Challenges to global mineral resource security and options for future supply

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Abstract: Minerals are vital to support economic growth and the functioning of modern society. Demand for minerals is increasing as global population expands and minerals are used in a greater range of applications, particularly associated with the deployment of new technologies. While concerns about future mineral scarcity have been expressed, these are generally unfounded and based on over-simplistic analysis. This paper considers recent debate around security of mineral supply and technical, geosciences-based options to improve utilization of the resource base and contribute to replenishing reserves. History suggests that increasing demand for minerals and higher prices will generally lead to technological and scientific innovation that results in new or alternative sources of supply. Recent assessments of global mineral endowment suggest that society should be optimistic about its ability to meet future demand for minerals, provided that there is continued innovation and investment in science and technology. Reducing energy consumption and breaking the current link between metal production and greenhouse gas emissions are among the greatest challenges to secure a sustainable mineral supply. However, widespread adoption of low-carbon mineral extraction technologies, underpinned by multidisciplinary research, and increased global utilization of low-carbon energy sources will allow these challenges to be met.

Increasing global demand for minerals

Minerals underpin every aspect of our daily life. They are essential for supporting economic growth, improving and maintaining quality of life and for the functioning of modern society. Minerals are used in larger quantities (Fig. 1) than ever before and in an increasingly diverse range of applications, particularly to meet the requirements of new technologies. Burgeoning demand for minerals is driven by a range of factors of which the most fundamental is population growth, predominantly in the developing world. Global population is projected to increase to 10.9 billion by 2100, an increase of more than 50% from 2013 (United Nations 2013). Unprecedented levels of urbanization and the spread of prosperity, especially in Brazil, Russia, India and China, and other emerging economies, are using raw materials in quantities unimaginable only 20 years ago. By 2025 China will have developed more than 200 cities with more than 1 million inhabitants, many incorporating mass-transit systems (Woetzel *et al.* 2009). Growth in emerging markets and developing economies is predicted to reach 5.7% in 2014, compared with 1.1% in the Euro area (International Monetary Fund 2013).

In addition to using minerals in far greater quantities, modern technology employs a considerably more diverse suite of metals. For example, a modern computer chip contains greater than half of the elements in the Periodic Table (Graedel *et al.* 2013). Even though they may be present in very small amounts, each is essential to the function and performance of the device. Proliferation of electronic devices, such as mobile telephones, tablet computers and flat panel displays, into every aspect of our daily lives, coupled with increasing demand from 'green' or clean energy technologies (e.g. autocatalysts, photovoltaic cells, high-strength magnets for motors in electric vehicles and wind turbines), has caused the rate of production of some metals (e.g. lithium, cobalt, platinum-group metals, antimony, rare earth elements and tungsten) to increase dramatically since the 1980s (Fig. 1c, d). Greater demand and higher prices for these commodities is reflected in increased global exploration activity for these metals. For example in May 2014 over 50 'advanced' rare earth element (REE) projects, involving more than 40 companies, operating in numerous countries were reported (Technology Metals Research 2014).

This contribution introduces subsequent papers, originally presented in a session at the 2011 Geological Society Fermor Meeting, considering mineral resource estimation, sustainability of mineral supply, associated energy demand and the criticality of metals to society.

