presenting significant issues in terms of negative environmental and social impact (e.g., Lottermoser, 2011; Weng et al., 2015, 2016). As discussed above, a thorough examination of the controls of the deportment of the critical metals during the generation of mineral deposits and the resulting mineralogy of the critical metals within a given deposit could enhance the chances of the extraction of these commodities during mineral processing, positively contributing to the economics of an operation. This would also increase our understanding of the phases that might host critical metals within mine waste. Mine and processing waste, in the form of mineralized waste rock, overburden, and tailings, is an increasingly costly environmental, social, and economic burden that is often met by the taxpayer.

The profitable reprocessing of mine waste to extract critical metals (as well as other economic commodities) could not only remove some of this financial burden but also supply significant amounts of critical metals to the market.

In terms of economics, an understanding of which critical metals may also undergo transformative growth is key information for mining companies considering exploring for these deposits. The size of critical metals markets (Table 4) is far smaller than the size of major commodity markets (Table 4), making critical metals relatively unattractive for mining companies, especially because smaller markets are often more volatile in terms of supply, demand, growth predictions, and pricing than major commodities. Sykes et al. (2016) focused on the potential for transformational market growth for 49 elements, the vast majority of which are considered critical by one or more institutions or governments. They examined the potential for the markets for these elements to transition from small, specialist commodity markets to more mainstream markets that are likely to attract interest from mid-capitalization and major mining companies. If so, then increasing exploration and production and reducing the criticality of these metals may result from market growth and improved economics. Sykes et al. (2016) used an approach that examined the crustal abundances, the likelihood of metals to be concentrated into mineral deposits, the ease of mining and mineral processing of the deposits that contain these metals, and the criticality and diversity of use of these elements. Their research indicated that although the vast majority of critical metals require a number of breakthroughs of various types to enable or cause transformational market growth, Mg, Si, Ba, B, Li, Co, Cr, V, Ga, Sr, Cr, La, and Sc have high potential for growth from minor to more major commodities (Sykes et al., 2016), although the absolute economic potential of this growth is variable. Sykes et al. (2016) highlighted the potential of Mg, Si, and Ba to have transformational market growth with a large absolute economic impact, suggesting that the criticality of these metals may be addressed by purely economic drivers that increase supplies of these commodities. However, criticality could also be addressed by lessening demand through increased recycling and substitution as well as enhanced recovery given that significant amounts of these commodities currently deport to waste (e.g., Mudd et al., 2013; Werner et al., 2017b)

Overall, although numerous studies (e.g., Ciacci et al., 2016; Graedel et al., 2015; Harper et al., 2014; Nassar et al., 2015a; Panousi et al., 2016) have identified the criticality of a wide range of elements, this criticality may be based on unclear information or could be addressed by reassessing the way mining companies consider mineral deposits. This is highlighted by the fact that the distribution, location, and processes that concentrate the critical elements within a range of mineralizing systems remain unclear. This indicates that addressing the criticality of these elements is somewhat compromised. In other words, the potential for extracting critical elements from resources that are currently being exploited and the economic basis and potential advantages of this extraction need to be researched in greater detail. This is at least as important as increased exploration for these critical elements, and may well provide useful information that can improve exploration success.

The environmental implications associated with critical metal extraction and processing have also been emphasized as a crucial perspective of the global supply chain for these metals (e.g., Mancini et al., 2013; Graedel et al., 2015; Mudd et al., 2017b). The indispensable role of critical raw materials in the global transition to a low-carbon, resource-efficient and more circular economy means that the sustainable extraction of critical metals from sources with low environmental and sociopolitical footprints represents an immediate challenge for both the mining industry and governmental organizations. Supporting secure and stable global critical metal supply chains requires the development of sustainable mineral exploration, extraction and processing technologies, all of which might provide unique, yet strategically important, opportunities for governments, industries, and other stakeholders. However, although our overall knowledge of the critical metals has increased significantly in recent times, we need to both further this knowledge and start applying it more widely within the global mining and resources communities, as discussed by Frenzel et al. (2017). The key to securing supplies of these critical metals goes beyond exploration and discovery to better understand the potential to recover critical metals from existing resources. The current uncertainties over the best solution reflect the data scarcity and inherent uncertainty of individual critical metal sectors. On the latter solution, increasing this understanding may increase the amount of critical metals resources and remove some of the opaqueness around these critical metals, enabling governments, mining companies, and other organizations to base policy, economic, strategic, exploration, environmental, and social decisions on precise and accurate information.

Conclusions

In this study, we have provided an overview of critical metals, discussing the nature of metal criticality, and key issues around the resources and future supply of these metals. Methods for quantifying the criticality of metals have become increasingly sophisticated, and it is now clear that some metals are more strategically important than others. Despite their importance to society and perceived risk of supply disruptions, critical metals remain greatly understudied. Methods exist to quantify the resources of critical metals with reasonable accuracy, although the use of these methods would be assisted by better reporting practices within both government and the mining industry. Numerous responses to metal criticality exist, including improved mineral exploration and discovery, increasing existing mine supply to refining additional by-products, reprocessing of mining/mineral processing wastes, and recycling intermediates or end-use products containing critical metals. These responses can be better informed through further studies in economic geology, mineralogy, mineral resource accounting, mineral economics, material flow analysis, and mineral processing, among many other branches of science and engineering.

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