

Discovery, supply and demand: From Metals of Antiquity to critical metals[†]

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Transformational growth amongst the various critical metals' markets would reduce supply concerns for industrial consumers and governments, whilst also providing commercial opportunities for the upstream industry. However, despite rapid market growth amongst some critical metal markets over the last decade, as a group they have lagged the market growth rates of the non-ferrous industrial and precious metals sectors. Research into the growth prospects of the critical metal markets is clearly required; however, their limited economic history and a paucity of data make this difficult. The economic history of the metals and mining industry as a whole, however, is better documented, and thus may provide insights into the potential for market growth amongst the critical metals. This paper therefore reviews the economic history of metals and mining, and in particular, that of the aluminium, nickel and uranium industries in an attempt to understand the key drivers behind transformational growth within the metals' markets. This historical review suggests that a combination of breakthroughs in discovery, supply and demand are required to catalyse transformational market growth; and thus that parties seeking to benefit from the transformational growth of the critical metals' markets must approach these markets in an integrated manner, considering each of the discovery, supply and demand issues in turn, rather than focusing on one specific constraint.

Keywords: Critical metals, Strategic metals, Mineral economics, Microeconomics, History, Aluminium, Nickel, Uranium, Metals of antiquity

Introduction

'Critical metals' are defined as those with important end-uses, but about which there are concerns over security of supply, either for geopolitical, environmental or sustainability reasons (NRC 2008). A variety of methodologies (e.g. Erdmann and Graedel 2011; Graedel *et al.* 2012; Achzet and Helbig 2013; Speirs *et al.* 2013; Bedder 2015; Graedel *et al.* 2015; Sykes *et al.* 2016) have arisen for assessing the 'criticality' of suites of metals, so the exact list of critical metals markets varies between

sources. Typically these studies cite some of the following as critical metals: antimony, arsenic, barium, beryllium, bismuth, boron, cadmium, chromium, cobalt, gallium, germanium, indium, lithium, magnesium, manganese, mercury, molybdenum, niobium, platinum group metals, rare earth metals, rhenium, silicon, silver, strontium, tantalum, tellurium, thorium, tungsten and vanadium (NRC 2008; Buchert *et al.* 2009; APS and MRS 2011; USDOE 2011; BGS 2012; Schulz and Bradley 2013; EC 2014; Sykes *et al.* 2016). The frequency by which these metals appear on criticality lists is summarised in Fig. 1.

By definition, critical metals have a number of important uses across various parts of the modern, globalised economy including communication, electronic, digital, mobile and battery technologies; and transportation, particularly aerospace and automotive emissions reduction. Critical metals also seem likely to play an important role in the nascent green economy, particularly solar and wind power; hybrid car and rechargeable batteries; and energy-efficient lighting (Fink and Culver-Hopper 1991; Alfantazi and Moskalyk 2003; Erbensperger *et al.* 2005; NRC 2008; Buchert *et al.* 2009; Yaksic and Tilton 2009; Scrosati and Garche 2010; APS and MRS 2011; Goonan 2011; USDOE 2011; Alonso *et al.* 2012; Grosjean *et al.* 2012; Schwela 2012; Massari and Ruberti 2013; Wubbeke 2013; Campbell 2014; Seo and Morimoto 2014; USGS 2014, 2015). In addition, there are also concerns amongst governments about the importance of

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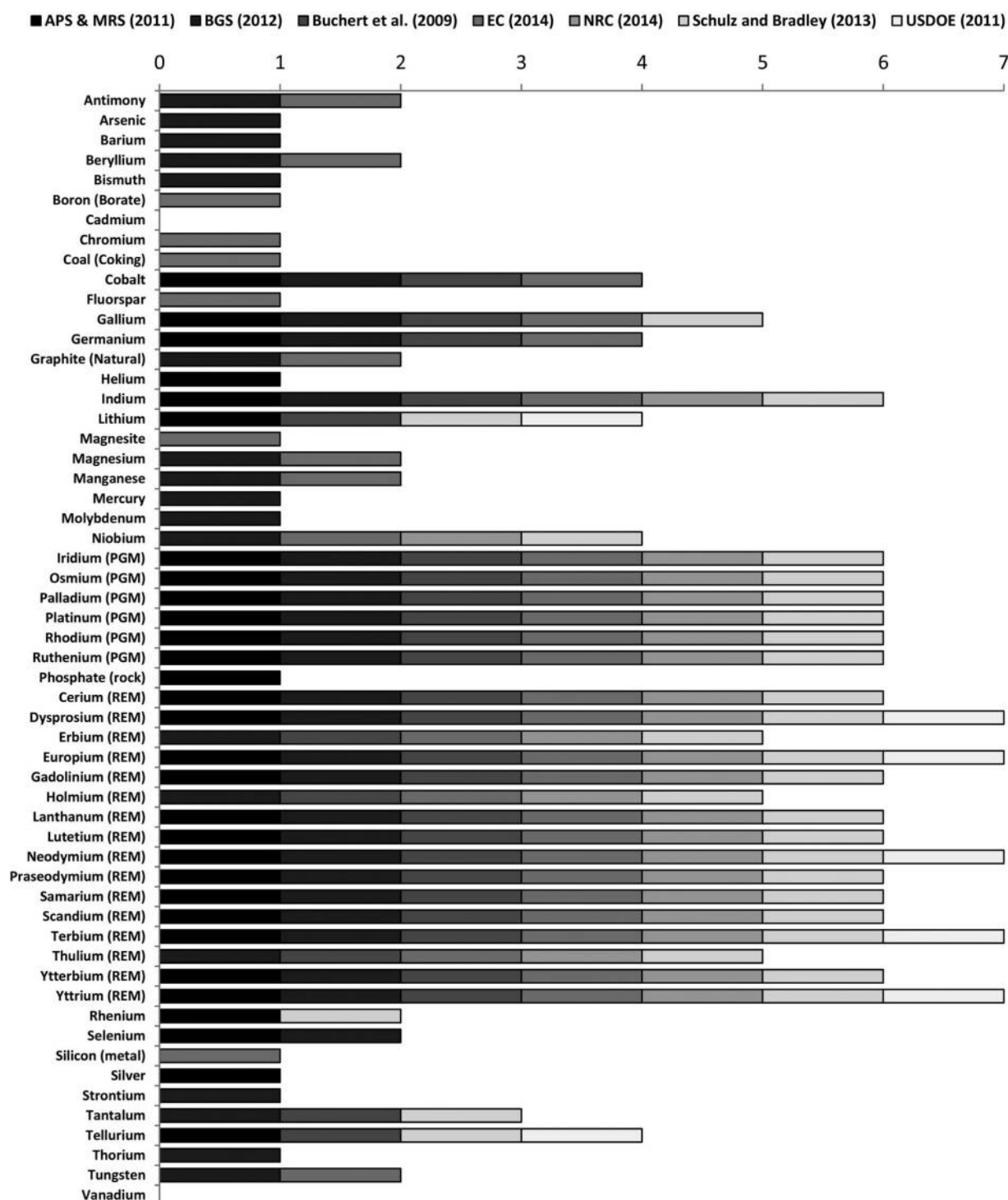
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Frequency of critical metals and minerals on seven different lists



- 1 Frequency of the metals and minerals included on seven different critical metals and minerals lists. For BGS (2012), elements which score more than seven on the 'Risk List' are included in this figure. For USDOE (2011) only metals deemed to be critical or near critical in the 'medium term' are included. The metals included in this list are defined as the critical metals in the context of this paper. Silver whilst considered a critical metal is generally considered as an established precious metal market in this paper. Cadmium and vanadium have been added at the authors' discretion due to their importance in critical battery markets, an important market for many of the critical metals, such as antimony, cadmium, cobalt, lithium, manganese, various rare earth metals, and vanadium. NB: REM = rare earths metals and PGM = platinum group metals

some critical metals in important military technologies such as drones, missiles, smart bombs, night vision, radar and sonar (Delaney 2009, 2010). As such,

governments, professional organisations and consumer industrial firms have all shown an increased interest in how to secure stable supplies of these metals (NRC

2008; Buchert *et al.* 2009; APS and MRS 2011; USDOE 2011; BGS 2012; Schulz and Bradley 2013; EC 2014). By contrast, exploration and mining companies have viewed these markets as potential new opportunities, hoping they can gain early access to fast-growing, new metals markets (Tyrer and Sykes 2013; Sykes *et al.* 2016). The future size of these metal markets is therefore of interest to producers, consumers and governments. The wider availability of these metals would alleviate governments and industrial firms' criticality concerns. Similarly, mining and exploration companies would benefit from the economic returns of early entry into fast growing commodity markets.

Thus far, however, the critical metals markets have remained relatively unimportant in absolute economic terms, with the collective critical metals market of the nearly 50 metals listed in Fig. 1, still worth only about US\$110 billion in 2013, in comparison to the non-ferrous industrial metals market (of aluminium, copper, lead, nickel, tin, titanium and zinc), which was worth about US\$313 billion, and the precious metals market (gold and silver) worth about US\$147 billion. In addition, over the last decade (figures for 2004–13) the same critical metals market has grown only 69%, in comparison to an 84% increase in the non-ferrous industrial metals market and a 230% increase in the precious metals market over the same period, as demonstrated in Table 1. This has disappointed exploration and mining companies hoping for fast-growing new commodity markets and governments and industrial firms hoping for larger, wider traded markets of these metals. In addition, Table 1 highlights that whilst in aggregate the critical metals have shown modest growth, the contributory performance of individual critical metals has been extremely variable over this period. Critical metal markets for lithium, germanium, gallium and mercury have grown in excess of 300% during this period, whilst the markets for cobalt, molybdenum, arsenic, borate (boron) and strontium have shrunk. The remaining critical metals show levels of market growth across the entire range between these two extremes.

