By mid-century, global population will exceed 9 billion, and millions of new consumers in emerging economies will be driving growth in demand for metals. Whilst metal stocks are unlikely to be exhausted, mankind will face serious challenges. These include improving our ability to find and extract metals from low-grade deposits in extreme environments and to understand crustal concentration processes of many relatively rare metals (critical to low carbon and digital technologies). Above all, we need innovative science to break the link between our resource use and human-induced environmental change.

The future of the global minerals and metals sector: issues and challenges out to 2050

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'If you can't grow it, you have to mine it'. Primary mineral and metal resources from the Earth will be vital to global economic development over the next 40 years. Tungsten mineralisation at Carrock Fell mine in north-west England.

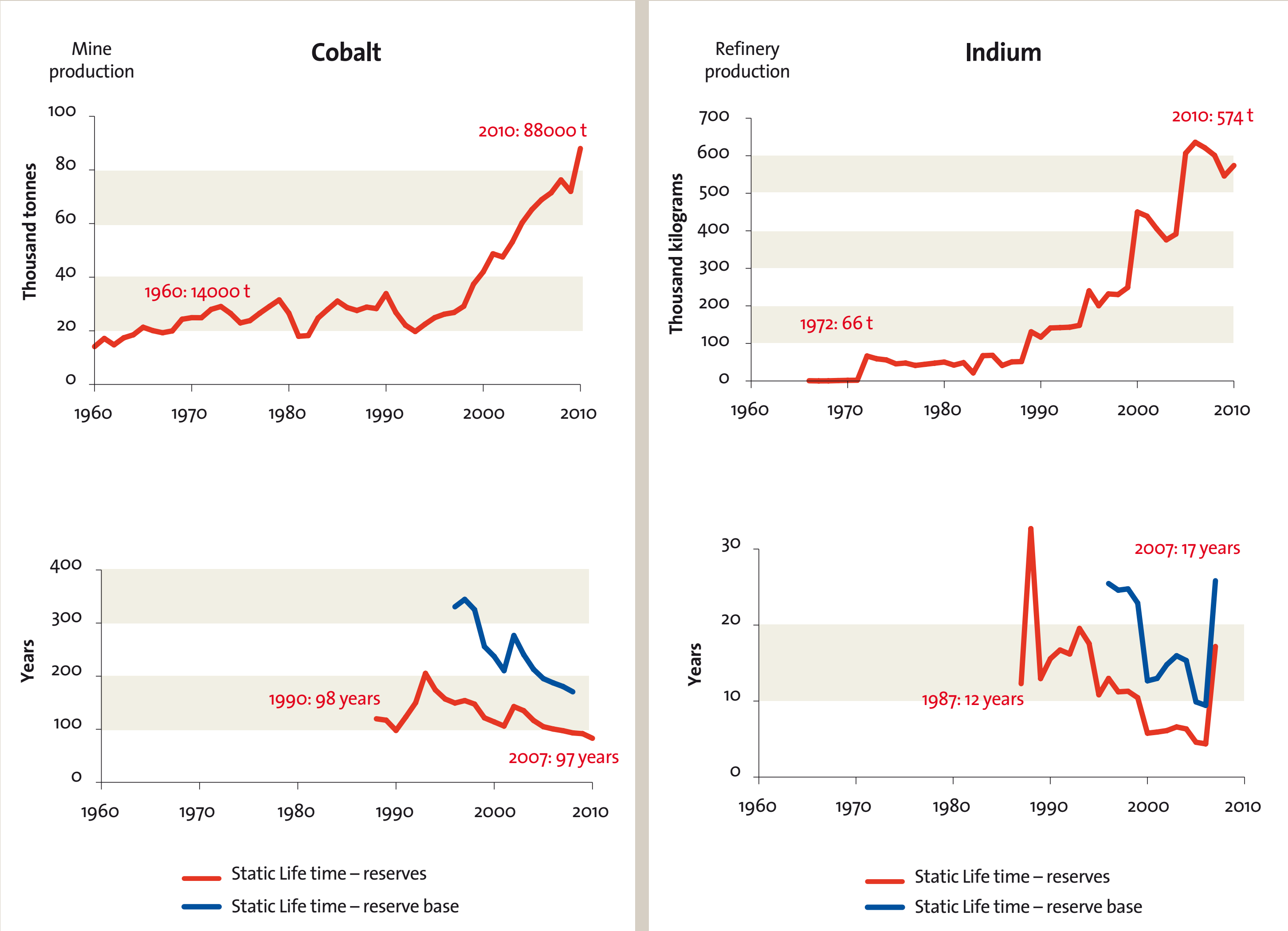
Les ressources primaires minérales et métalliques extraites de la Terre revêtiront une importance vitale pour le développement économique mondial sur les 40 ans à venir. Minéralisation de tungstène à la mine de Carrock Fell, dans le nord-ouest de l'Angleterre.

