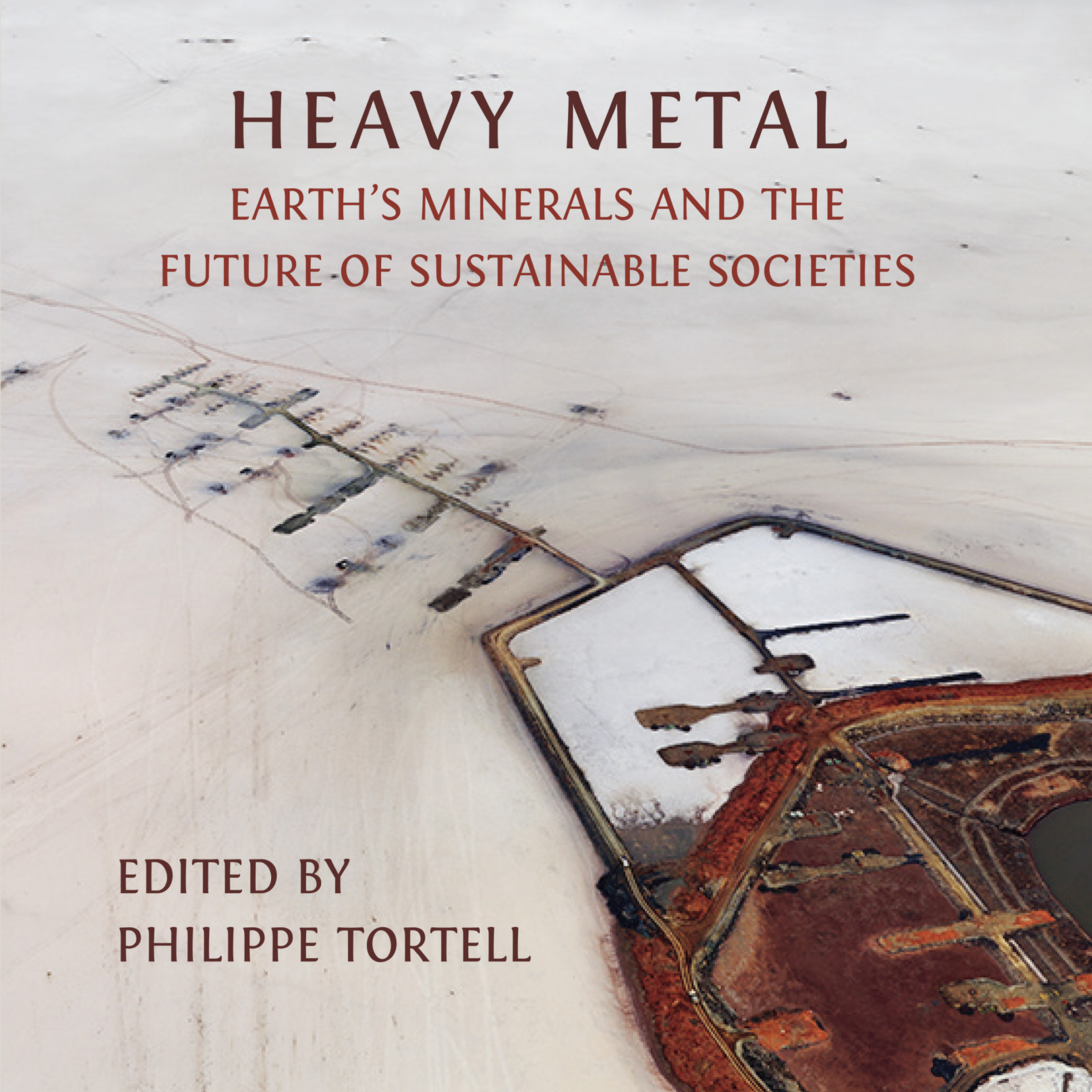

HEAVY METAL

EARTH'S MINERALS AND THE FUTURE OF SUSTAINABLE SOCIETIES

EDITED BY
PHILIPPE TORTELL

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The Copper Supply Gap: Mining Bigger and Deeper

Erik Eberhardt

Copper was among the first metals used by early societies, beginning about 10,000 years ago with the extraction of the pure element (native copper) from small deposits. The malleability and workability of this metal introduced new types of jewelry, cookware and tools, replacing those that had been previously made from stone. Copper alloys soon followed, with bronze (copper-tin) and brass (copper-zinc) delivering strength, durability and corrosion resistance, further expanding their decorative and functional uses. And thousands of years before the discoveries of Louis Pasteur (1822–95), Indigenous peoples, and ancient cultures—the Romans and Greeks, for example—exploited the anti-microbial properties of copper to treat a wide range of medical ailments, including headaches, burns, ulcers and venereal disease.