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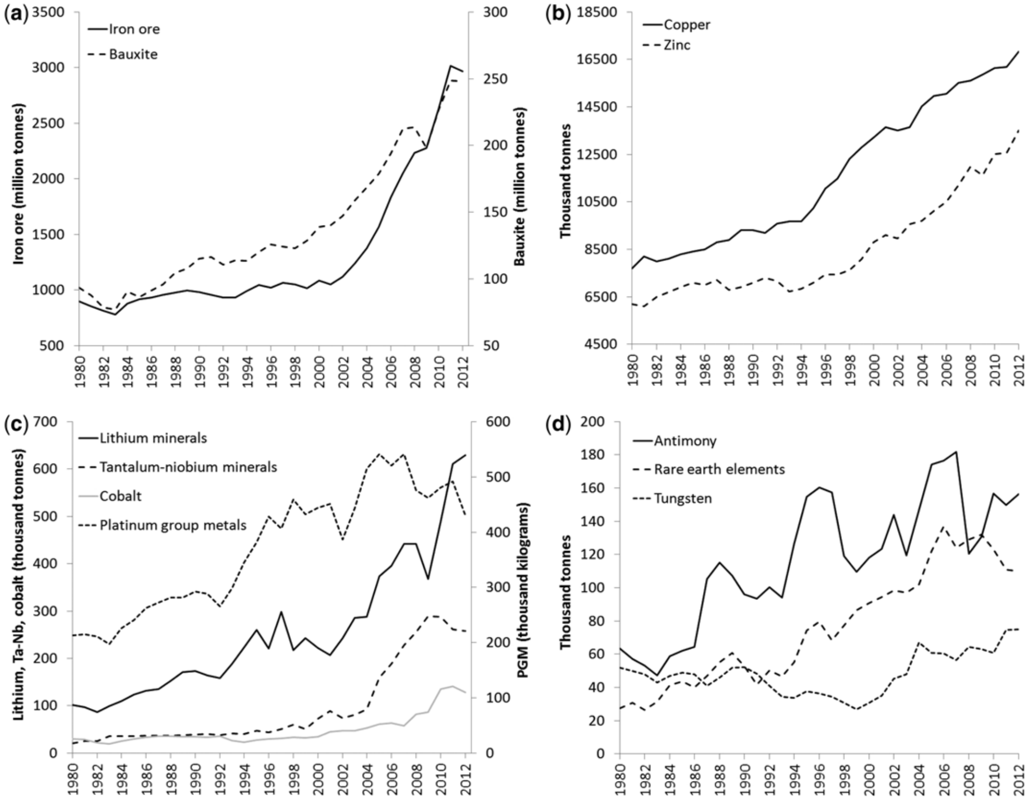

Fig. 1. Annual global production of industrial metals and critical minerals and metals 1980–2012. All units in metric tonnes except platinum-group metals (PGM) in kilograms. Data from British Geological Survey World Mineral Statistics database, 2014 © NERC, except for rare earth elements (REE) courtesy of the US Geological Survey (USGS 2012). (**a**) Production of iron ore and bauxite. (**b**) Mine production of copper and zinc (metal content). (**c**) Mine production of lithium and tantalum–niobium minerals, cobalt and PGM (metal content). (**d**) Mine production of antimony and tungsten (metal content) and REE (rare earth oxide equivalent).

How much is left?

Recent history is punctuated by concerns over the adequacy of natural resources to support population and economic growth. The eighteenth-century economist Thomas Malthus made dismal predictions that population growth would exceed the capacity of the Earth to provide resources. During the 1970s the Club of Rome modelled the relationship between economic and population growth and finite resources, considering varying scenarios. Many of these resulted in pessimistic predictions about population decline and environmental deterioration. Speculation over the future availability of adequate, secure and sustainable supplies of the mineral commodities required to sustain the growth rates and meet the demand outlined above continues to this day. A number of authors have recently forecast impending scarcity, and even exhaustion, of some raw materials within a few decades (e.g. Cohen 2007; Bardi & Pagani 2007; Ragnarsdóttir 2008). However, these alarmist views are frequently based on over-simplistic analysis and misunderstanding of the meaning of the terms ‘resources’ and ‘reserves’. A mineral ‘resource’ is a natural concentration of material in or on the Earth in such form and quantity that economic extraction of a commodity is potentially feasible (USGS 2013). Resources can be subdivided into different categories, reflecting the level of geological knowledge and associated confidence in their existence (Fig. 2). Reserves are that part of an ‘identified’ resource that could be economically extracted at the time of assessment (USGS 2013). Accordingly reserves are economic entities that represent only a very small proportion of the total amount of a mineral or metal in the Earth, sometimes referred to as the ‘resource base’ (Fig. 2).

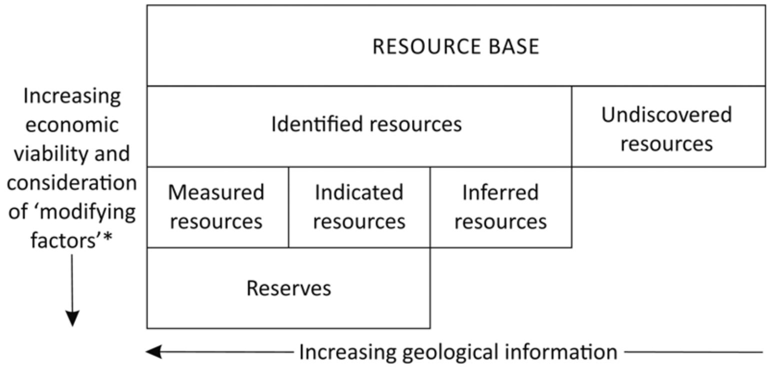

Fig. 2. The relationship between mineral resources and reserves. Mineral reserves generally only represent a tiny fraction of resources. Resource base refers to the total amount of a mineral or metal in the Earth's crust. *'Modifying factors' include mining, processing, metallurgical, marketing, social, environmental, legal and governmental considerations.

