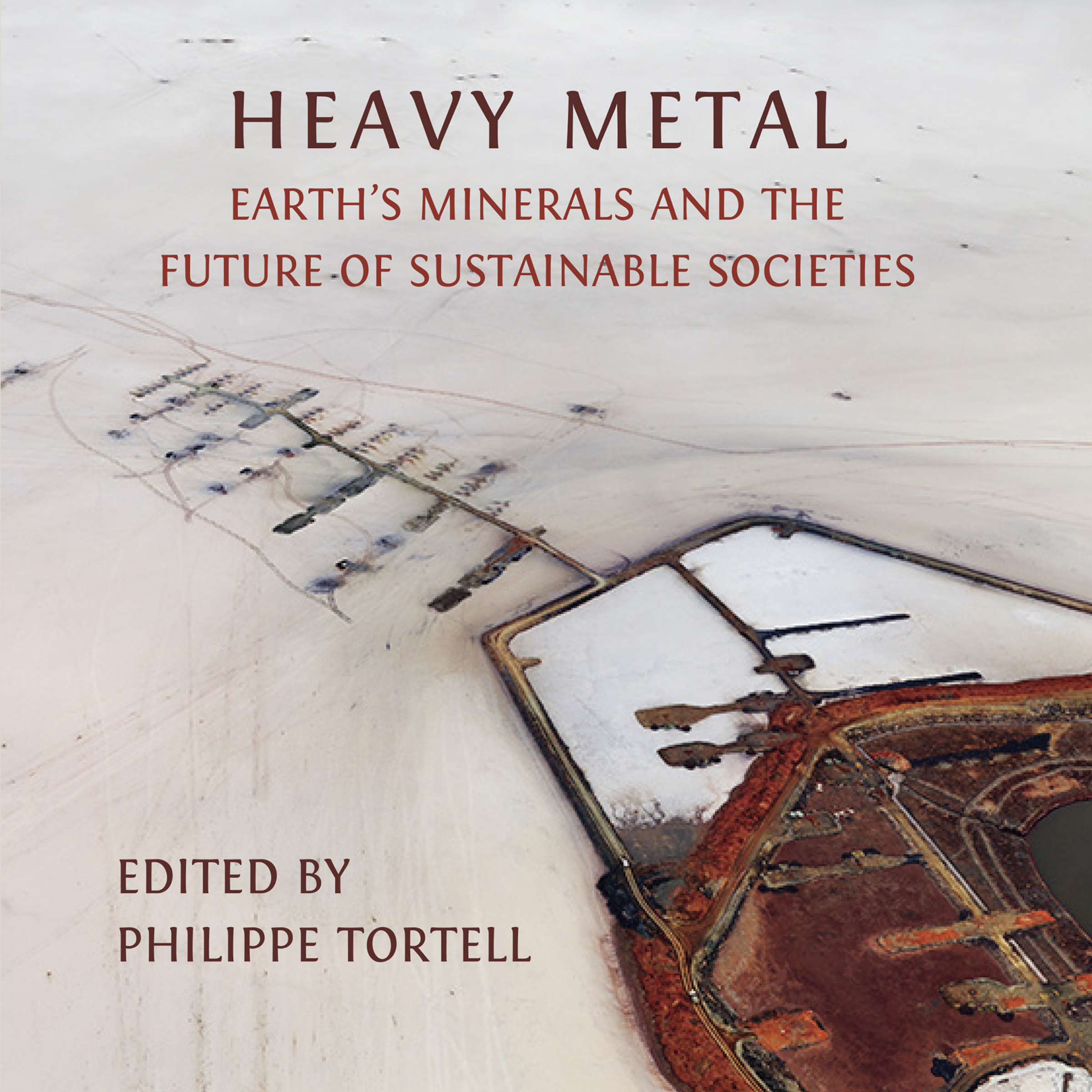
HEAVY METAL

EARTH'S MINERALS AND THE FUTURE OF SUSTAINABLE SOCIETIES



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Where We Find Metals

Shaun Barker

The great expanse of Western Australia stretches for over two million square kilometers, a landscape dominated by sparsely populated desert and scrubland. It has more than its fair share of poisonous creatures, and summer temperatures in the central regions regularly exceeding 40°C for weeks, if not months, at a time. Much of the landscape is otherworldly, with formations of red rock stretching off into the horizon as far as the eye can see. These rocks are among the oldest on Earth, dating back more than four billion years to the early days of our planet's history. With their great geological age, the rocks hold important clues about the first appearance of life on our planet. They also contain something else of great value—the largest iron ore deposits on Earth.