The weak overall growth of critical metals markets, combined with highly variable performance of individual metals underlines how all stakeholders struggle to understand these markets, especially when trying to understand their future evolution. What factors make some metal markets like lithium grow quickly, whilst others such as strontium shrink? Understanding of these markets is not aided by the fact that the critical metals generally have a relatively short economic history and are typically opaque, thinly traded, small markets, with few participant companies (Erbensperger *et al.* 2005; Naumov and Grinberg 2009; Tyrer and Sykes 2013; Sykes *et al.* 2016). A situation further complicated by the fact that many of the critical metals are produced as by-products of mining or smelting processes for other metals (Gupta and Krishnamurthy 2005; Naumov and Grinberg 2009; Alonso *et al.* 2012; Graedel *et al.* 2012; Packey 2012; Mudd *et al.* 2013b; Graedel *et al.* 2015; Werner *et al.* 2015; Sykes *et al.* 2016). There is as such often a scarcity of reliable data for both understanding the current market dynamics and also to form a basis for forecasting the likely future development of these markets (Yaksic and Tilton 2009; Erbensperger *et al.* 2005).

However, whilst there is a shallow history for the many small metals markets which often characterise the critical metals, there is a deep and well-documented history for

the metals and mining industry as a whole. Reviews such as Lynch's 'Mining in world history' (2002) and Street and Alexander's 'Metals in the service of man' (1998) are only some of the most recent additions to the archive of publications providing overviews of the entire history of metals production and use. Indeed, these recent references sit atop a lineage that goes back at least as far as the Renaissance with Agricola's 'De re metallica' (1556) and arguably to the Classical Era with Pliny the Elder's 'Naturalis historia' (ad77–79). It is our view (in agreement with Hewett in his classic 1929 paper on 'Cycles in metal production') that the history of the metals and mining industry as a whole highlights some important lessons which may help illuminate the future for the various critical metals.

The aim of this paper, therefore, is to review the economic history of metals and mining, to seek insights into what factors facilitate the sudden, transformational growth of minor metals markets (such as the present day critical metals' markets) into major industrial commodities (such as the present day base metals' markets). The paper begins with 'A brief history of metal supply, demand and discovery' in order to explain how these factors help drive both economic development and globalisation. The review covers the period from the Stone Age to the Industrial Revolution in the Western World. The next section: 'Rise of the critical metals?' considers the economic role of these metals in the twentieth and twenty-first century. The economic history of the aluminium, nickel and uranium metals markets, all of which have shown transformational market growth in the twentieth century is then reviewed in more detail to investigate the role of discovery, supply and demand in their rapid growth.

The review of the economic history of metals and mining, and the more detailed studies of the aluminium, nickel and uranium markets concludes that a combination of breakthroughs in discovery, supply and demand are required before transformational growth can occur in a metals market. In reality, progress towards breakthroughs in each area moves at different speeds, so it can be the case at any given time, that a breakthrough in only one or two of these areas is required, thus making some factors seem temporarily more important. However, any final breakthrough sits atop the other breakthroughs in discovery, supply and demand, and thus breakthroughs in all these areas are required, before transformational market growth is catalysed. This finding suggests that for governments and industrial firms hoping to resolve the critical metals issue, or for explorers and miners seeking opportunity in rapid market growth amongst the critical metals, they will all need to approach the sector from an integrated perspective. They will have to consider each of discovery, supply and demand in turn, identifying which of these areas still require breakthroughs, and set out to facilitate breakthroughs across all the required areas, rather than just focusing on one specific constraint in isolation.

A brief history of metals supply, demand and discovery

A classical microeconomic analysis of a market considers the interaction of supply and demand (Samuelson and Nordhaus 2010). However mineral (and petroleum) resources are defined not only by their finite nature in total, but also that they occur in finite, discrete deposits

Table 1 Ranking of market growth over the recent 10-year period of 2004–13 for the base, precious, and critical metals

Rank	Commodity	Type	2004–13 market growth (%)	Rank	Commodity	Type	2004–13 market growth (%)
1	Precious metals		227	19	Silicon	Critical	118
2	Industrial metals		84	20	Tellurium	Critical	116
3	Critical metals		69	21	Manganese	Critical	105
–	–	–	–	22	Zinc	Industrial	105
1	Lithium	Critical	388	23	REMs	Critical	93
2	Germanium	Critical	355	24	Tantalum	Critical	74
3	Gallium	Critical	327	25	Niobium	Critical	72
4	Mercury	Critical	320	26	Magnesium	Critical	62
5	Tungsten	Critical	298	27	Indium	Critical	57
6	Rutile (Ti)	Industrial	295	28	Cadmium	Critical	53
–	China	GDP	294	29	Ilmenite (Ti)	Industrial	51
7	Silver	Precious	271	30	Tin	Industrial	50
8	Gold	Precious	221	31	Aluminium	Industrial	44
9	Beryllium	Critical	215	–	World	GDP	41
10	Bismuth	Critical	214	32	Vanadium	Critical	24
11	Antimony	Critical	211	33	PGMs	Critical	19
12	Lead	Industrial	190	34	Nickel	Industrial	12
13	Rhenium	Critical	171	–	USA	GDP	10
14	Barite (Ba)	Critical	169	35	Cobalt	Critical	–5
15	Uranium	Energy	156	36	Molybdenum	Critical	–18
16	Copper	Industrial	155	37	Arsenic	Critical	–30
17	Thorium	Critical	146	38	Borate (Bo)	Critical	–57
18	Chromium	Critical	144	39	Strontium	Critical	–57

Market size is calculated as global mined or smelted production (as appropriate) volume multiplied by prevailing annual average market price. Growth is calculated as the percentage difference between the market size in 2004 and in 2013, as such the calculated growth rates could differ substantially if the starting (2004) or ending (2013) were unusually high or low. The growth rates should be seen as indicative only. The 'critical metals' are those defined in Figure 1. The selection of industrial and precious metals is based on industry norms, though it is recognised that various alternative groupings exist. Data is collated from Kelly and Matos (2014). Gross Domestic Product (GDP) growth data for the world, China and USA have been added for comparative purposes. Data is collated from the World Bank (2015) and normalised into real growth in 2013 dollars, by the same inflation index used for the historical metal prices. Ba = barium; PGMs = platinum group metals; REMs = rare earth metals; Ti = titanium; GDP = gross domestic product (2013 dollar normalised). Text and values in bold represent the Gross Domestic Product (GDP) growth of the world and key countries, to allow for comparison of commodity market growth to overall economic performance.

in which mineral resources have been concentrated by natural earth processes. Before these resources can enter the marketplace they must therefore be discovered, adding a third component to the microeconomics of mineral and petroleum markets, that of discovery itself (Hronsky and Groves 2008; Hronsky 2009; Sykes and Trench 2014). The economic history of civilisation, to some extent, can therefore be charted via the exploration (resulting in discovery), early exploitation and only then the full-scale use of such mineral resources (Maxwell 2013).

The origins of mining and exploration in the Stone Age

Some of the earliest hard evidence of deep mining, rather than simple surface collection (or gathering) of minerals, originates from 300 000-year-old flint tools in Africa. The levels of cosmogenic beryllium in these flints suggest they were sourced from at least two metres underground. Flint sourced at depth was of better quality than that discovered at surface as it was unweathered (Verri *et al.* 2004, 2005). Thus began the search for better mineral deposits and the beginning of the mining industry. Over the next few hundred thousand years, hominids, and then humans would begin to spread over the world, bringing their complex interconnected networks with them (Gosden 2003).

The age of metals

By 5000–8000 years ago, the age of metals had begun (Lynch 2002). Of the Metals of Antiquity, copper, gold,

iron, lead, mercury, silver and tin, all except tin occur as native metal in and upon the ground, though generally not in large abundance (Hammond 2015). More importantly, all, except iron, could be extracted from ores and formed into alloys such as bronze at temperatures in simple fires (Street and Alexander 1998; Lynch 2002). However, whilst many of the raw materials for early tools, such as stone and wood, were broadly distributed, the same is not the case for metals, and even those higher quality deposits of flint. Thus the great Bronze Age civilisations in the Mediterranean and China not only had to further develop mining and invent smelting to extract and process deeper and more prolific deposits, they also often had to source some of their metals from distant lands, via exploration and trade. The Greeks and Egyptians, for example, whilst hosting domestic mining industries for some metals, may also have needed to establish shipping and trading networks across Europe to gain access to the full range of desired raw materials, particularly tin (Hewett 1929; Smith 1998a, 1998b, 1998c; Lynch 2002).

Finally, the invention of higher temperature smelting techniques developed around 2000–4000 years ago (Smith 1998b, Street and Alexander 1998; Lynch 2002), meant the last of the Metals of Antiquity, iron, could be liberated from its ores, precipitating the Iron Age and further great empires, such as the Romans (Hewett 1929). By the time, Pliny the Elder published 'Naturalis historia' (ad77–79) the alloying of bronze, electrum, brass, and basic carbon steel were well established industries (even if not all of the elemental components were

known at the time). The Iron Age civilisations were supported by ever greater trading networks with Roman iron works across Elba and northern Italy; France and Germany; gold, silver, copper and tin mines in Spain (Hewett 1929; Lynch 2002); and lead mines in Britain (Smith 1998d, 1998e). It also seems possible that iron-working technology passed along the Silk Road fertilising the great Iron Age civilisation in Han China (Lynch 2002; Gosden 2003).

Renaissance and the Age of Exploration

The resurgence of European empires in the Renaissance coincided with significant mineral discoveries, particularly in Germanic and Slavic lands (Hewett 1929; Smith 1999c; Lynch 2002), alongside technological developments in mining, processing, science and engineering. Agricola's 'De re metallica' (1556), perhaps the first mining textbook, was published during this period. Johannes Gutenberg's printing press was the great new facilitator of communication and would not have been a success without good supplies of lead and tin (Smith 1999c). The period also marked the beginning of the 'Age of Exploration', with the Portuguese and Spanish exploring the New World. The discovery of the Americas brought with it further mineral discoveries, and ultimately occupation and empire, as the world began to globalise (Smith 1998e, 1999a, 1999b; Weaver 2015). Technology travelled across the oceans, with, for example, a new German silver processing technology (mercury amalgamation) implemented by Bartolome de Medina (of old Spain) in New Spain (now Mexico), and later Peru, leading to a surge in gold and silver production much to the benefit of the Spanish (Hewett 1929; Smith 1999a, 1999b; Bernstein 2000; Lynch 2002; Hylander and Meili 2005). Back in Europe, the nascent British, Dutch, French, Prussian (now German) and Russian empires began to see the benefits of exploration (Lynch 2002; Weaver 2015).