With its many useful attributes, copper rapidly became ubiquitous in domestic and industrial uses. By the late nineteenth century, growing demand necessitated a shift from the artisanal mining of native copper, to the large-scale mining of lower-grade copper ores. At the turn of the twentieth century, global annual production of copper was approximately 0.5 million metric tons per year. As industrial activity and urbanization expanded, this production scaled up rapidly, fueled by growing needs

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for copper tubing in plumbing and heating systems, and highly conductive copper wiring for electrification and power generation. Over the twentieth century, copper production roughly doubled every twenty years, reaching sixteen million metric tons per year by the early 2000s.

Today, the world is witnessing another step-change in copper demand, associated with the transition away from fossil fuels towards green energy and electric transportation systems. The intensity of copper use in renewable energy generation, particularly wind and solar, is five to ten times that of conventional sources per kilowatt of power generated. Electric vehicles require up to four times more copper than those powered by gasoline, and up to ten times more for electric buses and other larger vehicles. Significant amounts of additional copper will also be required for energy storage and charging infrastructure.

The anticipated and urgently needed transition to renewable energy and electric transportation leads to several staggering projections. By the year 2035, a little more than a decade from now, copper demand is expected to double from its current twenty-five million metric tons per year, to fifty million metric tons per year. This anticipated demand cannot be offset by substituting copper with other metals, and it has been estimated that twenty-five billion US dollars per year will need to be invested in new copper projects. These new copper projects do not yet exist and it is unlikely that they can be initiated rapidly; at present, it takes between ten and fifteen years, or longer, to start a new mine. As a result, a copper supply gap of ten million metric tons per year is expected by 2030. This shortfall is equivalent to the global copper supply required to meet the Paris Agreement targets.[1] To put these numbers in perspective, the world's largest copper mine, Escondida in northern Chile, produces around one million metric tons of copper per year. If we are to meet global Net Zero 2050 targets, new mines of this enormous size must be discovered and enter production every year for the next ten to fifteen years.

To better appreciate the impending copper supply gap, it is important to understand where copper comes from, and how it is mined. More than 60% of the world's copper is obtained from porphyry ore deposits.[2] Geologically, these deposits form where a continental and ocean plate meet (for example, along the west coast of the Americas), or along island arcs, where two oceanic plates collide (for example, in Indonesia and the Philippines). When the two plates meet, the denser oceanic crust subducts and sinks into the mantle, where it begins to melt, creating a buoyant magma plume that rises into the overlying crustal rocks. As the magma migrates upwards, it melts the crustal rocks and absorbs the minerals they contain. Upon cooling, the melted rocks begin to re-crystallize, releasing hydrothermal fluids rich in soluble minerals, including copper, gold, molybdenum, silver and other associated metals. These fluids move through rock fractures, precipitating and depositing metal-rich minerals in long skinny 'veins' or angular 'breccias'. On geological timescales, the formation of these porphyry deposits is relatively rapid, requiring about one to five million years.

From a copper supply perspective, the most important characteristic of porphyry deposits is their highly dispersed nature, with the metal distributed in low concentrations throughout a large volume of host rock. Typical copper ore grades are very low, ranging from 0.2–1%, but the large volume of the deposits (on the scale of a cubic kilometer) can make them economically viable. The value of copper deposits is often further increased by the co-occurrence of gold, silver and molybdenum.

The low grades found in many copper deposits require mining methods that can produce very high tonnages at low cost. Historically, this has been achieved through large open-pit mines, targeting near-surface deposits that are relatively easy to identify. Presently, 80–90% of the world's copper is mined from open pits, which offer three to five times the productivity of conventional underground mines, while requiring significantly less infrastructure, lower capital investment and lower operating costs per metric ton. Because open pits target shallow deposits, access and return on investment is faster, increasing flexibility and economic optimization. The use of large-sized equipment can maximize production and economic returns, while projects carry less technical and economic risk, as shallow deposits allow more thorough geological investigation and characterization. At the same time, near-surface open pits can have significant environmental impacts, and create large visible scars on the surface landscape. But there is no doubt that these mining operations have been invaluable, producing a ready supply of copper that has kept pace with demand and maintained stable prices. During the period between 1950 and 2000, copper traded at 0.5–1 dollar per pound, with an increase to between 2–4 dollars per pound since the commodities boom of the early 2000s. By comparison, the price of other metals, such as gold and platinum, have been subject to much greater fluctuations.

