シリーズ特集

明日を支える資源（172） ＜連載：オリンピックと資源④＞ ＊和文要約はP.○に掲載

Going for Bronze：Will Mineral Resource Depletion Make It Harder to Get an Olympic Medal in the Future?

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1．Introduction

The Olympic medals represent the hopes, dreams and perseverance of the human spirit. Athletes train and compete relentlessly in their pursuit of these medals and provide inspiration to society whilst doing so. The medals may also serve as a metaphor for our industrial systems. Production of gold, silver and bronze is a remarkable feat of human ingenuity and technological development. These production systems have helped shape the world around us, raising the living standards of society in the process. However, as the competition between athletes from different nations to win a medal is ever increasing, the competition to supply the metals to make these medals is also higher than ever. Some scholars argue that resource depletion, increasing complexity of fabricated materials, changing geopolitics and socio-economic conditions may make supplying these commodities more difficult in the future or create instability in their supply chains（Ali et al., 2017；Graedel et al., 2015）. Others argue that the production of gold, silver and bronze will become more resource intensive and cause greater environmental degradation in the future due to the preferential depletion of high quality mineral resources. This article explores the conceptual basis of some of these claims and in doing so attempts to answer the question：Will mineral resource depletion make it harder to get a bronze medal in the future?

2．The Tokyo Olympic Bronze Medal

The Tokyo 2020 Olympic and Paralympic Games are notable in that the medals were produced from recycled metals sourced from 78,985 tonnes of electronic devices collected by 1,621 Japanese municipal authorities and ～ 6.21 million used mobile phones collected by NTT Docomo（Tokyo Organising Committee, 2020）. These collection and recycling efforts yielded ～ 32kg gold, ～ 3,500kg silver and ～ 2,200kg ‘bronze’, which has been used to produce the Olympic medals. **Table 1** shows the composition of the Tokyo Olympic Medals. Interestingly, the Tokyo Olympic Games' “bronze” medals will not actually be made from bronze - a copper - tin alloy- but rather from red brass, which is a copper-zinc alloy. Given that copper is the dominant element within both bronze and brass alloys, we will focus our examination of future supply challenges and risks on the copper sector.

Table 1 Specifications of the Tokyo Olympic Medals（Tokyo Organising Committee, 2020）

	Diameter mm	Thickness Mm	Weight g	Composition
Gold	85	7.7－12.1	～556	＞6g gold plating on pure silver
Silver	85	7.7－12.1	～550	Pure silver
Bronze	85	7.7－12.1	～450	Red Brass（95% copper, 5% zinc）

3．Global Copper Production

Copper was one of the earliest metals to be exploited and used by humans. Archeological records suggest that copper has been in use for at least 7000 years, particularly once major innovations in copper and bronze smelting occurring around 5000 years ago, which ensured that copper was the dominant metal in use until iron metallurgy was advanced around 3000 years ago（Radetzki, 2009）. In historic times copper was used widely within tools and coinage, although production

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levels were also relatively low by current standards. However, with advent of the industrial revolution the use and production of copper has grown dramatically alongside the electrification of society (**Figure 1**). Current expectations are for growth in copper demand to continue alongside economic growth and with rollout of technologies required for decarbonisation of the economy (Ciacci et al., 2020; Giurco et al., 2019; Schipper et al., 2018). This dramatic increase in copper demand has raised concerns of whether we have sufficient mineral resources that society can draw upon to continue meeting this demand into the future.

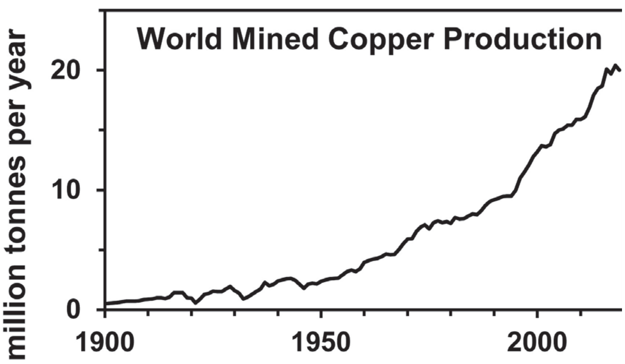

Figure 1 Global mined copper production, 1900 – 2019 (USGS, 2020)

4. Mineral Resource Depletion

Perhaps the biggest cliché in the resource depletion literature is to open a section with some variation of:

In 1972, the Club of Rome published "The Limits to Growth" that warned of the possibility of a future world with depleted resources and a society that had overshot its carrying capacity (Meadows et al., 1972).