Industrial revolution and the gold rushes

As the Renaissance became the Enlightenment, science and technology, along with the associated material goods derived from such advances, flourished, as did the other European empires. Mining technology was once again important to economic advancement. Thomas Newcomen's water pump for underground mines in England would provide the inspiration for James Watt's steam engine, an invention which literally drove the Industrial Revolution (Smith 1999c). The steam engine was coal intensive (Smil 2011), as were the next major technology changes in metallurgy: first as iron making was improved using charcoal smelting and then when steelmaking was perfected via Henry Bessemer's process (Hewett 1929; Street and Alexander 1998; Lynch 2002). Coal in close proximity to iron ore therefore became invaluable to the burgeoning industrial empires of Britain, France, Germany and later the United States (Hewett 1929; Smith 1998d, 1999c; Lynch 2002; Farooki 2012; Maxwell 2013). Coal, iron and copper combined in perhaps the symbolic transportation technology of the time – the railway (Street and Alexander 1998; Lynch 2002). As the European empires expanded overseas, further mineral discoveries were made, particularly in association with gold rushes first in North America, then Australia and South Africa in the mid- to late nineteenth century

(Smith 1999d, 2000a, 2000b; Bernstein 2000; Lynch 2002). By the end of the nineteenth century, Europe was importing gold, tin, copper, lead and many other metals and minerals from various parts of North and South America, Africa, Asia and Australia (Smith 1999d, 2000a, 2000b; Lynch 2002). The mineral discoveries helped drive the settlement of many of these countries (for example, in the settlement of Ballarat, Bendigo, Broken Hill and Kalgoorlie in Australia) as well as leading to further advances in mining and processing technology, such as base metals flotation and gold cyanidation, liberating yet more metals (Bernstein 2000; Lynch 2002).

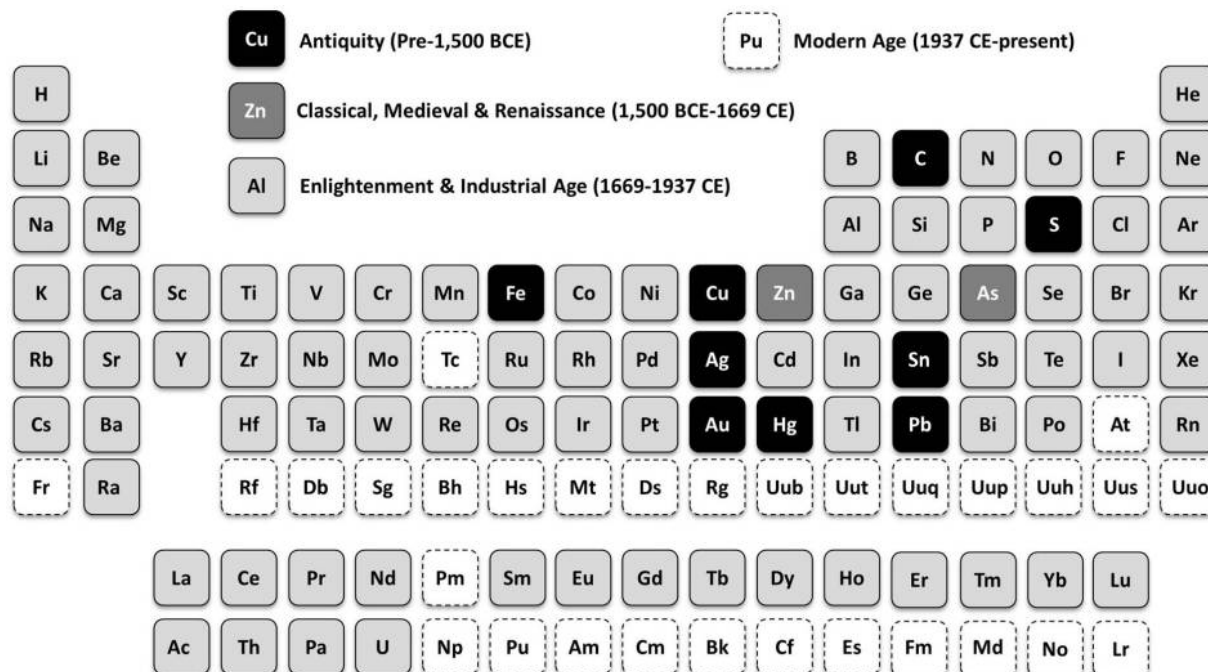
Reflections on the history of metals

The history presented above is somewhat dated in interpretation, not least in its Eurocentric perspective, but also because not everywhere in the world passed orderly from Bronze Age to Iron Age to Industrial Age and so on (Gosden 2003). Different parts of the world went through these periods at different times or not at all. For example, Africa's Bronze Age followed its Iron Age, whilst parts of the Americas only had copper, not bronze or iron. In both cases, this was due to differences in the availability of appropriate mineral resources and technological understanding (Gosden 2003). Some parts of the world, such as Papua New Guinea, essentially did not leave prehistory until the twentieth century, using stone tools and lacking written records up to this point (Gosden 2003). Other parts of the world thrived when Europe did not, particularly during Europe's Dark Ages and Middle Ages when China and India dominated the world economy (Maddison 2010). All of this however underlines the complex interactions of resource availability that have shaped economic development. There is a strong link between exploration (both geographic and for resources), greater raw materials provision and ultimately consumption and economic development (Hewett 1929). Without access to new discoveries of high quality metals deposits, improved extraction techniques and new uses of metals then economies do not progress rapidly.

The rise of the critical metals?

Although the industrial revolution saw many technological advances, the suite of metals and minerals used in the economy were largely the same as those available to the ancients – a few base and precious metals, iron, coal and sulphur (Hammond 2015), as demonstrated in Fig. 2. However, this was set change. It has already been noted that during the Industrial Revolution the European empires expanded geographically triggering a wave of minerals exploration and subsequent mineral discoveries on their way. However at same time another different form of rapid exploration and discovery was underway, primarily back in Europe. This second type of discovery could not, however, be charted on a map – it was not of geographical form. It was during this period that rapid scientific advances led to the discovery of most of the elements of the Periodic Table, again as demonstrated in Fig. 2.

Whilst these elements were too new to be used in a significant economic manner at the time, during the industrial revolution, they would become increasingly available to the global economy. Thus, unlike the first industrial



2 The periodic table coded by the historical order of discovery of the elements. A few elements were known in antiquity, but for a couple of exceptions (zinc and arsenic); most of the naturally occurring elements were discovered during the Enlightenment and Industrial Revolution. All of the naturally occurring elements had been discovered by 1925, with the discovery of rhenium. The discovery of artificially produced technetium in 1937 started a third period of element discovery in the modern age, focused entirely on the creation and discovery of artificial elements. Data gathered from Hammond (2015) and Ball (2002)

revolutions focused on Europe and North America, the modern industrial revolutions, particularly evident in Asia (Radetzki 2006, 2013; Radetzki *et al.* 2008; Humphreys 2009, 2010; Maddison 2010; Farooki 2012), have had a much wider variety of metals available to them for industrial use. The broader range of metals comes in addition to new abundant and cheap fuel resources of oil, gas (Smil 2011) and uranium (Lynch 2002) to complement the already existing coal-based fuels.

Industrialisation and globalisation in the modern age

Industrialisation in Asia has been typically intensive in its use of the traditional industrial metals such as steel, aluminium, copper, nickel and zinc (Radetzki 2006, 2013; Humphreys 2010; Farooki 2012; Kelly and Matos 2014), used in relation to urbanisation and infrastructure, as well as fossil fuels (Radetzki 2006; Humphreys 2010; Farooki 2012), such as coal for power infrastructure, and petroleum in transportation (Humphreys 2009, 2010; Farooki 2012). However, other economic trends have led to the use of an ever-greater list of metals, many of which are now classified as critical or strategic (NRC 2008; Buchert *et al.* 2009; APS and MRS 2011, USDOE 2011; BGS 2012; Schulz and Bradley 2013; EC 2014). Street and Alexander (1998) emphasise this trend, highlighting that there are now some 68 metals that are of interest to alloy metallurgists and thus the wider industrial economy.

Industrialisation, globalisation and communication

Globalisation is reliant on broader communication, facilitated by electronic and digital technologies. These use

traditional metals, such as copper, gold, silver and tin, but also increasingly critical metals such as arsenic, beryllium, bismuth, gallium, germanium, indium, platinum group metals, silicon and tantalum (Fink and Culver-Hopper 1991; Alfantazi and Moskalyk 2003; NRC 2008; Buchert *et al.* 2009; Schwela 2012; ICSG 2014; Silver Institute and Thomson Reuters GFMS 2014; USGS 2014, 2015).

Industrialisation, globalisation and transportation

Globalisation has also required great advances in travel, aided by the invention of the automobile and aeroplane and improvements in shipping (Lynch 2002). One of the most important trends in the use of metals since the industrial revolution is a reduction of weight per unit of use, which in particular has expanded consumption from the heavier metals of antiquity, such as iron, to a broader range of lighter metals and alloys (Street and Alexander 1998). With weight at a premium during transportation, this has been particularly beneficial for the aluminium industry, but also other lightweight metals such as beryllium, magnesium, manganese, scandium, titanium and vanadium (Lynch 2002; NRC 2008; USGS 2014, 2015). The strains placed on metals during transportation, particularly flight, have led to the development of superalloys using metals such as cobalt, niobium and rhenium (USGS 2014, 2015). Finally, the polluting effects of fossil fuel use during transportation have to be mitigated utilising catalyst metals including some of the platinum group metals and rare earth metals (NRC 2008; Buchert *et al.* 2009; APS and MRS 2011; Goonan 2011; Smil 2011; USGS 2014, 2015).