It is estimated that Western Australia, which represents about 1% of Earth's land area, holds about one-third of our planet's terrestrial iron deposits. These massive ore deposits formed more than 2.5 billion years ago, when the first oxygen-producing bacteria began to transform the chemistry of Earth's previously oxygen-free atmosphere and oceans. With the accumulation of oxygen, iron sulfide, present at high concentrations in ancient seawater, became insoluble, forming particles of iron oxide (rust) that sank rapidly to the underlying sediment. Over time, gigantic

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sedimentary iron deposits formed on the ancient seafloor, and through the process of plate tectonics, these deposits eventually became part of what is now Western Australia.

The story of iron in Western Australia highlights a broader truth about the distribution of metals and mining on Earth. Every great mineral deposit has a unique geological story behind it, explaining why and, perhaps more importantly, where it occurs. Over the long arc of Earth's history, the mineral deposits we find today can be traced back to a range of unique and fascinating geological and climate events—volcanic eruptions, enormous accumulations of salt in ancient oceans, collision of asteroids into Earth—all of these events, and more, have played a dominant role in shaping the mineral richness of countries around the world. These geological processes help us understand why we mine most of our copper in Chile and Peru; most of our cobalt in the Democratic Republic of Congo; much of our nickel in Indonesia, the Philippines and Russia, and so on. These processes, playing out over millions or even billions of years, have unwittingly created emerging geopolitical rivalries and societal challenges in the face of future anticipated mineral supply gaps.

The conditions needed to produce a large, economically viable mineral deposit are surprisingly rare. On average, Earth's crust (the rigid upper 10–20 kilometers of our planet's surface) contains relatively low concentrations of most metals. Consider copper, for example. This metal, which is needed in massive quantities for the generation and transmission of electricity, is typically found in surface rocks at concentrations of about 30–50 parts per million (ppm), meaning that every metric ton of rock contains only about 30–50 grams of copper. By comparison, copper concentrations in economically viable ore deposits are typically in the range of 1,000–50,000 ppm (1–50 kilograms per metric ton), up to a thousand times higher than background levels. Such copper enrichments are only formed under unusual geological circumstances.

Economic geologists are trained to read the 'pages' of Earth's geological and climate history trapped within rocks to identify why great mineral deposits form, and where the next large mineral ore body may be found. Over time, these geologists have developed conceptual models for how, where and when metals have become concentrated into ore deposits across the planet. These models were developed through extensive study of known mineral deposits, and they are widely used to help exploration geologists discover new sources of metal around the globe. Although the specific details are still debated, the main geological processes yielding most of the recognized types of large ore deposits are well understood by the scientific community and mining industry. Each of the processes is unique, and leads to distinct characteristics of the deposits, which affects the way they are extracted, and the potential environmental impacts of this extraction.

Understanding how and why large mineral deposits form requires an appreciation of Earth's three-dimensional structure, and the processes that mix the different layers that exist beneath the planet's surface. The large bulk of Earth's volume (more than 80%) is made up of a hot, semi-solid 'mantle' layer, about three thousand kilometers thick, which is enriched in many metals relative to Earth's crust. Many of the metal deposits we mine today were formed by the transport of mantle-derived molten rocks into the near-surface environment. This displacement of metal from deeper to shallow Earth layers can result from several processes.

Some of the world's largest metal deposits are located in geological 'subduction zones', where two tectonic plates collide, producing high concentrations of active volcanos and earthquakes. The largest such region, the Pacific 'Ring of Fire', extends down the entire west coast of the Americas and across the Pacific Ocean from Japan to New Zealand. Across this span of approximately forty thousand kilometers, dense oceanic crust sinks (subducts) below lighter continental crust. As it sinks into the mantle, the oceanic plate heats up, melting the rocks to form molten magmas. The heated magmas are relatively buoyant (like the heated gas in a hot air balloon), and they ascend towards the surface. Metals become concentrated in the ascending magma, and are released in hot, salty, sulfur-rich hydrothermal fluids, which cool and become trapped as large deposits in the surrounding host rocks. Ore bodies that form on top of magma chambers, known as porphyry deposits, can concentrate very large amounts of copper, alongside other metals including gold, molybdenum, silver, lead and zinc. The world's greatest copper porphyry deposits are found in the Andes Mountains of Peru, Chile and Argentina, where progressive subduction of the Nazca oceanic plate beneath the South American continental plate has led to the folding and buckling of Earth's crust to produce towering mountain ranges, active volcanos and large earthquakes. The ancient geological ancestors of the Andean volcanoes provided a pathway connecting mantle-derived magmas, rich in metals, to the upper layers of Earth's crust, where subsequent tectonic uplift and erosion exposed them at the surface.