For the foreseeable future, minerals and metals will continue to underpin the global economy. Transport, energy, manufacturing, health, agriculture and housing are likely to remain heavily dependent on raw materials derived from Earth resources – 'if you can't grow it, you have to mine it'. This article considers the future of the global minerals and metals sector. It will examine some of the key technical, environmental and socio-economic factors liable to impact on minerals and metals supply and demand over the next 40 years.

> *Despite increasing metal production over the past 50 years, reserves have remained largely unchanged.*

Primary metal supply and resource limits

The most fundamental generic issue facing this sector is the question of physical availability of metal from the Earth. Apocalyptic views first expressed in 1798 by Thomas Malthus (that the physical limits of some metal and mineral resources are approaching) have recently reemerged [Ragnarsdóttir (2008)]. In actuality, despite increasing metal production



over the past 50 years, reserves have remained largely unchanged *(figure 1)*. Concerns over physical exhaustion may be based on an over-simplistic view of the relationship between reserves and consumption *(i.e. number of years supply remaining equals reserves divided by annual consumption)*. Metals of which we know the precise location, tonnage and which we can extract economically with existing technology (known as 'reserves') are tiny in comparison to the total amount. Consumption and reserves change continually in response to scientific advances and market forces.

With scientific understanding improving over the next 40 years, reserves will replenish from previously undiscovered resources. For example, mineral deposit types largely unknown 50 years ago (such as porphyry deposits, now the principal sources of copper, molybdenum and rhenium – *figure 2, next page*) contribute

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Fig. 1: Despite escalating global production of metals, reserves of metals have been continually replenished. These graphs show that static life times (number of years supply remaining equals reserves divided by annual consumption), in this case of cobalt and indium, are extended ahead of production. The technological and economic drivers for this process are likely to continue into the future.

Fig. 1 : Malgré une production globale des métaux en forte augmentation, leurs réserves sont reconstituées en permanence. Ces graphiques montrent que les durées de vie statique (l'offre constituée par les réserves, en nombre d'années, divisée par la consommation annuelle), ici pour le cobalt et l'indium, s'étendent au-delà de la production. Les facteurs technologiques et économiques qui déterminent ce processus persisteront vraisemblablement à l'avenir.

Source: BGS, BGR, USGS

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Fig. 2: The Aitik mine in northern Sweden is one of Europe's largest copper mines. Porphyry-style mineralisation was discovered there in 1930, but was not exploited until the late 1960s when modern mining equipment and technology made it economically viable. Today, about 36 million tonnes of ore are mined annually, at a grade of about 0.25% Cu and 0.15 g/t Au.

Fig. 2 : La mine d'Aitik, au nord de la Suède, est l'une des plus grandes mines de cuivre d'Europe. Une minéralisation de type porphyrique a été identifiée en 1930 mais n'a été exploitée qu'à la fin des années 1960, lorsqu'elle est devenue économiquement viable grâce aux progrès de la technologie minière. Aujourd'hui, quelque 36 Mt de minerai sont extraits par an, à une teneur d'environ 0,25 % de Cu et 0,15 g/t d'or.

significantly to global reserves. These were discovered and developed largely due to improved scientific understanding of their formation and extractive metallurgy.