Industrialisation, globalisation and distributed power

The first industrial revolution in Europe and North America in the eighteenth and nineteenth centuries was facilitated by cheap energy in the form of coal power (Lynch 2002; Smil 2011). The widespread availability of two new fossil fuels, oil and gas, in addition to increased availability of coal has helped fossil fuels continue their dominance as energy sources in the twentieth century (Smil 2011). Oil, of course, is perhaps even more important as a transportation fuel, than energy fuel (Smil 2011). The combination of increased energy needs and increased transportation and communication requirements has however also led to a proliferation of mobile devices, making batteries ever more important to the global economy, as a source of distributed power. Again, the battery industry uses some more familiar metals such as lead, nickel and silver (NRC 2008; Mudd 2010a; USDOE 2011; USGS 2014, 2015). However, the battery industry is also increasingly reliant on a range of critical metals, such as antimony, cadmium, cobalt, lithium, manganese, various rare earth metals and vanadium (Erbensperger *et al.* 2005; NRC 2008; Buchert *et al.* 2009; Yaksic and Tilton 2009; Scrosati and Garcke 2010; APS and MRS 2011; Goonan 2011; USDOE 2011; Grosjean *et al.* 2012; USGS 2014, 2015; Goodenough *et al.* 2016).

Industrialisation, globalisation and security

Finally, the combined factors of a wide range of metals mined in different places around the world and then shipped to different competing countries for consumption raises a geopolitical concern for modern governments. Many of the same applications described above, in demand by the modern economy, also have uses in the military. Examples include rare earth metals used in permanent magnets in drones, missiles and smart bombs; as phosphors in avionics, displays and night vision equipment; and for signal amplification in radar and sonar (Delaney 2009, 2010). The fear by governments that they may not be able to access supplies of required metals for their military is an important part of critical metals ideology, discussed in the next sub-section.

Critical metals ideology in the modern age

The combination of a wider range of metals of use across industry and the rise of powerful economies in Asia through the twentieth and early twenty-first centuries has led to increasing concerns about both the availability and security of supply of various minerals and metals.

The origins critical metals ideology

Each of the three major commodities booms of the last 100 years (Radetzki 2006) have coincided with concerns over critical and strategic metals and minerals. As finite resources, concerns of the continued supply of metals and minerals have always existed. Thomas Malthus in his 1798 study 'An essay on the principle of population' noted exponentially growing populations would soon exhaust available finite resources. Tilton (1996, 2003) notes that the conservation movement began to arise in the late nineteenth and early twentieth centuries in the USA, whilst at the time the United Kingdom was also concerned about the depletion of its coal resources.

These concerns were largely alleviated by a vast expansion of the mining sector, in the late nineteenth and early

twentieth century, as the industry, in particular for metals, moved from smaller scale underground mining to bulk open pit mining. This switch arose from a complex mix of minerals discovery, mine supply, minerals demand and other factors. In copper, for example, new mineral discoveries in Chile (such as Chuquicamata) and the USA (such as Bingham Canyon), combined with new bulk mining technologies (based on steam power, mechanisation and dynamite), and bulk processing technologies (such as flotation and smelting-refining improvements) to make large-scale mining viable. In addition, public infrastructure investment improved access to previously remote mining regions, and economic changes such as a push towards free trade, the use of forward contracts for commodities, and the rise of the corporation and 'mining barons' all facilitated the financing of large mines, aiming to ship large volumes of commodities around the world (Hewett 1929; Lynch 2002; Hronsky and Groves 2008; Hronsky 2009; Schodde 2010; Crowson 2012; Sykes and Trench 2014).

Strategic metals and the wars of the early to mid-twentieth century

Concerns over the critical or strategic nature of metals arose again in the early to mid-twentieth century. Hewett in his classic 1929 paper 'Cycles in metal production' was concerned that his observed near exhaustion of Europe's metal mines would one day be repeated in the United States. Hewett's (1929) example of Malthusian concern was added to by the geopolitical context associated with the world wars of this period (Kemp 1942; Lynch 2002; Tilton 2003). Both sides worried about supplies of important armament-related metals. These concerns would continue throughout the early stages of the Cold War (Lynch 2002; Tilton 2003). Realistically, metals supply did not have a big impact on the outcomes of the First and Second World Wars (Lynch 2002); however, rearmament in advance of the Korean War was associated with a commodities boom (Radetzki 2006).

Critical metals, environmentalism and conservationism

The next major period of concern about metals availability in the twentieth century was associated with the oil crises of the 1970s (Tilton 2003). Clearly the oil crises had a geopolitical dimension; however other trends were also re-emerging. Rachel Carson's 'Silent spring' (2000) was first published in 1962 increasing concerns about the environment, and was followed by the Club of Rome's 'Limits to growth' a decade later (Meadows *et al.* 1972). The highly popular 'Limits to growth' report drew from Malthusian, conservationist and environmentalist influences and forecast under some economic growth scenarios that the planet would either run out of various mineral resources by the end of the twentieth century or in the early twentieth-first century, or would become overwhelmed by pollution as a by-product of resource use (Tilton 1996, 2003; Mudd 2010b, 2013; Sykes and Trench 2014). Amongst the geopolitical concerns of the oil crises, rapid growth of the Japanese and Korean economies (Maddison 2010) and a second major commodities boom (Radetzki 2006) the argument for resource shortages seemed particularly compelling.

The subsequent decades of falling real-term commodity prices (Tilton 1996, 2003; Tilton and Lagos 2007;

Yaksic and Tilton 2009), and a vast expansion of the volume of minerals produced and made available to the economy, however, largely alleviated these fears again, as with the late nineteenth and early twentieth century, discussed above. The oil shocks of the 1970s and 1980s led to a certain amount of demand destruction, as did shocks in copper and cobalt prices, relating to de-colonisation in Central Africa, as a further example. On the supply side, technologies such as solvent-extraction-electrowinning, and computation improved the efficiency of mines, whilst improved geophysical surveys and lower cost drilling, combined with globalisation and political change led to important new minerals discoveries, for example, Grasberg and Escondida in the copper industry (Hewett 1929; Hronsky and Groves 2008; Hronsky 2009; Schodde 2010; Sykes and Trench 2014). In summary, this period saw a taming of metals demand, combined with an expansion of low cost metals supply leading to overall falling real commodity prices.

Current critical metals ideologies

A third commodity boom, this time due to demand from China (Radetzki 2006, 2013; Radetzki *et al.* 2008; Humphreys 2009, 2010; Maddison 2010; Farooki 2012) in the first decade of the twentieth-first century, once again arose concerns of minerals supply risk. The source of these concerns include classic Malthusian ideas of shortage (Yaksic and Tilton 2009; Friedrichs 2010; Mudd 2010a; Rhodes 2011; Rosa and Rosa 2011; Giurco *et al.* 2012; Grosjean *et al.* 2012; Prior *et al.* 2012; Vieira *et al.* 2012; Harmsen *et al.* 2013; Wubbeke 2013; Sykes and Trench 2014) and traditional strategic geopolitical concerns, for example, in the frequent discussion of the military uses of germanium (Fink and Culver-Hopper 1991) and rare earth metals (Delaney 2009, 2010; Martin 2010; Grasso 2013; Massari and Ruberti 2013; Packey 2013; Wubbeke 2013; Campbell 2014; Golev *et al.* 2014; Weng *et al.* 2014, 2015).

However, even stronger environmental concerns are also present following the lineage of the conservationists and environmentalists. Although the fears over resource exhaustion *per se* as highlighted by the 'Limits to growth' (Meadows *et al.* 1972) were largely ameliorated by the rapid expansion of metals and minerals production described above, the concerns over pollution and other undesirable externalities also highlighted by Meadows *et al.* (1972) and discussed by Mudd (2010b, 2013) remained. Indeed such concerns about undesirable externalities are likely amplified given the higher levels of resource production now prevailing. As such the later editions of 'Limits to growth' (Meadows *et al.* 1992; Meadows *et al.* 2004) focused more on the impact on the external environmental and social consequences of resource extraction. This coincided with (and potentially contributed to) the rise of the sustainable development movement, focused on balancing economic benefits with environmental and social costs (WCED 1987; Meadows *et al.* 1992; Meadows *et al.* 2004; Tilton 1996, 2003; Cook and Sheath 1997; Gordon *et al.* 2006; Mudd 2007a, 2007b, 2010a, 2010b, 2013, 2014; Giurco *et al.* 2012; Prior *et al.* 2012; Harmsen *et al.* 2013; Mudd *et al.* 2013a; Mudd and Jowitt 2014; Sykes and Trench 2014; Weng *et al.* 2014, 2015). As such, many of the concerns over critical metals and minerals nowadays also

have a strong environmental, socio-political or sustainability influence, alongside the more traditional geopolitical and militaristic concerns (Hylander and Meili 2005; Gordon *et al.* 2006; Rhodes 2011; Grosjean *et al.* 2012; Massari and Ruberti 2013; Mudd *et al.* 2013a; Packey 2013; Wubbeke 2013; Campbell 2014; Golev *et al.* 2014; Seo and Morimoto 2014; Weng *et al.* 2014, 2015; Goodenough *et al.* 2016).

The role of critical metals in a green, clean, sustainable future

In response to the environmental and sustainability concerns, along with increased recognition of the forecast implications of climate change in the latter half of the twentieth century, industry and society has shown an interest in the potential development of a green, clean and/or sustainable economy. Once again, both traditional and critical metals seem likely to be an important part of any future green-focused economy (NRC 2008; Buchert *et al.* 2009; APS and MRS 2011; USDOE 2011; Alonso *et al.* 2012; Massari and Ruberti 2013; Packey 2013; Wubbeke 2013; Campbell 2014; Golev *et al.* 2014; Seo and Morimoto 2014; Weng *et al.* 2015).