In the shallower parts of subduction zones, 'epithermal' (on top of a heat source) deposits of gold and silver are found in geothermal environments, such as the Taupō Volcanic Zone of the North Island of New Zealand. Other volcano-associated metal deposits include massive sulfide deposits in submarine environments, which form around the world, and are particularly abundant in areas near Papua New Guinea. These deposits form where active hydrothermal vents discharge black particle-laden fluids rich in copper, gold, lead, zinc, silver, cobalt and other metals onto the seafloor. Remarkably, these 'black smokers' were only discovered in the late 1970s with the first deep-sea submersible expeditions. Their discovery has fueled significant interest in undersea mining.[1] These active hydrothermal processes, which we observe today, can also be recognized in the prehistoric rock record, dating back millions and, in some cases, billions of years. Examples of ancient black smokers are found in the Abitibi region of Eastern Canada, where an ancient seafloor rich with sulfide deposits was buried, heated and later returned to the Earth's surface through plate tectonics.

In addition to deep magmatic sources of metals, other geological processes can lead to significant ore deposit formation in near-surface environments. Sedimentary basins form in oceanic environments when sediment eroded from the land or deposited from the remains of marine organisms accumulates on the seafloor. Over millions of years, these sediments can accumulate in great quantities, sometimes to a thickness of more than ten kilometers. Marine sediments often contain significant concentrations of metals and brines (highly concentrated salt solutions). High salinity brines are extremely effective at extracting metals from sediments, including lead, zinc, copper, iron and gold (amongst others), leading to the formation of significant ore deposits. A prime example of this is the Central African Copper Belt, which runs along the border between Zambia and the Democratic Republic of Congo. These copper-rich deposits were formed between 800 and 550 million years ago, when a sedimentary basin formed under an ancient ocean, capturing high metal concentrations associated with extensive salt deposits. The copper belt was discovered in the late nineteenth century and was one of the world's largest sources of copper during the mid-twentieth century.

Water also plays a significant role in concentrating metals on Earth's surface. So-called placer deposits are formed when flowing water bodies (rivers and streams) transport sand and gravel, separating materials by particle size and density. Coarser, denser particles containing heavy metals including iron, gold, platinum and titanium accumulate where slower water flow allows them to settle out of solution, depositing the metals into places where they can be more easily accessed. The nineteenth-century gold rush was based on placer deposits, with individual prospectors panning for gold in gravel streams and rivers in New Zealand, California, Alaska and the Yukon territory. Erosion by water also helps concentrate metal deposits by breaking down various minerals, leaving them enriched in particular metals, such as aluminum. This process is most common in warm and wet tropical environments in northern Australia, Africa and South America, where there is little tectonic activity and crustal uplift, which allows deep erosion to occur.

And what of extra-terrestrial sources of metals and minerals? It turns out that the same processes that have left Earth's crust depleted in metals have also caused many asteroids to be hugely enriched in nickel, gold, molybdenum, platinum and other important elements. This has led some individuals and companies to suggest that the solution to our future mineral needs could come from extra-terrestrial mining.[2] The increasing success and decreasing cost of private space flight make this prospect more realistic than ever, but there are still significant technical and economic challenges to overcome. In the meantime, here on Earth, we are still benefiting from mineral resources that were formed during meteorite impacts.

At various times in Earth's history, large meteor and comet impacts have significantly affected our planet, including the meteor impact that wiped out the dinosaurs about sixty-five million years ago. Much earlier, about two billion years ago, two large impacts—one near Johannesburg, South Africa and the other near Sudbury, Canada—left visible craters on Earth's surface. The Sudbury Crater is about sixty kilometers long, thirty kilometers wide and fifteen kilometers deep. It was discovered by workers during the construction of the Canadian Pacific Railway in 1885, and soon recognized as an important source of copper and nickel. Today, the crater has among the highest concentrations of mines in the world, producing thousands of metric tons of nickel and copper each year. Similarly, the Vredefort Crater in South Africa, about two hundred kilometers wide, hosts some of the world's richest gold and platinum deposits. Meteorite impacts serve as direct sources of metals, and also help to bring up metal-rich magmas into the surface. These accidents of Earth history have concentrated enormous mineral resources in a small number of locations scattered around our planet.