Market forces influence reserve size, as most metals occur in graded deposits: if prices rise, reserves will extend into lower-grade ore; if prices fall, reserves will contract to include only higher-grade material.

Although physical exhaustion of primary metal resources is unlikely, there are no grounds for complacency. Outside the relatively small group of industrial, base and precious metals exploited for centuries, our knowledge of the processes behind the mobilisation and concentration (metallogenesis) of many other metals is poor.

"The variety and volume of the so-called 'critical metals' will grow."

Over the next 40 years, the variety and volume of the so-called 'critical metals' we require to deliver a high-technology, low-carbon economy will grow *(see next page)*. If supply is to be maintained, then science will be vital in understanding the metallogenesis of this group *(figure 3)*. As geological targets for most metals become larger, deeper and lower-grade, advances will also be needed in the technologies used to discover and define deposits and in organisation of the exploration process *(figure 4)*. For example, it is likely that imaging and logging techniques, commonplace in the hydrocarbons sector, will be used increasingly in this context.

Changes in the character of geological targets are driving major technical developments in mining and processing, along with health and safety requirements, environmental footprint reduction and labour/skill shortages. Programmes such as CSIRO Australia's 'Mining Down Under' and Rio Tinto's 'Mine of the Future' are prompting innovations such as *in-situ* mining, autonomous haulage and drilling, and rapid tunnelling. Such developments are likely to be commonplace in the next 40 years, made more efficient by systems innovations in spatial positioning, data management and analysis.

Besides less accessible terrestrial resources, a major new 'frontier' for exploration and mining is likely to be the ocean floor. Targets include massive polymetallic sulphides associated with black smoker hydrothermal vents and manganese nodules scattered across the deep ocean floor. Exploration has already begun in relatively shallow water in the SW Pacific, and a number of countries have taken out exploration licences. Although the technical challenges are immense and the environmental consequences unquantified, interest in these deposits is growing and mining is likely to follow the hydrocarbon sector and begin routine extraction in deep water.

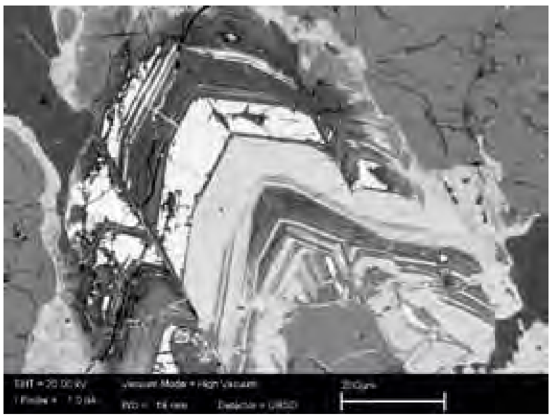


Fig. 3: Zoned allanite [(Ca, Ce, La, Y)^2(Al, Fe)^3(SiO^4)^3(OH)] from a rare earth element enriched alkaline intrusion in north west Scotland. Better understanding of the metallogenesis of critical metals such as rare earths will be vital if we are to find new deposits to meet the rapid growth in demand for these commodities.