Preferential growth in renewable energy demand over fossil fuels will benefit both traditional metals such as silver and critical metals such as indium, gallium, germanium and tellurium used in solar power (NRC 2008), and the various rare earth metals used as permanent magnets in wind power generation (Buchert *et al.* 2009; APS and MRS 2011; USDOE 2011; Alonso *et al.* 2012; Massari and Ruberti 2013; Wubbeke 2013; Campbell 2014; Seo and Morimoto 2014; Goodenough *et al.* 2016). The variability and distributed nature of renewable energy suggests that battery metals, such as cobalt, lithium and rare earth metals, will become ever more important, especially if automobiles move to battery power (Erben-sperger *et al.* 2005; Buchert *et al.* 2009; Yaksic and Tilton 2009; Scrosati and Garche 2010; APS and MRS 2011; USDOE 2011; Alonso *et al.* 2012; Grosjean *et al.* 2012; Massari and Ruberti 2013; Wubbeke 2013; Campbell 2014; Seo and Morimoto 2014; Goodenough *et al.* 2016). More energy efficient transportation also seems likely to benefit demand for light metals, such as aluminium, magnesium, manganese, scandium and titanium. Reduced emissions from transportation, requiring catalytic convertors, in the absence of battery power, will continue a reliance on some platinum group metals and rare earth metals (NRC 2008; Buchert *et al.* 2009; APS and MRS 2011; Massari and Ruberti 2013; Nieto *et al.* 2013; Campbell 2014). In addition, energy efficient lighting may lead to more reliance on phosphor rare earth metals (APS and MRS 2011; USDOE 2011; Massari and Ruberti 2013; Wubbeke 2013; Campbell 2014; Goodenough *et al.* 2016). The role of electronic and electrical metals, such as indium, tantalum and ruthenium, potentially also have an important role in a green economy, though the linkage is less obvious (Buchert *et al.* 2009).

The current economic status of the critical metals

The critical metals' market was only worth around US \$700 million in 1900 (in 2013 dollars), peaking at US \$3.5 billion (2013 dollars) at the height of the First World War, before declining to about US\$1.3 billion

(2013 dollars) by the end of the war as demonstrated in Fig. 3 (based on data from Kelly and Matos 2014). In 2013, the critical metals markets are worth nearer US \$110 billion, again, as demonstrated in Fig. 3 (Kelly and Matos 2014). This represents an 85-fold increase in real market size since the First World War. By comparison the non-ferrous industrial metals market (including aluminium, copper, lead, nickel, tin, titanium and zinc) and precious metals (gold and silver) markets have grown 26-fold and 20-fold in real terms since the end of the First World War. The non-ferrous industrial metals market was worth about US\$9 billion (2013 dollars) in 1900, about US\$12 billion (2013 dollars) by 1919 and today (2013) is worth US\$313 billion, as demonstrated in Fig. 3. The precious metals market was worth about US\$9.5 billion (2013 dollars) in 1900, declining to about US\$7.5 billion (2013 dollars) by 1919, and today (2013) is worth about US\$147 billion, again as demonstrated in Fig. 3.

The rapid growth of the critical metals markets over the twentieth century arises from the fact discussed earlier in the paper that most of these metals were not discovered until the eighteenth and nineteenth centuries, and thus uses were not developed until the twentieth century. Indeed, many of the critical metals were not produced in significant volumes until the mid-twentieth century. Hewett in his 1929 review of European metals mining only covered copper, iron, lead, mercury, silver and tin. The United States Geological Survey (USGS) only recorded accurate production and price figures for germanium from 1957, thorium from 1960, niobium and silicon metal from 1964, tantalum from 1969, indium from 1971, and gallium and rhenium from 1973 (Kelly and Matos 2014). Similarly, several metals such as gallium, germanium, hafnium, palladium and the rare earth metals, were not mentioned in the first edition of Street and Alexander's 'Metals in the service of man', published in 1944, but were covered in the 1998 edition.

However, since the turn of the millennium, whilst most metals markets have grown in size in response to Chinese economic growth, the critical metals' market as a whole has lagged behind. The size of the critical metals' market only increased by 1.7 times between 2004 and 2013 (the latest year of data from Kelly and Matos 2014), slightly less than increase in the size of the non-ferrous industrial metals' market (which recorded a 1.8 times increase) and a 3.3 times increase in the size of the precious metals markets, over the same period, as demonstrated in Fig. 3 (Kelly and Matos 2014). Despite containing nearly 50 different individual metal markets, the critical metals market as a whole is still only slightly more than a third the size of the non-ferrous industrial metals market (in this case defined as including seven metals). The minor nature of the critical metal markets is further demonstrated by the fact that many of them are still produced as by-products of mining and smelting processes for other metals (Gupta and Krishnamurthy 2005; Naumov and Grinberg 2009; Alonso *et al.* 2012; Graedel *et al.* 2012; Packey 2012; Mudd *et al.* 2013b; Graedel *et al.* 2015; Werner *et al.* 2015; Sykes *et al.* 2016).

As this brief history of metals above has shown, each time concerns about critical or strategic metals arise (such as in the late nineteenth century, or the 1970s) these fears are alleviated by an expansion of metals markets, and the increased availability of low cost supplies of these metals. Why has this not yet happened in the present

critical metals markets? Currently, despite the apparent importance of the various critical metals in the modern industrial complex, they remain a market of economic potential, rather than one of actual economic importance in absolute terms. The question therefore remains which, if any, of the current small, critical metals markets will become a significant future industrial metal market?

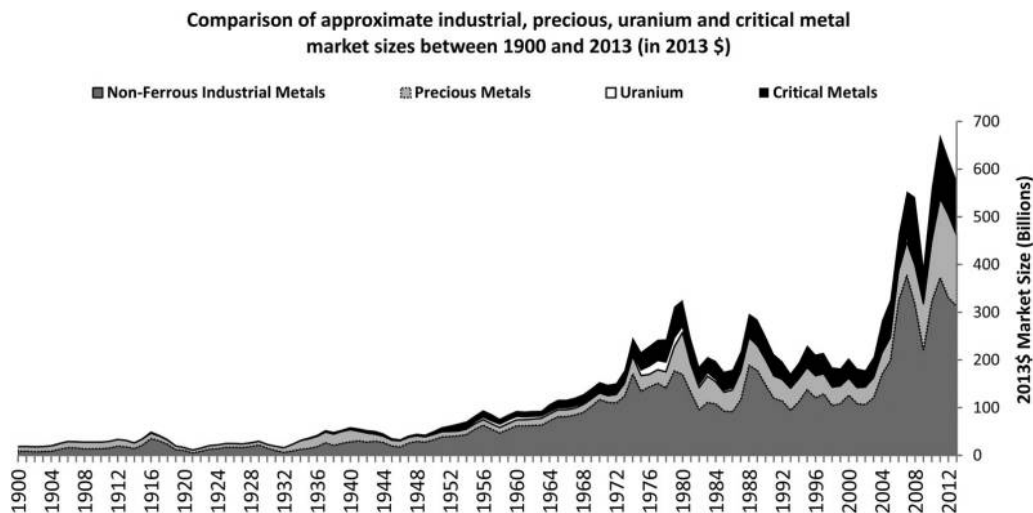
The brief history above also showed that each time a major metals market expansion occurred it was due to a complex interaction of factors, including minerals discovery, changing technology, and changing economic conditions. It is therefore worth investigating the dynamics of transformational metals market growth, in particular for metals that were once, but no longer, considered as minor markets, with some of the characteristics of modern critical metals markets.

Primary example: the story of aluminium – bauxite, bulk mining, Bayer, Hall-Heroult and mass transportation

Many of the current crop of critical metals have so far disappointed in generating rapid transformational market growth. This has not always been the case. Occasionally minor metal markets do transform into significant industrial metal markets. The aluminium market is perhaps most illustrative of this change undergoing substantial transformation in the late nineteenth and early twentieth centuries. Nickel and uranium also present interesting case studies, with the nickel market transformation occurring about the same time as that of aluminium, and transformation of the uranium market occurring in the early to mid-twentieth century.

Aluminium as a scientific curiosity

Although *alum* (aluminium oxide) was used by the Greeks and Romans in both medicines and fabric dyes (Hammond 2015), unlike copper, one of the Metals of Antiquity, aluminium as a metal has a far shorter history. The first part of its history was principally as a scientific curiosity. Guyton de Morveau named the relevant base, *alumine* in 1761. In turn, Antoine Lavoisier predicted that *alumine* was an oxide of an undiscovered element in 1787. Humphrey Davy (who discovered a number of other elements), then tried, but failed to isolate the metal in 1807, but did nonetheless name it. Finally, Hans Christian Orsted isolated an impure form of metallic aluminium in 1825, and two years later Friedrich Wohler was credited with generating the first pure sample of the metal (Hammond 2015). Wohler, amongst others, was then able to analyse aluminium's properties over the coming years and establish the relative low density of the new metal in comparison to other metals. From an economic perspective, the first ingot was not made until 1854, by Henry Etienne Sainte-Claire Deville (Street and Alexander 1998). Although there was commercial, militaristic interest from both Emperor Napoleon III of France and Kaiser Wilhelm II of Prussia, only small amounts of aluminium were produced in this period, just enough to make ornamental helmets, cutlery and toys for the European royalty (Lynch 2002). Despite these small scale, albeit grandiose, beginnings in the



- 3** A comparison of the non-ferrous industrial, precious and critical metal market sizes between 1900 and 2013, based on market size estimates of mine production multiplied by average yearly commodity price, normalised into 2013 US\$, utilising data from Kelly and Matos (2014). The industrial metals group includes aluminium, copper, lead, nickel, tin, titanium (as ilmenite and rutile) and zinc. The precious metal group includes gold and silver, where it is important to note that silver does not fall within the critical metals group, which it could plausibly, based on the evidence from Figure 1. The critical metals include antimony, arsenic, barium (as barite), beryllium, bismuth, boron (as borate), cadmium, chromium, cobalt, gallium, germanium, indium, lithium, mercury, magnesium (metal), manganese, molybdenum, niobium, platinum group metals, rare earth metals, rhenium, silicon (metal), strontium, tantalum, tellurium, thorium, tungsten and vanadium. The figure demonstrates that despite much publicity and discussion the critical metals market is still not a significant part of the global metals markets

mid-nineteenth century, by the mid-twentieth century, just 100 years later, aluminium had become one of the world's most important and widely used industrial metals.