Although metals can accumulate on Earth's surface through a variety processes, the conditions needed to produce truly large 'mega-deposits' occur in just a few places around the world, often in clusters within a few tens or hundreds of kilometers. The gigantic iron ore deposits of Western Australia, which formed approximately 2.5 billion years ago during Earth's 'Great Oxidation Event', subsequently became further enriched in iron by geological processes that selectively removed other mineral constituents. In northern Russia, approximately two hundred and fifty million years ago, a gigantic 'flare up' of magma from deep in the Earth led to the eruption of about a million cubic kilometers of basaltic lava. This eruption is believed to have triggered the late-Permian mass extinction event through a rapid release of greenhouse gases. The eruption also led to the formation of some of the world's largest copper-nickel-platinum deposits, as the basaltic lava interacted with sedimentary rocks rich in coal and other organic materials. The largest copper deposit in North America (at Bingham Canyon in Utah) was also formed from the same processes that cause volcanic eruptions. In that case, material released from the eruption became trapped in the rocks surrounding the magma chamber, leading to the accumulation of a high-grade copper ore body. And in Chile, the world's largest copper deposit, Escondida in the Atacama Desert, was formed about thirty-eight million years ago when a subducting tectonic plate became temporarily 'locked', shutting down volcanic activity and trapping metal-rich magmas in the surrounding rocks. Today, Escondida contains more than twenty-two billion metric tons of copper ore, with enough copper to build approximately seventy-five million wind turbines. In Chile, as in Utah, northern Russia, Western Australia, and Sudbury and South Africa, rare geological events, almost unique in Earth's history, have endowed particular parts of the world with enormous quantities of metals. These geological 'one-off' events help explain why enormous amounts of mining activity are often focused in areas of just a few hundred square kilometers, and why some communities are disproportionately impacted by metal extraction.

Driven by an economic imperative, mining companies seek the richest and largest metal reserves, as these reduce the cost of production through economies of scale. Large mines are expensive to construct and operate, with significant up-front capital expenses (typically in the billions of dollars) for initial construction, and high operating expenses to support the workers and manage wastes. For this reason, economic geologists continue to explore in places where they know, or believe (based on the underlying geology), that large deposits are most likely to be found. This exploration takes geologists to some of the most remote, and, at times, environmentally sensitive, parts of the world. For example, the recent drive for lithium to power electric vehicles has led to extensive exploration of the Atacama Desert, Greenland and the remote Northwest Territories of Northern Canada. In each of these locations, different geological processes have caused the enrichment of lithium in either salt brines, in the case of the Atacama Desert, or in rock-based minerals within pegmatites in the case of Greenland and Canada.[3] Ironically, global warming has led to the significant retreat of glaciers in Greenland, revealing new deposits of the very mineral resources needed to electrify the economy and reduce carbon emissions.[4]

In some ways, exploration geologists are fighting an uphill battle. Over the last twenty years, new discoveries of large, high-grade ore deposits have decreased significantly. And where new deposits have been found, they have often been at significant depth (more than one kilometer deep in the earth), or in environmentally sensitive or socially contentious areas. At the same time, ore grades (the amount of metal relative to surrounding rock) have been decreasing, resulting in an increasing amount of waste for each per unit of metal extracted. Over the last ten years alone, average mined copper grades have declined by 25%, pushing economic geologists to develop new methods for finding richer ore deposits at greater depths, while mineral exploration companies take on greater economic and technical risks. At the same time, geotechnical and mining engineers are developing methods to construct new types of mines,[5] while working to reduce the quantities and environmental impacts of waste.[6]

Over the coming years and decades, the future of mining may look quite different. But the fundamental elements of mineral exploration and discovery will remain—economic geologists searching the Earth (and outer space) for mineral resources to supply the needs of society. One day, mineral exploration may wind down when we have found sufficient new mineral resources and developed advanced recycling technologies to enable a truly circular economy.[7] We must work hard to realize this sustainable path forward, but, in the meantime, the future of 'minimal mining' is many decades away.

Endnotes

1 See also 'Ocean Minerals' by John C. Wiltshire in this volume.

2 See also 'Mines in the Sky' by Sara Russell in this volume.

3 See also 'Lithium' by Lee Groat in this volume.

4 See also 'Mining in Icy Worlds' by Anita Dey Nuttall and Mark Nuttall in this volume.

5 See also 'The Copper Supply Gap: Mining Bigger and Deeper' by Erik Eberhardt in this volume.

6 See also 'Mine Waste' by Roger Beckie in this volume.

7 See also 'A New Life for Old Metals' by Maria Holuszko in this volume.