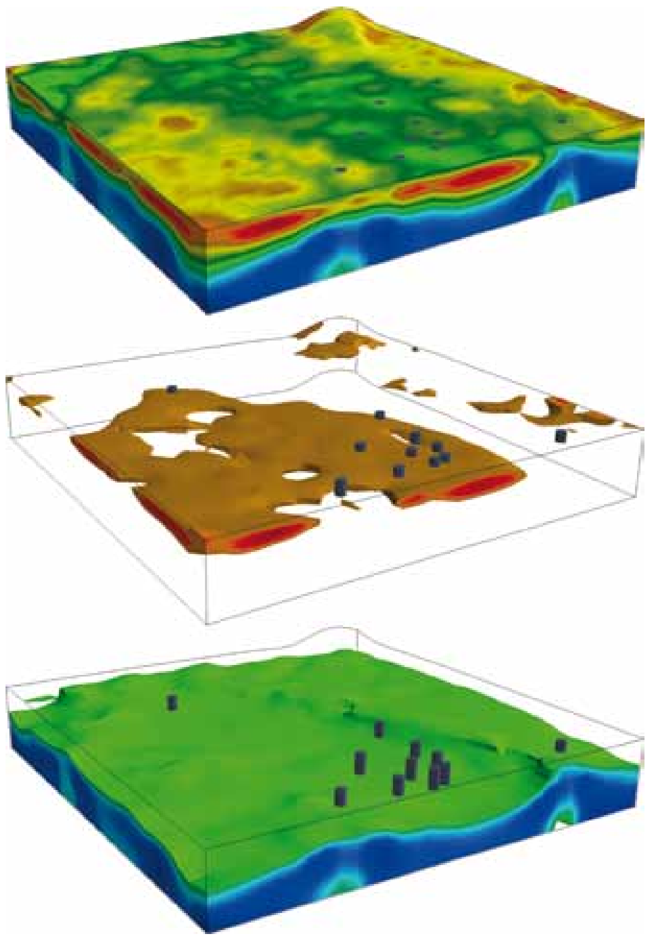
Fig. 3 : Allanite zonée [(Ca, Ce, La, Y)^2(Al, Fe)^3(SiO^4)^3(OH)] issue d'une intrusion alcaline enrichie en éléments des terres rares au nord-ouest de l'Écosse. Une compréhension améliorée de la métallogenèse des métaux critiques tels que les terres rares sera cruciale afin de nous permettre d'identifier de nouveaux gisements pour satisfaire à l'augmentation rapide de la demande vis-à-vis de ces substances.

Recycling and its role in future metal supply

For the foreseeable future, the bulk of human requirements for metals will have to be sourced from primary Earth resources. The upper limit on recycling is determined by what comes back from society i.e. what was consumed 40 to 60 years ago. For example, global consumption of copper in 1970 was about 8 million tonnes per annum: 5 million tonnes from mining and 3 million from recycling. In 2008, copper consumption was about 24 million tonnes, with 8 million from recycling, and the remaining 16 million from primary production (BGS World Mineral

Fig. 4: Non-invasive technologies such as electrical resistivity tomography (ERT) will be increasingly used for rapid assessment of larger, more diffuse mineral targets. Image shows results of an ERT survey of a complex gravel deposit: complete image (top); mineral volume (middle); bedrock surface (bottom).

Fig. 4 : On fera appel de plus en plus largement aux technologies non invasives telles que la tomographie résistivité électrique (ERT) afin d'évaluer rapidement des cibles minérales plus diffuses. L'image montre les résultats d'une reconnaissance ERT d'un gisement complexe de graviers : image complète (haut) ; volume du minéral (milieu) ; surface du socle (bas).



> *For most metals, recycling currently provides 10-20 per cent of demand.*

Statistics Database). For most metals, recycling currently provides 10-20 per cent of demand and less than 1 per cent for elements such as gallium, indium, tantalum and rare earths (UNEP, 2011). Even if recycling rates for these materials were much higher, the critical metal 'resource' currently residing in the anthropogenic environment is very small compared to that needed to meet the predicted increase in demand from low carbon technology and digital devices. Assessing the potential contribution of recycling is hampered by lack of figures on imports of metals contained in finished and semi-finished goods, although active efforts are now being made to quantify material flows through society *(see article by Carencotte* et al.*, this issue)*.