Reserves are best considered as working inventories at a particular point in time, varying in response to the rate of extraction of raw materials, and to new discoveries and numerous economic, political, social and environmental factors. For example, innovations in mining and processing technologies can result in some previously uneconomic deposits becoming reserves. Non-sulphide zinc deposits (also referred to as 'zinc oxide') were largely ignored in the latter part of the twentieth century, but new developments in hydrometallurgy have transformed them into attractive exploration targets characterized by large size and low processing costs (Hitzman *et al.* 2003). Where a political intervention or some other event creates an actual or perceived shortage, then increased mineral exploration activity can also lead to the identification of new reserves. For example, reserves of the REE grew by 25% between 2008 and 2010 (USGS 2009; USGS 2011) because of trade restrictions imposed by China commencing in 2008, which caused prices to rise and stimulated a major increase in exploration activity for REE. New exploration and development can also have a dramatic impact on resource estimations for individual mineral deposits. The resource at the Kamoa copper deposit in the Democratic Republic of Congo, the world's largest underdeveloped high-grade copper deposit, is a good example with indicated mineral resources doubling in less than a year (Ivanhoe Mines 2013). Similarly, measured and indicated mineral resources (Fig. 2) of gold at the Goldrush deposit in Nevada increased by more than 500% between 2011 and 2012 (Barrick 2012).

It is important to note, however, that even the best estimates of global mineral reserves, provided by the United States Geological Survey (USGS), are not necessarily reliable. For many commodities uncertainty in these estimates arises from the fact that they are derived from a wide range of disparate sources that do not use a common system for classifying and reporting reserves. In fact, for some minor metals, such as indium and gallium, no quantitative global reserve figures are published by USGS because of the lack of suitable high-quality data. Consequently, because of their dynamic nature and the inherent uncertainties in global totals, published reserve estimates should not be regarded as reliable indicators of future availability of mineral commodities. Graedel & Nassar (2013) suggest that, in the interests of long-term planning and policy aimed at ensuring future supply security, more robust reserve data are required for a wide range of mineral commodities. However, this is a major challenge and would require fundamental improvements in our understanding of the geological distribution of many metals and in data collection and harmonization.

In an attempt to reduce the bias and sometimes subjective nature of mineral resource assessment, the USGS has pioneered a probabilistic approach for quantifying mineral endowment. This method, based on established mineral deposit models and delineation of prospective geology, estimates that there may be approximately 1.3 times as much copper still to be discovered in porphyry copper deposits in the upper 1 km of crust of the Andes region as identified to date (Cunningham *et al.* 2008). While providing a valuable indication of the amount of metal remaining in undiscovered deposits in the uppermost part of the Earth, in terms of the total thickness of the continental crust, this is barely scratching the surface. The deepest current mine is approaching 4 km and, as technology evolves, deeper deposits may become economically viable to develop. One of the key objectives of current

European initiatives on raw materials is to better define the potential for indigenous resources at greater depths (European Commission, 2013*a*).

An alternative approach to mineral resource assessment is the tectonic-diffusion method, which estimates the number of mineral deposits of a specific type at all levels in the crust. This computational technique, which uses age–frequency data of known deposits of a particular type, models the formation of new deposits and tracks their vertical movement in the Earth's crust through time (Kesler & Wilkinson 2008). Applying this approach to porphyry copper deposits, Kesler & Wilkinson (2008) estimate that the amount of copper in deposits above 3.3 km (a suggested limit of mining in the foreseeable future) in the Earth's crust could support global mine production of copper at current rates for more than 5000 years. The tectonic-diffusion method is best suited to deposit types, such as porphyry copper mineralization, with approximately log normal age–frequency distributions (Kesler & Wilkinson 2008). Kesler & Wilkinson (2013) apply this technique to tin deposits associated with granites in an attempt to evaluate the use of tectonic-diffusion analysis for a deposit class with non-ideal age–frequency distributions. Their modelling estimates that, even if only half of the tin identified above 1 km in the Earth's crust can be discovered and mined, the amount of recoverable tin far exceeds global reserve estimates by the USGS.