Current methods of copper mining have literally just scratched the surface of most existing deposits. In a geological sense, the geometry of these deposits is more vertical than horizontal, whereas the open-pit geometry is more horizontal than vertical. Open-pit mines are shaped like inverted cones, with slope angles in the range of thirty to forty degrees needed to ensure stability. This poses both a technical and economic limit on their maximum depth. The deepest open pits typically reach 500–600 meters in depth, with a few exceptions, such as the Bingham Canyon Mine in Utah, which extends down to 1,200 meters in depth. Since the highest grades are often found at the center of the deposit, as the pits get deeper, they need to become wider to maintain stable slopes. This results in an exponential increase in excavated waste rock. Over time, the value of additional recovered metal from deeper pits is accompanied by the increasing costs of mining, storing and treating waste rock, creating diminishing economic returns. The deepening and widening of open pits generate immense volumes of waste rock and tailings, leading to increased impacts on the land surface area.

The challenges facing open-pit copper mining will become more significant in the future, as the size and grade of newly discovered deposits continue to decrease, following a trend in recent decades. Some analysts believe that the mining industry may have already reached the point of peak copper supply. Near-surface copper deposits that are easy to mine have mostly been found and are being exhausted. Efforts to meet increasing demand must, therefore, look to greater depths and underground mining.

The transition to deep underground mining requires economically viable methods that can produce high tonnages of low-grade ores. At present, the most commonly employed method for such large-scale underground operations is cave mining, also known as block or panel caving. In this method, a series of tunnels are built immediately below the target ore body. The rock above each tunnel is then undercut to reduce its stability, and the unsupported rock fractures under the pull of gravity, collapsing into the underlying tunnel space. The broken ore is extracted from a series of draw-points connected to the tunnels. As broken rock is extracted, more of the overlying rock fractures and collapses, creating a recurring cycle of fracture, collapse and extraction that continues until the cave eventually consumes the ore body.

One attractive feature of cave mining is its ability to scale up or down with the size and footprint of the deposit, yielding tonnages as large or larger than those obtainable through open pits. In addition, cave mines have lower operational costs than conventional underground mining methods, since gravity does most of the work of fragmenting the rock, eliminating the need for constant cycles of drilling and blasting. On the other hand, cave mining requires far greater up-front capital investments. Traditional mining methods can begin exploiting a mineral resource in the early phases of mine development; a small number of tunnels are constructed, allowing a portion of the ore body to be accessed and mined. This generates early revenue while development expenses are being incurred. In contrast, cave mining requires the full network of tunnels to be constructed before significant ore recovery begins. The upfront costs range anywhere between two and ten billion dollars, and it can take many years before any meaningful revenue is generated. PT Freeport Indonesia's Deep Mill Level Zone cave mine is expected to be fully developed over twelve years. The Oyu Tolgoi panel cave mine in Mongolia will similarly require more than a decade of development work to reach full production before any net profit is generated.

The long development times of cave mines expose these projects to additional risk factors, as highlighted by the Oyu Tolgoi project. Initial negotiations between the proponents and the Mongolian government dragged on for five years against a backdrop of political and legal uncertainty, and the government subsequently demanded that the mine's financers forgive over two billion dollars of loans and interest associated with its stake in the project. These protracted negotiations coincided with the discovery of unanticipated complexity in the geological and mining conditions, resulting in a two-year production delay and a 1.5-billion-dollar capital cost increase. Given these potential uncertainties and risk factors, cave mining requires patient investors seeking long-term benefits rather than quick payoffs.

Even with its challenges and complexities, current projections suggest that copper production from deep underground caving will double by 2030, approaching the levels seen in large open pits. These projected increases include a series of planned 'super caves' that are about ten times larger than historic caving operations. Together, just four new cave mines in Chile, Indonesia and Mongolia could extract about two hundred million metric tons of copper ore each year, yielding 1.5 million metric tons of copper annually over the next twenty to fifty years. For comparison, the world's most productive copper mine, Chile's Escondida open pit, currently extracts eighty-six million metric tons of ore to produce one million metric tons of copper each year.

The new generation of cave mines are envisioned to operate as automated 'ore factories', designed, built and run with predictable production rates, grades, costs and schedules. Cave mining is, indeed, amenable to a high degree of automation. The operations can use driverless loaders controlled from the surface to extract ore from the draw points, with the extracted material transported to underground crushers and brought to the surface using conveyors. Such automation significantly reduces health and safety risks, and the use of smart sensors on loaders and conveyors can improve the efficiency of operations, reducing energy use and mine waste. For example, ore grades and rock types can be automatically sorted, selecting higher-grade materials to be run through the mill for processing. These operations increasingly rely on sophisticated technology and artificial intelligence methods. They point to a high-tech future for the global mining sector.