Transformational growth in the aluminium market

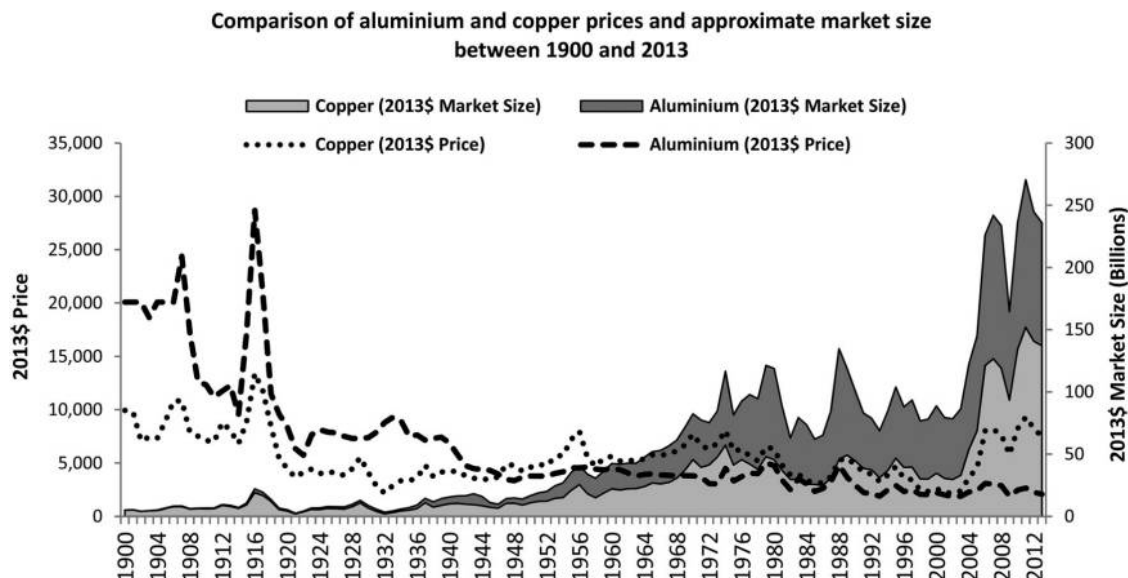
Even as late as 1900, global production of aluminium was just 6800 tonnes, worth only around US\$135 million in 2013 dollars (Kelly and Matos 2014). By contrast, copper cost half as much per tonne, but because about 500 000 tonnes per year was produced, the global market was worth about US\$4.9 billion in 2013 dollars (Kelly and Matos 2014), as demonstrated in Fig. 4. However, by the early 1960s, the aluminium and copper markets were of similar size, both worth about US\$20 billion each in 2013 dollars, and with annual production of both in the region of 4–5 million tonnes (Kelly and Matos 2014).

Today, the aluminium and copper industries are two of the biggest metals markets globally (Kelly and Matos 2014). In 2013 the aluminium market was worth slightly less than US\$100 billion and the copper market around US\$135 billion. The copper market has been the larger over the last decade, but this follows a period in the 1980s and 1990s when the aluminium market was larger than the copper market in value (Kelly and Matos 2014). However, despite the similar size of the aluminium and copper markets, the scales of production and prices have diverged dramatically. For example, in 2013, 47.6 million tonnes of aluminium was produced, but on average was priced at only US\$2080 per tonne (Kelly and Matos 2014). By contrast, just less than 18.3 million tonnes of copper was mined that year, but it sold for an average price of US\$7490 per tonne (Kelly and Matos

2014). Aluminium has therefore become the substantially cheaper and far more abundant metal, with the market increasing in value by three orders of magnitude since the First World War as demonstrated in Fig. 4.

Can the critical metals repeat the growth of the aluminium market?

For one of the present day critical metals to undertake the transition from a niche critical metal to a major industrial metal, and follow the story of aluminium, the correct combination of discovery, supply and demand characteristics need to be in place. Gupta and Krishnamurthy (2005), based on their observations of the small size of the rare earth metals market, despite the apparent geological abundance of the elements, suggest a framework for determining why a metal is mined in substantial volumes or not. First, to be discovered in sufficient quantities across the world, a metal must be both naturally abundant in the crust and geologically concentrated, readily forming into mineral deposits in the crust. In addition, for a substantial flow of supply to be generated the metal must be relatively easy to mine, allowing extraction of the ore from the ground; and easy to process allowing extraction of the metal from the ore. In addition to the Gupta and Krishnamurthy (2005) framework, a consideration of economics and the history of metals markets suggest that some demand or at least potential demand for the metal must exist, in both important industrial sectors and ideally across a broad range of industrial sectors. This classification bears some resemblance to Hewett's (1929) classification of geology, technology, economics and politics as the key factors that control metals mining, with Hewett himself conceding that politics and economics are perhaps parts of the same factor.



4 A comparison of the aluminium and copper markets between 1900 and 2013, showing prices and market size in 2013 dollars (Kelly and Matos 2014). Market size is a simple estimate based on multiplying annual mine production for copper or smelter production for aluminium with the price. In 1900, the aluminium market was considerably smaller than the copper market, but by the 1960s they were of equal size and have remained so (in approximate terms) since

Overcoming challenges in the bulk mining of bauxite

Applying the Gupta and Krishnamurthy (2005) framework helps explain the sudden rise of the aluminium industry in the early twentieth century. First, aluminium is abundant in the crust (Rudnick and Gao 2003). Next, aluminium also forms expansive bauxite deposits across the world, and more to the point was known to do so even in the late nineteenth century (M'Calley 1894; Branner 1897). However, it was not until the early twentieth century that the mechanisms for cheap and easy extraction were put into place.

Bauxite is soft, so relatively easy to bulk mine in open pits; however in the late nineteenth century mining was still mainly utilising underground techniques (Lynch 2002; Crowson 2012), which presented stability issues for mining bauxite (Branner 1897). However, a series of inventions and other factors came together to allow bulk open pit mining to occur on a large scale around the beginning of the twentieth century. Mechanisation and steam power, allowed the deployment of steam shovels and drills, which in combination with the invention of dynamite greatly increased the rate with which ore could be extracted, capturing the economies of scale required for bulk open pit mining (Lynch 2002). The spread of railways meant it was possible to ship the large volumes of ore to port and move labour and materials to the mine site, whilst the more ready availability of coal provided sufficient power to drive the mine machinery and trains (Lynch 2002). The invention of bulk mining perhaps had the greatest effect on copper mining during this period (Lynch 2002; Schodde 2010; Crowson 2012; Sykes and Trench 2014); however, it did also facilitate the mass mining of bauxite.

Overcoming challenges in the processing of bauxite and alumina

Aluminium proved considerably more challenging to liberate from its ore (bauxite) than copper was from its

sulphide ores. Two further inventions were thus required to allow the large scale production of aluminium. Bauxite, hydrated aluminium oxide (usually as $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$), requiring at this time economic levels of aluminium oxide between 40% and 60% (M'Calley 1894; Branner 1897; Street and Alexander 1998), first had to be dehydrated and purified into aluminium oxide, or alumina. This process, named after its inventor Karl Josef Bayer, was developed in 1888, and utilised hot caustic soda (NaOH) to dissolve the alumina and separate it from water and impurities (Street and Alexander 1998). The aluminium then had to be separated from the alumina.

Alumina has a high melting point of about 2000°C , so was unsuitable for conventional smelting techniques. In the mid-1880s, however, both Charles Martin Hall in the USA and Louis Toussaint Heroult in France developed a suitable process. Utilising the much lower cost energy now available through coal (Smil 2011), in addition to the invention of the electric dynamo by Gramme Zenobe, both realised that by dissolving the alumina into a solution with a lower melting point, the aluminium could be extracted via electrolysis. By dissolving alumina in cryolite the solution melts at about 1000°C . The aluminium can then be separated using an electric current and reduced on to carbon anodes. The Bayer and Hall-Heroult processes are both energy intensive, but especially the latter, thus the availability of cheap electricity was critical in the commercialisation of the technology, as well as a defining competitive factor for producer companies and countries (Street and Alexander 1998; Lynch 2002).

Developing new uses for aluminium in transportation

The invention of the Hall-Heroult and Bayer process, along with bulk mining of bauxite meant that, theoretically, aluminium could now be produced on a large scale. However, because it had been so difficult and expensive to liberate aluminium from the vast deposits

of bauxite for much of the nineteenth century, little focus had gone into its potential uses; the latent demand for the metal in the late nineteenth century remained unclear. Aluminium's low density and corrosion resistance meant it found some use as cutlery, whilst its conductivity meant it also occasionally competed with copper for use in electric wiring. Initially however the market was almost always in oversupply, as production required economies of scale, but sufficient demand was not yet in place to absorb it (Lynch 2002).

The final technologies that facilitated the transformation of the aluminium market were therefore on the demand side of the economic equation. The nascent automobile industry was the first to recognise the use of the metal's light weight and ease of forming within the transportation sector (Lynch 2002). However, it was the First World War that turned aluminium into a major industrial metal market. Not only was this the first major war between industrial nations, heavily reliant on sourcing supplies and troops via vast rail networks, but also the first war to use both automobiles and aircraft, in addition to the trains and ships, which were already familiar to the military (Lynch 2002). Within two years of the outbreak of war, aluminium had more than tripled in price, whilst annual production exceeded 100 000 tonnes. Though prices normalised after the war, production had shifted to a new scale: 1922 was the last year less than 100 000 tonnes of aluminium was produced (Kelly and Matos 2014). Demand, and thus production grew throughout the 1920s before declining in the Great Depression. The Second World War, and the rearmament in the lead up to it, however, then provided a second demand stimulus (Lynch 2002). Both automobiles and aircraft played a much larger role in the Second World War. As such, 1941 was the first year in which over one million tonnes of aluminium was produced (Kelly and Matos 2014).