Although these studies demonstrate that more robust, quantitative estimates of global mineral endowment are being developed, these are generally restricted to the industrial or precious metals occurring in relatively well-constrained deposit classes, which have been the focus of decades of research and for which voluminous data exist. However, even for these commodities, the resource assessments are restricted by our current understanding of ore deposit formation.

Security of supply and criticality

In recent years certain metals have been designated as 'critical', chiefly owing to their economic importance and likelihood of supply shortage, also termed 'supply risk'. Many factors affect mineral resource availability, ranging from the crustal abundance of a particular element to social, environmental and geopolitical factors. However, the supply risk for many metals is due mainly to the geographical concentration of production in a few countries, such that many consumer nations are almost entirely dependent on imported supplies. For example, China produces more than 90% of global REE, while Brazil accounts for a similar proportion of the world's niobium production (Brown *et al.* 2014).

A number of recent national and international studies have attempted to identify materials at risk of supply shortage and to provide a basis for the development of appropriate mitigation strategies. High-profile examples include the European Commission's assessment of critical raw materials for the European Union (European Commission 2010) and the US Department of Energy's raw materials strategy focusing on the clean energy sector (US Department of Energy 2011). These studies use a wide range of metrics to measure criticality and, perhaps unsurprisingly, they have delivered widely divergent, and frequently criticized, results. Apart from selection of metrics, a common problem facing all such criticality assessments is the availability of complete, high-quality data for many metals. For some, such as gallium, indium and germanium, reserve and/or production data are either completely lacking or seriously deficient. Graedel & Nassar (2013) focus on the geological factors which influence criticality evaluation. They indicate that significant opportunity exists for the economic geology community to inform the debate and enhance the geological information on which these assessments rely. However, the by-product nature of many of the critical metals means that acquiring such data is particularly challenging. Many are currently produced exclusively as the by-product of the extraction of major industrial metals such as copper, lead, zinc and aluminium. The critical metals are found in low concentrations in the ores of the major metals. For example, most tellurium and selenium are by-products of copper production, derived from the anode slimes produced during electrolytic refining of copper. Processing 500 t of copper ore typically produces less than 0.5 kg tellurium (Selenium–Tellurium Development Association 2010). During electrolytic copper refining only a very small proportion of the tellurium in the copper ores is currently recovered. Although demand for tellurium is growing and its price is much greater than that of copper, existing levels of global production are so small, estimated to be 450 t in 2011 (Willis *et al.* 2012), compared with 19.7 million t of refined copper in 2011 (Brown *et al.* 2014), that there is currently little economic incentive for copper producers to invest in the recovery of additional tellurium. This reliance on production of another metal may give rise to so-called 'technical' or 'structural' scarcity for some of the critical metals. The normal supply–demand market mechanism may not function effectively to alleviate scarcity of this type. For example, although global production of copper is continuing to increase (Fig. 1b), a growing proportion of the total is produced by hydrometallurgical techniques (acid leaching followed by solvent extraction–electrowinning), which do not permit recovery of tellurium (American Physical Society 2011). Consequently future tellurium availability may be constrained by this change in copper extraction technology.

Global responses and supply options

Although current resources and reserves are unreliable indicators of long-term mineral availability, there seems to be a consensus, among geologists at least, that physical scarcity and exhaustion of metals in the Earth's crust are unlikely (e.g. Williams 2008; European Commission 2010). Although there are no grounds for complacency, this view is supported by history: in the past increasing demand and associated higher prices have generally led to technological innovation and breakthroughs that have resulted in the discovery of new or alternative sources of minerals and metals. As Cathles (2013) sets out, optimism, preparation and, we would add, excellent science are key to ensuring that mankind can meet the resource demands of a growing, and increasingly wealthy, global population. In coming decades a spectrum of non-geological issues, such as geopolitics, social and cultural issues, competition for land, resource nationalism and environmental challenges, are likely to represent the largest obstacles to secure and adequate mineral supply (Otto 2006; MacDonald & Gibson 2006). However, the following discussion focuses on selected technical options that rely on geology to improve utilization of the resource base and to contribute to replenishing reserves.