Despite considerable progress in the development of cave mining, several challenges remain. These relate primarily to the geological uncertainty and increased hazards associated with larger and deeper caves. Over the past twenty years, the areal footprint and depth of mine caves has extended beyond that of any previous operations, pushing the boundaries of current knowledge and experience. As the lower grade margins of the ore body become viable economic targets, footprint areas have quadrupled in size, from less than 100,000 square meters to over 400,000 square meters. Block heights have also increased, from less than 200 meters to over 1,200 meters. These taller blocks allow the full vertical extent of a porphyry ore body to be mined using a single cave as opposed to a series of smaller, short caves, significantly reducing development costs. And as block heights increase, so does the depth of the overall mine. Historic 'deep' cave mines reached depths of around 400–500 meters. The new caves are now reaching more than a kilometer below the surface.

As mines grow ever deeper, the underground tunnels experience greater physical stress from the increased weight of the overlying rocks. This creates significant challenges related to excavation stability, caving dynamics and rock fragmentation. Designs must now consider the full range of stresses impacting the excavated tunnels, including the initial redistributed pressure as the tunnels are first developed, the stresses created by the undercuts, and the operating stresses related to shifting cave loads as rock is excavated from the draw points. These stresses can sometimes lead to catastrophic failures, known as rockbursts, in which the rock surrounding a mine tunnel suddenly and violently explodes, creating a wide swath of destruction. Unlike traditional underground mining, where tunnels are built incrementally, cave mines require the simultaneous construction of many tunnels, exposing more underground infrastructure to potential rockbursting.

Further problems result from the taller block heights used in deep cave mines. For one thing, stronger rock usually occurs at greater depths, creating challenges for a method that relies on gravity to collapse and fragment weak rock. Ensuring the proper flow of the broken rock requires understanding the factors governing the size, shape and interaction of rock movement zones, the internal stresses that develop in the cave, and the secondary fragmentation of broken rock. As broken pieces grind against each other, the longer travel paths through taller blocks expose the fragmented rock to more shearing. The resulting silt and sand-sized particles can accumulate in significant volumes and mix with water infiltrating into the cave. Under certain conditions, this can result in a catastrophic underground debris flow with the power to inundate and bury anything in its path. Videos recorded from some deep cave mines have demonstrated the enormous power of such ‘mud-rushes’ as they bury automated vehicles.

The impacts of cave mines are not restricted to depth. Like the falling sand at the top of an hourglass, a significant depression can develop on the surface above a cave mine, resulting in ground collapse and sinking (subsidence). This can occur not only directly above the mine, but also for significant distances across the surrounding surface. Although cave mines are expected to have a much smaller surface footprint than open pits of comparable size, the uncontrolled nature of cave propagation can expand surface subsidence away from the central cave in unpredictable ways. Uncontrolled ground disturbance can pose significant safety and economic risks to surface infrastructure, including mine waste storage facilities. At the New Afton Mine in southern British Columbia, an underground cave is operating adjacent to an older tailings dam, raising concerns regarding subsidence on the dam’s integrity. At the Palabora Mine in South Africa, near the world-famous Kruger National Park, caving-induced subsidence triggered a significant landslide on an existing open-pit slope. Such unexpected surface effects must now be considered in the development of new cave mining projects, such as the Resolution Mine in Arizona, which was redesigned to avoid potential failure of rock slopes at Apache Leap, a site of Indigenous cultural importance.

There is no current path away from fossil fuels that does not involve significant quantities of newly mined copper. This is both a hard truth, and a pragmatic reality. And here is another hard truth; a large copper shortage is expected to emerge within the next decade, leaving little time to identify and exploit new sources of this critical metal. No doubt, mining of any new copper deposits will be encumbered by numerous environmental, social, financial and technical challenges. But as copper mines become bigger and deeper, we will need to move beyond current experience, stretching the limits of knowledge and ingenuity in the face of significant geological and environmental uncertainty. In this we have no choice; success in this endeavor is critical to the green energy transformation.

Endnotes

1 United Nations, ‘The Paris Agreement’, *United Nations*, https://www.un.org/en/climatechange/paris-agreement

2 See also ‘Where We Find Metals’ by Shaun Barker in this volume.