A combination of discovery, supply and demand factors

Aluminium continues to be vital to the various transportation industries, but also has significant end uses in the packaging, construction, electrical, machinery and consumer durables industries (USGS 2014). In 2013, 47.6 million tonnes of aluminium worth just under US\$100 billion was produced (Kelly and Matos 2014). It is clear that discovery, in both the physical and scientific forms was important: first, in the unveiling of large bauxite deposits, particularly in North America; and second in gaining an understanding of the material properties of aluminium, developing new extraction technologies and finally new industrial products, such as aircraft. All these factors therefore had to come together to propel the otherwise geologically abundant aluminium to the status of a major industrial metal market.

Other examples: the economic emergence of nickel and uranium

In addition to aluminium, Lynch (2002) highlights two further, now familiar metal markets that arose from the wars of the early to mid-twentieth century: nickel and uranium. Building upon Lynch's observations of the importance of the demand stimulus and technological innovation from the wars of this period, it is possible to

make a more subtle argument. The war-related demand was often just the last of a series of key factors falling into place. Important supply-side changes, relating to both minerals discovery and extraction technology, were also required in advance to prime these metal markets for industrial scale production. The economic emergence of nickel and uranium again are illustrative of how discovery, extraction and demand factors combine to transform a metals market.

Nickel: New Caledonia, Sudbury, Norilsk, smelting and naval armour

As with aluminium, nickel was not a 'Metal of Antiquity'. Nickel was only discovered in 1751 (Mudd and Jowitt 2014). Small scale commercial production began in 1848 in Norway (Mudd and Jowitt 2014), but large-scale industrial production was not catalysed until there were a coincidence of major discoveries, supply technology breakthroughs and new uses in the late nineteenth and early twentieth century.

Discoveries of nickel deposits in New Caledonia, Sudbury and Norilsk

With the expansion of the European empires, two significant nickel discoveries were made in the late nineteenth century, firstly on New Caledonia, a French dependency, and then at Sudbury, Ontario, Canada during the construction of the Trans-Canadian railroad, following the unification of Canada (Street and Alexander 1998; Lynch 2002; Mudd 2010a; Mudd and Jowitt 2014). In addition, the world's largest operating nickel sulphide field, at Norilsk, Russia, was discovered in the 1920s (Mudd and Jowitt 2014).

Overcoming challenges in mining, processing and smelting nickel

It was however the copper that attracted early prospectors to Sudbury, not nickel. Like some of the present day critical metals, nickel was viewed as a deleterious element associated with the copper, that made smelting more difficult, hence why it was known as *kupfernickel* (Devil's copper) by the German metallurgists of Agricola's time (Street and Alexander 1998; Lynch 2002). However, breakthroughs in smelting technology in the late nineteenth century at the Orford Smelter in New Jersey resolved these issues (Lynch 2002; Mudd 2010a). The extraction of nickel also benefitted from many of the same bulk mining and processing technologies (such as flotation) that helped the copper (and other base metal markets, such as lead and zinc) expand greatly around the same time (Lynch 2002; Schodde 2010; Crowson 2012; Sykes and Trench 2014).

Developing new uses for nickel in armaments

Even so, nickel still lacked substantive demand, beyond limited use in coinage. The Rothschild family, who controlled the New Caledonian nickel supply at the time, promoted the toughening effect of nickel in steels (Street and Alexander 1998; Lynch 2002; Mudd 2010a), in a hope to increase nickel demand. The effect was noted by the US military, who invested in research into nickel steels in the navy. Nickel plate was tested in Spanish American War in 1898 and deemed a success (Lynch 2002). The subsequent major wars in the early twentieth century

therefore generated substantial demand for nickel within armaments and was thus the last factor to fall into place in transforming nickel into a substantial metal market. The invention of corrosion resistant nickel-chromium austenitic steels in Germany in 1914 led to increased use of nickel in stainless steel kitchen equipment and utensils (Mudd and Jowitt 2014), beginning the diversification of the nickel usage base.

Transformational growth in the nickel market

The USGS estimates that less than 10 000 tonnes of nickel, worth about US\$285 million (in 2013 dollars) was produced in 1900 (Kelly and Matos 2014). During the First World War, production had quadrupled exceeding 45 000 tonnes with an annual market value peaking at US\$900 million (in 2013 dollars). During the Second World War, production levels nearly quadrupled again exceeding 160 000 tonnes annually with an annual market value of nearly US\$2 billion (in 2013 dollars). Following the Second World War, annual nickel production would never again drop below 100 000 tonnes. Production in 2013 was around 1.7 million tonnes worth about US\$25 billion (Kelly and Matos 2014). Since World War I, nickel production has increased more than 75-fold, less than the 395-fold increase in aluminium production, but nonetheless clearly transformational. This market growth is shown in Fig. 5.

A combination of discovery, supply and demand factors

Like the case study of aluminium, the study of the nickel market highlights how discovery, supply and demand factors need to come together before transformational growth is precipitated. The discovery of major, high quality ore deposits in New Caledonia and Sudbury, Canada was one factor on the supply side; as were improvements specifically in nickel smelting and more generally in the bulk mining and processing (by flotation) of base metals. Important end uses were then developed in the military, and like aluminium, the wars of the early to mid-twentieth century stimulated demand, and encouraged a broader use of nickel as it became more available. In addition, this study of nickel also demonstrates how former by-product or deleterious metals to other primary ores can grow to become primary mined metals themselves – if the appropriate set of discovery, supply and demand factors come together and allow the market to expand rapidly. This final point is of particular salience to the critical metals industry, as many of the metals are still produced as by-products (Gupta and Krishnamurthy 2005; Naumov and Grinberg 2009; Alonso *et al.* 2012; Graedel *et al.* 2012; Packey 2012; Mudd *et al.* 2013b; Graedel *et al.* 2015; Werner *et al.* 2015; Sykes *et al.* 2016).

Uranium: Katanga, radium mining and the Manhattan Project

Initial commercial interest in uranium focused on its co-occurrence with radium, which in the 1920s was worth between 20 000 (Lynch 2002) and 75 000 (Mudd 2014) times more than gold (dependent on source of information and time period chosen), as at the time it was subject to a fashionable frenzy somewhat similar to that which surrounds some of today's critical metals (Aldersley-Williams, 2012; Trench, 2013). Initially mining occurred on small deposits in the Erzgebirge (Ore Mountain) region of

Germany and Bohemia (now Czech Republic) and on the Colorado Plateau, USA, during the early twentieth century (Mudd 2014).

Major discoveries of uranium deposits in the Belgian Congo and Canada

The discovery of a rich radium-uranium deposit at Shinkolobwe, Katanga, then in the Belgian Congo, which was developed by the colonial mining company Union Minière in 1921–22, and another major discovery at Great Bear Lake, Northwest Territories, Canada, in the 1930s were contributory factors that helped facilitate the creation of a new metals market for uranium.

Overcoming challenges in mining low concentrations of radioactive ores

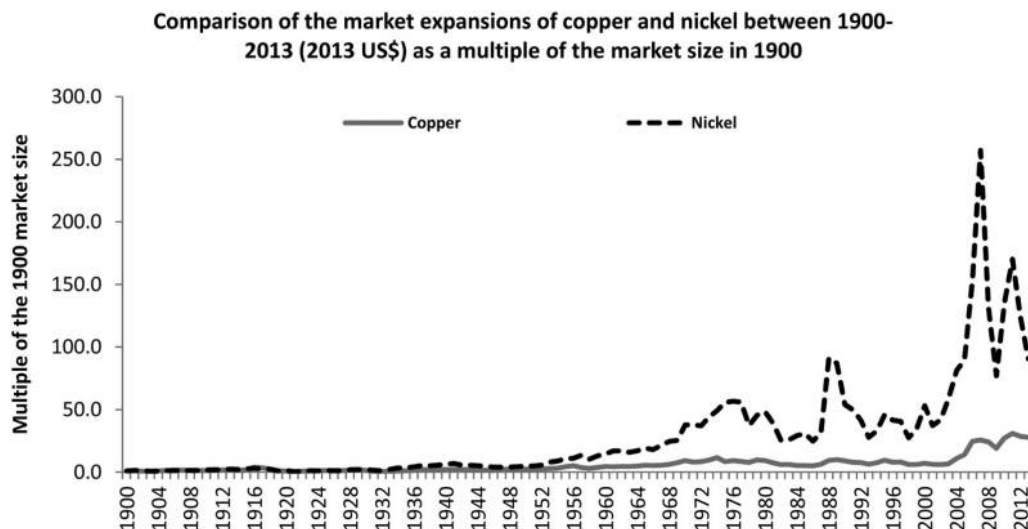
The discovery of Shinkolobwe and Great Bear Lake were only the first steps in changing the nascent uranium industry dynamics (Lynch 2002; Mudd 2014). At this time, the uranium was essentially waste from the radium extraction; thus, mining techniques targeting the very small concentrations of about 0.3 gram per tonne of radium locked within the ore had to be developed (Lynch 2002). In turn, this experience helped improve the eventual economic extraction of the more abundant uranium.