Scientific research and improved mineral deposit models

Academic research and commercial mineral exploration are continually adding to our knowledge of the processes responsible for ore deposit formation and of controls on the distribution of mineralization within the Earth's crust. Ore deposit models will continue to evolve as they have done over the last 50 years, enhancing our ability to predict where mineral exploration should be conducted and how it should be undertaken most effectively. Even for the major industrial metals and their main deposit classes, such as porphyry copper deposits, which have been the subject of decades of study, researchers are continuing to enhance the knowledge base and to question some of the fundamental controls on their formation, particularly for giant systems (Sillitoe 2010*a*). There are likely to be continued developments in our understanding of the role of biological processes and bacteria in ore deposit formation and the importance of 'economic geomicrobiology' (Southam & Saunders 2005; Shuster *et al.* 2013). This knowledge will have applications in mineral exploration, mineral processing, tailings management and site remediation (Zammit *et al.* 2012; Kalmar 2014). Until recently many of the critical metals have largely been neglected by the research community owing to their limited economic importance and, consequently, little is known about the processes mobilizing and concentrating these elements in natural systems. New research, coupled with exploitation of critical metals in a broader range of geological environments, is likely to result in a step change in our understanding of the global distribution of these resources.

History suggests that entirely new ore deposit classes will potentially contribute to future mineral supply. Unconformity-related uranium deposits, which host more than 30% of the Western world's uranium resources and represent some of the largest and highest grade deposits known (World Nuclear Association 2010), were first described in the 1970s (Jefferson *et al.* 2007). The processes responsible for formation of iron oxide–copper–gold deposits, which are important sources of several metals, are poorly understood. These deposits were not known about until the fortuitous discovery of Olympic Dam in Australia in 1975, one of the world's largest mineral deposits. The geological setting and characteristics of the Olympic Dam deposit were unlike any other deposits known at the time. However, since then, broadly comparable deposits have been identified in several other countries, notably Brazil, but no unifying genetic model has been developed (Williams *et al.* 2005). For some critical metals that are used in small quantities and have very low abundances in the crust, new deposit types or a small number of additional operations (probably as by-products of other metals) could have a major impact on future supply. For example, production from the Kankberg gold–tellurium mine in Sweden is estimated to contribute an additional 10% to global tellurium output (Metal Bulletin 2011). Another potential source of tellurium supply is provided by small, very high-grade deposits associated with alkaline igneous rocks in China (Zhenhua *et al.* 2005). Accordingly, even for a geologically scarce metal such as tellurium, which is one of the rarest elements in the Earth's crust with estimated concentrations in the range of 0.36–10 ppb (Hein *et al.* 2003), comparable to platinum (0.4 ppb, Wedepohl 1995), a range of future supply options exist.

Refinement of mineral deposit models and the identification of new classes of ore deposit will lead us to re-evaluate the mineral potential of terranes that have previously been little explored.

In some instances non-geological factors, such as changing political climate and improved infrastructure, may be important drivers in this respect. During the last 30 years a number of world-class mineral deposits have been discovered or delineated in what may be considered frontier terranes. Examples include the Aynak sediment-hosted copper deposit in Afghanistan, the Oyu Tolgoi porphyry copper–gold deposit in Mongolia and the Reko Diq porphyry copper–gold system in Pakistan.

The increasing demand for minerals and associated higher commodity prices, together with the availability of new datasets and improved mineral exploration technology, will encourage re-evaluation of mature exploration terranes and known deposits. For example, although the Lumwana copper deposit in Zambia was discovered in 1961, it was not seriously explored until the late 1990s. This led to the delineation of a very large resource and the development of one of Africa's largest copper mines at Lumwana. The Hemerdon tungsten–tin deposit in Devon, UK, is another example of how reassessment of well-known deposits is likely to contribute to future supply. This deposit, worked on a small scale during the Second World War, was further explored in the 1970s, but was not developed owing to depressed commodity prices. However, with higher metal prices and concerns over future tungsten supplies (tungsten is commonly defined as a critical metal, e.g. European Commission 2010), an updated mineral reserve has been defined at Hemerdon and funding has been secured for development of what will be one of the world's largest tungsten mines. The recent greenfield discovery of the Sakatti magmatic copper–nickel–platinum–group metal deposit in northern Finland, attributed to the determination of the exploration team, coupled with the use of conventional exploration techniques, illustrates the potential for further significant mineral deposit discoveries in known European mining regions (Mining Journal 2012*a*; Brownscombe *et al.* 2014).