Environmental limits

Over the next 40 years, environmental costs of mineral resource extraction, processing and use may begin to present a significant threat to supply. Between 3 and 5 per cent of total global energy demand is used solely to crush rock for mineral extraction [Daniel and Lewis-Gray (2011)]. Carbon emitted in this process poses a significant environmental limit to our resource use. Only major research and innovation can break the current link between metal use and greenhouse gas emissions. Examples of low-carbon extraction technology include *in-situ* leach mining of uranium and microbial bio-leaching from extracted copper and nickel ores. If environmental impact can be minimised, such processes will significantly extend the resource base by allowing working of previously uneconomic ore types and grades *(see article by Nurmi* et al.*, this issue)*.

Geopolitical and ethical issues

Global resources are unevenly distributed and demand does not always coincide with supply. Sustained growth in demand has caused significant real price increases for metals in the last decade. This pattern looks set to continue, and it is likely that most metal-exporting countries will seek a larger share of the wealth generated by extraction. In most jurisdictions, this will be through taxation and royalties, but in a few countries, extractive operations may be nationalised. International tensions over resources will increase over the next few years and the scramble for resources looks set to continue in Africa and elsewhere. Although mineral endowments should enable poorer countries to embark on a path to economic development, the evidence shows that resource-rich developing countries often move toward poverty and instability. These factors are a major driver for informal artisanal and small-scale mining (ASM) in the developing world *(figure 5)*. Millions of people worldwide are economically dependent on ASM, and the social, environmental and economic issues associated with ASM pose a considerable developmental challenge. As a consequence, ethical considerations related to metal sourcing are likely to become a more pressing issue *(see article by Christmann* et al.*, this issue)*.

Fig. 5: Small scale mining for tantalum-niobium ('coltan') in Namibia. Improving the social and environmental performance of ASM represents a major future challenge as it concerns millions of people in the developing world.

Fig. 5 : Exploitation minière à petite échelle du tantale-niobium (le coltan) en Namibie. Améliorer les résultats sociaux et environnementaux de l'ASM représente un défi majeur pour l'avenir, puisqu'il concerne des millions de personnes dans le monde en voie de développement.

FP7 FarHorizon Project: Breakthrough technologies for the security of supply of critical minerals and metals in the EU economy

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The methodology implemented in the FarHorizon project – part of the EU FP7 European Foresight Platform[2] – aims to federate key stakeholders to explore longer-term challenges and build a shared vision that could guide the development of the relevant European research agenda. The "Success Scenario approach" was applied to critical minerals and metals *(Table)*. Having identified the drivers, three dimensions of challenge were addressed:

– **Challenge 1:** Geology and Minerals Intelligence: access to data on mining, production and geology, knowledge of deeper resources, improved models of how deposits are produced and for better exploration, data sharing, and exploitation of 'exhausted' mines

– **Challenge 2:** Mining, Ore Processing and Metallurgy: exploiting deeper deposits, accessing seabed deposits, prevention of natural or man-made hazards, water and energy saving, reducing CO2 footprint, by-product handling and improving social and business organisation

– **Challenge 3:** Sustainable Use, Efficiency, Recycling and Re-use: downstream resource efficiency, better citizens' understanding/attitude, building capabilities and providing training, transforming waste into mines/urban mining, more systemic view of different critical minerals, global governance of extractive activities

Against these challenges, breakthroughs were sought in four areas and expressed in terms of policy recommendations: new applications, substitution, new sources of materials and rare metals, and changes in demand.

– **Key Action 1:** Establish an integrated strategy for raw materials supply and support it by providing continuous funding. Research in the area of raw materials supply must be underpinned by the right conditions for successful innovation. A holistic, complementary and more horizontal approach is needed to tackle the various issues involved in securing Europe's mineral resources supply within the sustainable development context. Regulators need to understand that they must stimulate innovation, if not for today at least for tomorrow, placing an accent on foresight. There is a 7-8 year challenge to develop a new lead market.