Developing new uses for uranium in nuclear weapons and power

The third and final step came in the transformation of the economic importance of uranium by the discovery of nuclear fission and the fact that vast amounts of energy could be released by bombarding uranium with neutrons (Street and Alexander 1998; Lynch 2002). Although the potential for civil power generation was recognised, with the outbreak of the Second World War, both German and US scientists quickly realised the possibilities of a fission bomb. The United States' Manhattan Project was brought into being in 1942, and utilised the waste uranium ore that had been stockpiled at Shinkolobwe (Lynch 2002; Mudd 2014), as well as ore from Great Bear Lake and the Colorado Plateau (Mudd 2014). The first atomic bomb test was undertaken at Los Alamos, New Mexico, USA, in July 1945. Bombs were dropped on Hiroshima and Nagasaki, Japan, in August, bringing to an end the war in the Pacific (Street and Alexander 1998; Lynch 2002). However, it was already clear before this point that uranium was a metal of vital strategic importance. Following the Second World War, the United States (and more generally the democratic West) and their new enemy the Soviet Union would play out the Cold War, with both focusing great energy on strategic nuclear arms programmes.

Transformational growth in the uranium market

Prior to the Second World War, uranium production was essentially negligible. In 1945 it had risen to slightly over 500 tonnes. Production had a first peak in 1959 at nearly 48 000 tonnes. A second peak came in 1980 with production just short of 70 000 tonnes. Production went into decline after this, reaching lows of just over 30 000 tonnes in 1990s (Nuclear Energy Agency (NEA) 2006). Production has since somewhat recovered, reaching nearly 60 000 tonnes in 2013 (NEA 2006; World Nuclear Association (WNA) 2015c). Trends in market size have



- 5 A comparison of the expansion of the nickel and copper markets between 1900 and 2013, based on data from Kelly and Matos (2014). Market size is a simple estimate based on multiplying annual mine production with the price. The lines represent the multiple of increase from the 1900 market size (in 2013 dollars): US\$4.9 billion for copper and US\$285 million for nickel. Over this period the copper market expanded 28-fold compared to a much more rapid expansion of the nickel market, by 91-fold. Recent volatility in the nickel price, for the much larger market of recent decade, when compared to very small market size in 1900, exaggerates the market expansion multiple for the most recent years. However, if this analysis was ended in 2007, rather 2013, the nickel market would have grown 257-fold since 1900. The rapid growth of the nickel market compared to the copper market during the Second World War, referred to in the text can be seen, as well as rapid post-War growth, volatility associated with strikes at the major Sudbury nickel mines in Canada during the late-1980s, and the recent expansion of the market in response to Chinese industrialisation

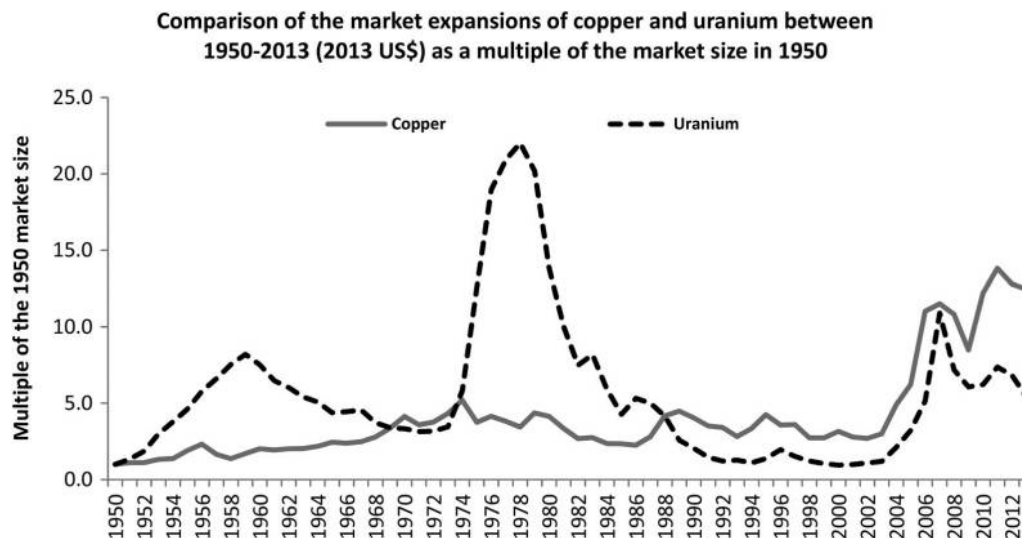
largely mirrored this pattern. In 1950, the world uranium market was worth less than US\$1 billion (in 2013 dollars), peaking at just over US\$7.5 billion (2013 dollars) in 1959, and again at over US\$20 billion (2013 dollars) in 1978 (Pipe 2015), before declining to less than US\$1 billion by the end of the century (Indexmundi 2015). The size of the market has since recovered, with a price spike in 2007 pushing the market size over US\$10 billion in 2013 dollars (Indexmundi 2015; WNA 2015c). Prices have since declined and the market now stands at US\$5 billion (Indexmundi 2015; WNA 2015c). This pattern was driven partly by demand trends. Uranium was initially consumed primarily by the military (WNA 2015a), but by the 1970s and 1980s civilian demand for nuclear power, had also grown in importance making up about 80% of demand. As military demand declined in latter part of the twentieth century, and civilian demand also stalled as nuclear power became less popular, substantial inventories, particularly in the military built up, which when released to the civilian market, reduced the requirement for uranium mining. The inventories are now much smaller, and annual mine production (60 000 tonnes) is now not too far off annual demand (70 000 tonnes), which comes almost entirely from the civilian sector (WNA 2015b).

A combination of discovery, supply and demand factors

This case study of the uranium mining industry is informative on the issue of transformational market growth amongst the minor metals. As with aluminium and nickel, the rapid growth of the uranium market, with mine production increasing three orders of magnitude from 1945 to 1959 (NEA 2006) demonstrates how supply, demand

and discovery factors come together to allow this growth. Whilst the demand side factors arising from the development of nuclear weapons and nuclear power are more historically obvious, the discovery and supply factors should not be underestimated. The discovery of uranium deposits in the Belgian Congo, Germany, Canada and the USA was also required (Lynch 2002; Mudd 2014), as were the advances in mining low concentration radioactive minerals, that came from previous experience mining less abundant radium (Lynch 2002). This transformational market growth is seen in Fig. 6. As with the study of the nickel market, the uranium market is also another example of a formerly by-product metal (this time of radium) growing to become a primary mined metal in its own right, a challenge that many of the critical metals of today will have to overcome (Gupta and Krishnamurthy 2005; Naumov and Grinberg 2009; Alonso *et al.* 2012; Graedel *et al.* 2012; Packey 2012; Mudd *et al.* 2013b; Graedel *et al.* 2015; Werner *et al.* 2015; Sykes *et al.* 2016).

Conversely, uranium is also informative on why transformational market growth does not occur. The uranium market was a broadly similar size to the nickel market in the late 1970s (about US\$10–15 billion in 2013 dollars), but is now five times smaller (about US\$25 billion compared to US\$5 billion). Potentially this could be due to a lack of diversity of demand, as uranium has few substantial end uses beyond nuclear weapons and power (WNA 2015a, 2015b), leaving the commodity vulnerable to changes in demand for key end uses. In the case of uranium, demand from the military has declined, whilst from the civilian sector it has stalled, severely limiting market growth, despite abundant resources, stocks and supply sources (WNA 2015b). Aluminium and nickel



6 A comparison of the expansion of the uranium and copper markets between 1950 and 2013, based on data from Kelly and Matos (2014). Market size is a simple estimate based on multiplying annual mine production with the price. The lines represent the multiple of increase from the 1950 market size (in 2013 dollars): US\$11 billion for copper and US\$937 million for uranium. Over this period the copper market expanded 13-fold whilst the uranium market expanded just five-fold. However the chart does demonstrate the transformative growth of the uranium market following the Second World War, discussed in the text, as well as the boom in uranium prices in the 1970s. The chart also clearly shows how this transformative growth halted after the 1970s, which the authors contend in the text is due to a lack of diversity of demand, leaving the uranium market vulnerable to major switches in end-use as nuclear weapon and nuclear power programmes were eased. The recent boom in prices, partly associated with Chinese industrialisation and partly due to depletion of stocks built up post-1970 can also be seen

both seem to have broader usage bases and therefore seem less vulnerable to this type of demand destruction and partly explains why these markets continued to grow in the late twentieth century, whilst uranium did not. Again, for transformational market growth to occur, discovery, supply and demand factors must all be in place. For uranium this was the case in the mid-twentieth century, but not in the late twentieth century. The stalling of this transformational market growth is also seen in Fig. 6.

Conclusions

The recognition of future potential will not of itself lead to transformational growth in critical metals' markets. History shows that it requires a combination and interaction of discovery, supply-side and demand factors to allow transformative growth in a metals market. That is, the lessons from the history of the metals markets and the case studies of aluminium, nickel and uranium are that for one of the current crop of niche, critical metals to in future form a major industrial metal market, not only must it be relatively geologically abundant and concentrated within potential extractable discrete deposits, but it must also be cheap to extract (supply-side breakthroughs), and there must not only be critical uses, but a wide range of economic uses (demand-side breakthroughs).

The fact that a combination of breakthroughs in discovery, supply and demand are required before transformational market growth can occur suggests that such growth will not occur within the critical metals' markets until these combined requirements can be met.

It must be acknowledged that progress towards overcoming constraints in each of these areas moves at

different speeds, so it can for a time appear that progress in only one or two of these areas is required for a given metal and thus that some of these factors seem temporarily more important. However, it remains that the final breakthrough is merely the last of a series breakthroughs in discovery, supply and demand, and ultimately breakthroughs in all these areas were required, before transformational market growth occurs.

Importantly therefore, for governments and industrial firms hoping to resolve the critical metals issue by catalysing transformational growth in these metals markets, or explorers and miners seeking opportunity in the transformational market growth, they will need to approach the sector from an integrated perspective. Each of discovery, supply and demand will have to be considered in turn, with the aim of identifying which of these areas still require breakthroughs. In light of this complexity, efforts will have to be made to facilitate breakthroughs across all the areas that still require improvements, rather than focusing on just one specific constraint in isolation. It seems likely that more than one 'silver bullet' will be required for each critical metal market, before they can be considered the next aluminium (or even nickel or uranium).

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