New baseline datasets and mineral exploration technologies

Globally the acquisition of new baseline datasets, comprising geological, geochemical and geophysical data, will continue to stimulate mineral exploration interest, both in areas previously regarded as unprospective and in well-explored regions. Northern Ireland is now considered one of the best surveyed parts of the planet as a result of recent geochemical and airborne geophysical surveys of the province. These high-resolution datasets contributed to a significant revival in mineral exploration in the region, with the land area under licence increasing fourfold following release of the new data (Lusty 2010). Scientists are also developing novel methodologies to improve baseline data capture with applications to mineral exploration. For example, airborne Light Detection and Ranging (LiDAR) and airborne multispectral imaging have been applied to geological and structural mapping in areas of dense vegetation cover (Grebby *et al.* 2010, 2012).

During the last 50 years there have been major advances in geochemical, geophysical and remote sensing technologies (Sillitoe & Thompson 2006), and further improvements in resolution and accuracy are likely to continue. For example, high-resolution geochronology is improving our understanding of the duration and timing of hydrothermal systems, with significant implications for mineral exploration (e.g. Braxton *et al.* 2012; Rohrmeier *et al.* 2013), and geochemical methods for exploring under superficial cover are continually evolving (e.g. Lilly *et al.* 2014).

Our ability to quickly and efficiently manage, process, model and visualize large and complex digital datasets is constantly evolving and will continue to have a major impact on how we approach mineral exploration. For the modern geologist Geographic Information Systems (GIS) capable of managing and integrating large volumes of spatial data are becoming as important as the geological hammer. Field-portable systems place an array of data at the geologist's fingertips and allow digital field mapping and logging (Brimhall *et al.* 2006). GIS facilitates effective visualization, analysis and dissemination of disparate exploration datasets and is increasingly being used for mineral exploration targeting and assessment of resource potential (e.g. Carranza & Sadeghi 2010). There are suggestions that amalgamated datasets, currently considered too large and complex to process using conventional data management tools and applications ('big data'), cloud computing and more efficient 3D inversion could impact on future discovery rates (Heffernan 2013). Numerical simulations and modelling are also contributing to improved understanding of ore forming processes (Weis *et al.* 2012) and providing new insights into resource availability (Kesler & Wilkinson 2013). Improved mineral exploration targeting will be supported by more advanced mineral exploration and resource characterization technologies, for example, real time, on-site geochemical analysis, measuring while drilling, geophysical tomography and 3D visualization.

Despite our optimism, there is no disputing that the last 50 years have seen a decline in major mineral deposit discoveries (Beaty 2010), which some commentators have attributed to declining grassroots mineral exploration activity (Sillitoe

2010*b*). It has been suggested that much of the planet is well surveyed and has been intensively explored (Beaty 2010), and that it is harder to discover new ore deposits than it was several decades ago (Wood 2012). We would agree that mineral exploration has become more challenging, particularly in mature terranes in the developed world, such as parts of Australia, North America and Europe. In these regions most exposed deposits, or those with a significant surface expression, are likely to have been identified and legal, regulatory, policy and social factors can deter investment (Otto 2006; Bloodworth *et al.* 2009; Tiess 2010). However, the subsurface in these regions has huge potential for new discoveries and the next phase of major mineral deposit discoveries is likely to be made under cover, where deposits have little or no surface expression. For example, although Australia is considered to be a mature exploration terrane, approximately 80% of its land area is covered by regolith and sedimentary rocks. However, the buried basement is as prospective as that exposed at the surface and which has supplied the majority of Australia's mineral production to date. The key to unlocking this potential is improved understanding of the 'distal footprints' of mineral deposits under cover and the associated development of cost-effective mineral exploration techniques (Australian Academy of Science 2012). Elsewhere, in Brazil for example, the geology is known to be potentially favourable for the development of a wide variety of mineral deposit types, but mineral exploration is hampered by the lack of reliable geological maps at a useful scale. Even in Europe, although the geology is relatively well studied and mapped, the reality is that in some countries, such as the UK, Austria and Italy, there has been little mineral exploration activity in recent years (Mining Journal 2012*b*, 2013) and modern high-resolution geoscience datasets are available only for limited areas. Despite a surge in mineral exploration activity in the Nordic countries (Mining Journal 2012*b*), Europe only attracted 4% of global exploration for non-ferrous metals in 2012, less than countries such as Peru and Mexico (Metal Economics Group 2013). Since 2008 the European Commission has developed new policies and funded associated research programmes aimed at boosting raw material supply from European sources and increasing mineral exploration in the region (European Commission 2008, 2011, 2013*b*). With regard to mineral exploration the European Commission is implementing a number of actions focused on improved and cost-effective exploration technologies, provision of high-resolution 3D data to depths of 4 km and the development of new models for mineral deposit formation and/or mineral belts (European Commission 2013*a*).