– **Key Action 2:** Move from a stop-and-go to a lasting approach with three central aspects for a research, technology and innovation programme. Research should deal with mineral resources intelligence, lead to new or better technologies and focus on mitigation and understanding of environmental impacts. This presupposes adopting 1) a holistic approach to the innovation cycle implying the full range of mechanisms: basic R&D, integrated projects or their equivalent and joint technology initiatives and 2) a joint programming approach: currently there is little or no coordination between European-level and national research, while some governments are in a position to take the initiative in this area – notably Germany, the United Kingdom, France, Finland and Poland.

– **Key Action 3:** Increase the flow of trained people. This represents a significant constraint: lack of investment in research and teaching in this area over the past 20 years has depleted the availability of expertise to undertake these key tasks. A pool of excellence should be developed, a platform coordinating supply and demand. Efforts should also be made to attract Interest from researchers outside the area, for breakthroughs are liable to come from people currently working in other fields and who accordingly have a fresh perspective on the issues at hand.

– **Key Action 4:** Governance issues are critical. Securing raw materials is a task that goes beyond the competence and capability of the individual member states and is inherently European. A collective voice for Europe is more likely to be heard in the international arena, including influence to halt environmentally damaging or politically dangerous approaches in other parts of the world. The momentum from the current EU Raw Materials Initiative needs to be carried forward into FP8, the EU's innovation policies and also its wider policies including those concerning interaction with the ACP States.

(1) Abstract from EFP Brief N°181 by: L. Georghiou, J. Varet & Ph. Laredo, 4 p., April 2011.

(2) The EFP is part of a series of initiatives intended to provide a 'Knowledge Sharing Platform' for policy makers in the European Union. More information is provided at www.foresight-platform.eu

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Raw Material	Emerging Technologies
Antimony	Antimony Tin Oxide, flame retardant, micro capacitors
Cobalt	Li-ion batteries, synthetic fuels
Gallium	Thin layer photovoltaics, IC, WLED
Germanium	Fibre optic cable, IR optical technology
Indium	Displays, thin layer photovoltaics
Platinum	Fuel cells, catalysts
Palladium	Catalysts, seawater desalination
Niobium	Micro capacitors, ferroalloys, high speed low alloy steel
Neodymium	Permanent magnets, laser technology

▲ **Raw materials considered as critical.**
Matières premières considérées comme stratégiques.

Fig. 6 : Zinc ingots, Skorpion Mine, Namibia. The rapid growth in automobile ownership in the emerging economies is a key driver of demand for zinc, which is used to galvanise steel car bodies.

Fig. 6 : Des lingots de zinc de la mine Skorpion, en Namibie. La croissance rapide des ventes d'automobiles dans les économies émergeantes est un moteur pour la production de zinc, utilisé pour galvaniser les carrosseries en acier des véhicules.

Population growth, emerging economies and future demand for minerals and metals

Global human population will grow to just above 9 billion by 2050 (UN estimates). Most growth will be in the developing world and will be matched by rapid economic growth in the large emerging ('BRIC') economies. BRIC GDP is likely to exceed that of the G7 by 64 per cent by 2050 (PriceWaterhouseCoopers, 2011). This is partly manifested in growth in per-capita income amongst the populations of those countries, leading in turn to massive increases in consumption of raw materials for housing and consumer goods such as cars and electronics.

By 2025, China will have 221 cities with more the 1 million inhabitants, compared to about 35 such cities in Europe. This equates to a requirement to build about 50 000 new steel-framed tower blocks within this time period. The impact of burgeoning demand for minerals and metal from emerging economies is also illustrated by the automotive sector *(figure 6)*. Of 35 million cars and lorries manufactured globally in 2010, 13.8 million were sold in China. 1 in 16 Chinese people currently own a car, versus 3 in 4 in the USA. Between 2000 and 2010, car ownership in China increased twentyfold. It is estimated that, by 2030, there will be more cars in China than there were in the entire world in 2000.

> Institute sound raw material policy and diplomacy (for producers and consumers).