That study and the narrative surrounding it became the new starting point for discussions of the long-term impacts of resource use and consumption. Many viewed it as a dire warning for society of the implications of exponential growth taking place within a finite world, bringing the seminal work of Malthus (1798) into the modern era. However, critics pointed towards shortcomings in the Limits to Growth modelling and the data sources used, whilst also highlighting the role of technology and human ingenuity in shifting the boundaries of what can be considered sustainable levels of resource consumption (Meadows, 2007). The model components addressing mineral extraction was also criticised for ignoring the factors that govern mineral extraction costs, as well as definitions for mineral resources and mineral exploration dynamics. Economic behaviours described in earlier literature were used to attempt to discount the study. Such as the work of Hotelling (1931) who described rising prices due to increasing scarcity as being a feedback that would then slow rates of demand and effectively optimise the economic utility gained overtime. Recent examinations of the arguments underpinning these competing narratives have unveiled an area of research where it is very difficult to draw clear conclusions due to the complexity of mineral extraction economics, mineral resource definitions and datasets, as well as the future economic conditions, technological progress and the material needs of future society (Reynolds, 2013; Mudd, 2010).

Overtime competing paradigms have emerged for understanding resource depletion, such as the fixed stock paradigm that assume there is a finite amount of a resource that is available for extraction, or the marginal cost paradigm that assumes the resource exists along a continuum from inexpensive through to expensive material to exploit (Gordon et al., 2006; 2007; Tilton and Lagos, 2007). Detailed analysis of the impacts of mineral depletion from either of these perspectives are hindered by uncertainty surrounding the magnitude, extent and location of mineral accumulations in the earth's upper crust, the degree to which these should be considered economically accessible, and how this accessibility changes overtime given market conditions and technological progress. Some useful concepts, such as that of the geochemical barrier first described by Skinner (1976; 1979), allow us to begin to place limits around the magnitude of mineral resources potentially available for use in the future society, whilst also providing understanding of how extraction costs may change as resources become depleted. **Figure 2** shows the early depiction of the geochemical barrier, where the majority of easily extractable resources exist in high-grade (i.e. concentration) mineral ores. However, as the availability of high-grade ores declines with preferential extraction, the energy requirements of production increases. Mineralogical barriers occur between different types of mineral ores and geological stocks, and transition from exploiting one mineral stock to another may result in substantial increases in the energy required to exploit each unit of resource. The results of life cycle assessment studies demonstrate that the energy and resource requirements of mineral production increase as the grade of ore being extracted decreases (Norgate et al., 2007), which is further supported by data disclosed through industry sustainability reporting (Mudd, 2010 ; Northey et al., 2013).

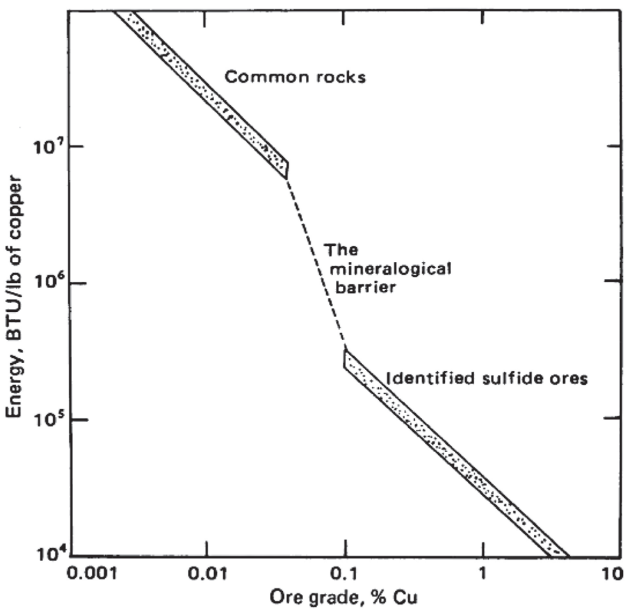

Figure 2 An early depiction of the geochemical barrier for copper, showing the jump in mining and extraction energy required between mineral ores and common rock. Reproduced from Skinner (1979) .

Concepts such as the mineralogical barrier are partially supported by studies that show a long-term trend of declining mined ore grades through multiple economic cycles (Crowson, 2012 ; Mudd, 2010), which suggests that high grade mineral occurrences are being preferentially extracted. Some authors have attempted to model how the average grade of copper ores being mined may change into the future with continued extraction through consideration of the distribution of the size and grade of known mineral deposits and using these to construct cumulative grade-tonnage relationships (Gerst, 2008 ; Northey et al., 2014 ; Vieira et al., 2012). The results of these forms of study may only be valid if we assume that the economic assumptions used to define mineral resources are static, that the grade and size of future mineral deposit discoveries align with the distribution of historic discoveries, and that the order of extraction of mineral resources occurs from highest to lowest grade. Given that there are weaknesses with each of these assumptions (economic conditions change, large-shallow deposits are easier to discover, mined grades are also determined by market prices and production costs) (Ericsson et al., 2019 ; West, 2011), only very narrow insights into future resource availability can be gleaned from any individual study of resource depletion. There have been attempts to incorporate understanding of ore grade and mineral resource extraction dynamics into decision-making tools such as material flow analysis or life cycle assessment. However, limited consensus exists for best practice model design or for their use or applicability for answering different research questions (Berger et al., 2020 ; Sonderegger et al., 2020 ; Northey et al., 2018).