New frontiers

Increased demand for minerals and higher commodity prices will lead the minerals industry into more extreme and technically challenging environments. Cathles (2013) suggests that seafloor mineral resources, and the oceans in general, offer huge potential for the recovery of a range of elements including uranium, copper, zinc, cobalt, nickel, lithium, REE and phosphate. Enormous resources of copper and zinc are calculated to exist on the ocean floor: even half of the estimated copper resource would be capable of supplying a global population of 10.5 billion for many centuries (Cathles 2013). Appreciation of the mineral potential in the marine environment is not new, with the first resource estimates being made in the 1960s. However, in recent years there has been a revival of interest in seafloor minerals, as illustrated by the number of exploration licences for polymetallic sulphides and nodules issued to a host of countries (International Seabed Authority 2014). Nautilus Minerals Inc. has been assessing the potential of seafloor massive sulphide deposits in the territorial waters of Papua New Guinea for a number of years. UK Seabed Resources was recently granted a licence to explore a 58 000 km^2 area of the Pacific's Clarion-Clipperton Zone for polymetallic nodules (Lockheed Martin 2013). Development of minerals in new environments will not come without its challenges, not least the potential impact on delicate ecosystems. However, with sufficient regulation, underpinned by improved scientific understanding and new research, this is unlikely to be an insurmountable hurdle. Many would also question the economics of seafloor mineral recovery and the potential for commercialization, given the technical challenges of operating in very deep water environments. However, preliminary analysis (Cathles 2013) and the recent enthusiasm of some seabed explorers suggest that metal recovery from some seafloor resources is economically competitive with terrestrial deposits.

Returning to the example of tellurium, should demand continue to rise and production from existing sources not increase, it will be necessary to consider alternative sources of supply. A number of critical metals are highly enriched in hydrogenous iron–manganese crusts that precipitate from seawater onto the surface of seamounts. Tellurium is enriched more than any other element, by a factor of 10^4 relative to the Earth's crust. While the levels of enrichment of cobalt are less impressive, mean concentrations are 3–10 times greater than in currently economic land-based cobalt deposits (Hein *et al.* 2010). Crusts in the 'prime iron–manganese crust zone' in the central Pacific are estimated to contain 9 times more tellurium and 3.8 times more cobalt than the global terrestrial 'reserve base' reported by the USGS (Hein *et al.* 2013). The majority of work on iron–manganese crusts has focused on the Pacific. However, the Atlantic also has significant potential, particularly for platinum-enriched crusts (Muiñosac *et al.* 2013).

The polar regions represent another potentially huge, but largely untapped, source of minerals (e.g. Lindholt 2006; Gautier *et al.* 2009). Reduced sea ice in the Arctic over the last decade, improved ship access and new infrastructure have contributed to heightened mineral exploration interest in the region (e.g. Rosenthal 2012; Braden 2014). Although this largely under-explored region has the potential for the discovery of new world-class mineral deposits, the challenges and risks for explorers and miners are significant. In addition to the practical issues of operating in this remote and extreme environment (e.g. Sengupta *et al.* 1990), there are ongoing territorial disputes (Isted 2009; Geopolitical Monitor 2012), and major concerns about the vulnerability of the environment and social impacts (Gibson & Klinck 2005; Fridtjof Nansen Institute 2012; European Commission 2013*c*).