Over the next 40 years, aspirations for better housing, infrastructure and lifestyles in the emerging economies are likely to sustain demand for industrial metals such as iron, copper and aluminium. In comparison, per capita consumption of these materials in the developed world is likely to stabilise or begin to fall. However, there are other factors influencing demand for a wider group of minerals and metals that are likely to apply across most economies.

Future demand for critical metals for environmental and energy technologies

Concerns regarding the negative impact of climate change are driving a major effort to develop and introduce low-carbon technologies. Renewable and low-carbon energy generation technologies (e.g. wind turbines, nuclear and solar PV) generally rely on a number of so-called 'critical metals' for their manufacture, as do technologies for low-emission vehicles and energy storage. Although uptake of all the environmental and energy technologies currently under development seems unlikely, large-scale adoption of some is inevitable. As such, demand for certain critical metals will grow rapidly from what is currently a low base. European and US studies [Moss *et al.* (2011)] suggest that the rare earths cerium, dysprosium, terbium, europium, neodymium and yttrium are particularly critical for 'clean' energy technologies, as are a range of other metals including indium, tellurium, gallium, cadmium, niobium and selenium.

Some of these critical metals are currently derived as by-products from the extraction of 'carrier metals' from ores where they are present in low concentrations. Examples include gallium (in aluminium ore) and germanium (in zinc ore). Production from these ore types is therefore predominantly driven by demand for the carrier metal. Future producers may have to examine the economic and technical feasibility of 'stand alone' production should demand increase independently of the carrier metal.

Conclusions

The major factors influencing the future of the global minerals and metals sector are human population growth, economic development and environmental change. Although this review has attempted to examine the key implications of these trends on the sector, space constraints mean that some related issues which are just 'appearing on the horizon', such as mineral resources that may be required for climate geoengineering and carbon mineralisation, have not been discussed. Nonetheless, a number of conclusions have emerged which might assist the sector in meeting the considerable challenges it will face in the next 40 years, including:

– invest in the science and technology of where and how to look, extract, recycle and substitute metals and minerals;

– ensure good metrics to improve understanding of material flows;

– recognise that the market can deliver and that it drives exploration, innovation and recycling, but also that it is subject to distortions such as state capitalism, resource nationalism and speculation;

– institute sound raw material policy and diplomacy (for producers and consumers) and more diversified global supply;

– mobilise innovative science and technology to break the link between resource use and human-induced environmental change.

Acknowledgement

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L'avenir des minéraux et des métaux : défis à l'horizon 2050

Cet article aborde l'avenir du secteur des minéraux et des métaux. Il recense notamment les facteurs environnementaux et socio-économiques susceptibles d'affecter l'offre et la demande en matières premières minérales sur les 40 prochaines années. La recherche scientifique, notamment en métallogénie, et les développements des techniques d'exploration et d'extraction seront nécessaires pour éviter d'être trop rapidement confronté à un épuisement des ressources. En raison de barrières économiques et sociales, il paraît peu probable que l'on puisse compter massivement sur le recyclage des métaux. Les problèmes liés aux émissions des gaz à effet de serre constituent une autre contrainte pour la production des minéraux et des métaux.
Par ailleurs, des facteurs humains d'ordre géopolitique feront vraisemblablement peser une menace significative sur l'offre future. Si, pour les pays émergents, l'exploitation des minéraux et des métaux représente bien une opportunité, celle-ci n'est pas sans danger. La ressource sera de plus en plus exploitée dans les pays pauvres et suscitera des questions d'éthique sur les liens entre exploitation, pauvreté, instabilité et conflits. La croissance démographique mondiale, l'évolution rapide des économies émergeantes et la forte demande en minéraux et métaux seront des moteurs du changement. La politique mise en place pour lutter contre le changement climatique aura nécessairement une influence sur la demande future en métaux critiques utilisés dans les technologies environnementales et énergétiques.
En conclusion, quelques solutions sont proposées pour aider le secteur des minéraux et des métaux à faire face aux défis auxquels il sera confronté durant les 40 ans à venir.

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