5. Studies of Copper Resources and Depletion

Given the theoretical complexity of understanding mineral resource depletion and the potential for long-term supply of particular elements, it is difficult to describe generalities that may hold across all commodity groups or timeframes. This also makes it difficult to capture and synthesize our current understanding of future copper supply within a single article. Therefore, a summary is provided here of the key insights from studies covering research domains of importance to understanding future copper supply. Readers are encouraged to refer to each study to gain further perspective.

Mineral Reserves and Resources of Copper

Mudd and Jowitt (2018) identified that at least 640.9 and 3,034.7 million tonnes of copper was contained within identified mineral reserves and mineral resources respectively in 2015.

Singer (2013 ; 2017) demonstrated that copper deposit ore grades and ore tonnages both follow lognormal distributions, and that this can be used to inform our understanding of undiscovered copper resources through combination with tract assessment and deposit density distributions.

Gerst (2008) used understanding of the lognormal distribution of copper ore grades and tonnages to construct cumulative grade-tonnage curves for different mineral deposit types.

Kesler and Wilkinson (2008) estimated a potentially recoverable resource of 89 billion tonnes (~5500 years of supply) of contained copper occurring within a surface depth of 3.3km, based upon a model for the formation of porphyry copper deposits as a result of tectonic plate diffusion.

Copper Supply and Demand Modelling

Ayres et al.（2002）modelled scenarios for the demand, use, primary production and recycling of copper from 1990 to 2100 under the IPCC's SRES scenarios, showing that factors such as recycling rates and the in-use lifetimes dramatically influence future primary copper demand.

Northey et al.（2014）estimated that identified copper resources are sufficient to allow supply to grow for at least the next twenty years（excluding the benefits of any further mineral exploration）and that future rates of ore grade decline may be lower than was historically the case.

Gerst（2009）modelled the in-use stock of copper overtime and observed that dematerialization can be an emergent property of stock dynamics, and also that an upper bounding scenario would require between 5.82 to 7.73 billion tonnes of cumulative copper extraction by 2100（this was not meant to be ‘realistic’ scenario, but rather used to find a theoretical maximum）.

Key Factors Shaping the Copper Sector

Azadi et al.（2020）provided an overview of greenhouse gas emissions associated with copper production and highlighted the need for improved emissions accounting to facilitate future emissions reduction in the sector.

Norgate and Jahanshahi（2010）described how mineral processing routes influence the energy requirements and greenhouse gas emissions of copper production, and how we may need to change our copper processing routes to adapt to declining ore grades and reduce greenhouse gas emissions.

Rötzer and Schmidt（2020）articulated a more nuanced understanding of the relationship between copper ore grades and the energy requirements of production, highlighting the role of exploration and technology improvement to offset the exhaustion of copper resources overtime.

Northey et al.（2017）assessed how copper resources were distributed in relation to water scarcity, showing that undeveloped copper resources are located in regions with substantially higher water and climate risks than other base metal commodities.

Lèbre et al.（2019）showed that 63% of global copper reserves are located in regions with complex environmental, social and governance risks that may constrain mine development.

Flores et al.（2020）described future challenges facing copper mineral processing and smelting given the long-term need to process more marginal, complex ore that can have elevated concentrations of deleterious elements such as arsenic present.

Economics of Copper Supply

Svedberg and Tilton（2006）showed that the real, inflation adjusted price of copper had not changed substantially between 1870 and 2000. When we consider this study alongside the fact that demand grew substantially through this period and that ore grade declined（likely due in large part to technology substantially reducing production costs）, it suggests that copper has become more economically available overtime despite continued depletion of the crustal resource. This highlights the importance of differentiating between economic scarcity and geologic scarcity.

6．Conclusions

This article aimed to answer a seemingly simple question：Will mineral resource depletion make it harder to get a bronze medal in the future? The answer to this question is complex and not entirely certain. It is likely that the continued preferential extraction of copper from high grade mineral deposits will lead to a long-term decrease in the average grade of remaining mineral deposits overtime. This will place upwards pressure on production costs, as more material will have to be mined and processed to produce the same amount of copper product, which in turn also creates greater cumulative environmental degradation at mining and mineral processing facilities. However, it is also possible that technology improvements and improved economic efficiencies will counteract this and place downwards pressure on production costs through time. Therefore, it is very difficult to judge the degree to which the economic scarcity of copper will change through time despite growing geologic scarcity. As the stock of copper in-use by society grows into the future, we will also see larger flows of scrap material overtime that brings greater potential for secondary, recycled copper production that will offset primary, mined copper production. Through continued effort to implement circular economy strategies into our economic and industrial systems, we can increasingly decouple copper production from mineral resource extraction. Although there will likely always be depletion of copper mineral resources occurring, we may have a future where copper itself is more abundant within society due to improved production technologies and adequate supplies of recycled copper. Perfect conditions for ensuring a stable supply of bronze medals to our future athletes.

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