Eco-efficiency

Cathles (2013) suggests that 'energy is the most essential resource'. The mining industry is a very energy-intensive sector. For example, the Chilean mining industry accounts for 16% of the country's total industrial sector fuel consumption (US Energy Information Administration 2013). Comminution of ore alone accounts for more than 50% of mine-site energy consumption and is estimated to consume up to 3% of global power production (Coalition for Eco Efficient Comminution 2013). The deficiencies of energy infrastructure and the high cost of energy supplies already pose a significant threat to mine production in several parts of the world, particularly Africa (e.g. Visser 2013). As the industry is forced into more challenging environments (e.g. the development of ultra-deep open pits >1 km, deeper underground mines >3 km, the marine environment and the Arctic), coupled with the general trend of reducing ore grades (Wood 2012), energy demand is likely to increase. Mining companies are already making major investments to increase security of energy supply and reduce costs: for example, 20% of Brazilian miner Vale SA energy supply is derived from renewable sources (Green 2014). Water scarcity is a further major challenge facing the mining sector (Carbon Disclosure Project 2013). The scale of this risk is illustrated by the number of water-related issues impacting on mining operations globally and the investments that the mining sector is making in securing sustainable water supplies (Carbon Disclosure Project 2013; BHP Billiton 2013).

Although major research and innovation will be required to address these challenges, mining companies are already investing in related research. Future developments in this area are likely to focus on automated drilling and mining, more selective or 'smart blasting', improved ore sorting, more effective waste removal and pre-concentration, enhanced grinding technology, *in-situ* mining, re-working of tailings and slags, improved water management and increased application of bio-technology, particularly improving the performance and cost-effectiveness of microbial bio-leaching and its application to low-grade and complex ores. Geometallurgy, the integration of geological and mineralogical understanding with mineral extraction and processing, will also become increasingly important, particularly in the early stages of project planning and decision-making, as the minerals industry seeks to become more efficient and reduce costs and environmental impacts (Hoal 2008). A transition from fossil fuels to 'low-carbon energy sources' (Cathles 2013) will also significantly contribute to reducing the future environmental impact of the mining sector.

Conclusions

As the world population increases over the next 100 years and living standards are raised across the globe, demand for all natural resources, including minerals, is expected to continue growing. The trend of using an increasingly diverse range of minerals and metals is also likely to persist. The evidence presented above and the papers in this section suggest that society has every right to be optimistic about meeting this demand, provided that there is continued innovation and investment in science, research and technology. The geological community has an integral role to play. While mineral deposit science and our understanding of ore forming systems have evolved greatly over the last century, our understanding of the geological distribution of some metals, which hitherto have been of marginal economic interest, is very poor. New focused research will improve our understanding of the processes mobilizing and concentrating these elements, enhancing our exploration models and ability to identify new deposits. Researchers will increasingly need to adopt a multidisciplinary approach, working at the interface of the biological, chemical and physical sciences. Improved understanding of ore deposit formation and more sophisticated targeting will lead to both the re-evaluation of well-characterized geological terranes and known deposits, and the assessment of regions that have previously been little explored. Increasing demand for minerals will push mineral exploration and extraction into new environments. This will require significant innovation and investment (e.g. equipment for deep sea resource evaluation and mining) and new regulatory frameworks to ensure that these resources are recovered in a sustainable manner. Our ability to explore under cover and to identify concealed mineralization will also be key to replenishing mineral reserves. This will require improved understanding of the distal signatures of mineral deposits at depth, coupled with more cost-effective exploration, potentially employing remote data-capture techniques and with increased emphasis on 3D modelling of the sub-surface.

Advances in mineral deposit science will inform, and be complemented by, developments in mining and mineral processing technology, which may significantly augment resources by allowing the working of previously uneconomic ore types and grades. Further efficiency savings will be achieved through economies of scale, delivered via larger mines and equipment, and by more cost-effective transportation, including autonomous methods. However, the greatest challenge facing the mining sector is breaking the current link between metal production and greenhouse gas emissions. This requires significant multidisciplinary research and innovation, the widespread adoption of low-carbon extraction technologies and increased global utilization of low-carbon energy sources.

Geoscientists and all those involved in the mineral resource lifecycle have a major role to play in providing better and regularly updated resource and reserve data for a wider range of metals. Although this is not a trivial task, this information is essential to activities such as criticality assessment and material flow analyses, which are used to inform long-term planning and policy-making in relation to future security of mineral supply. This information will also serve to counter concerns about physical scarcity and exhaustion of metals.

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