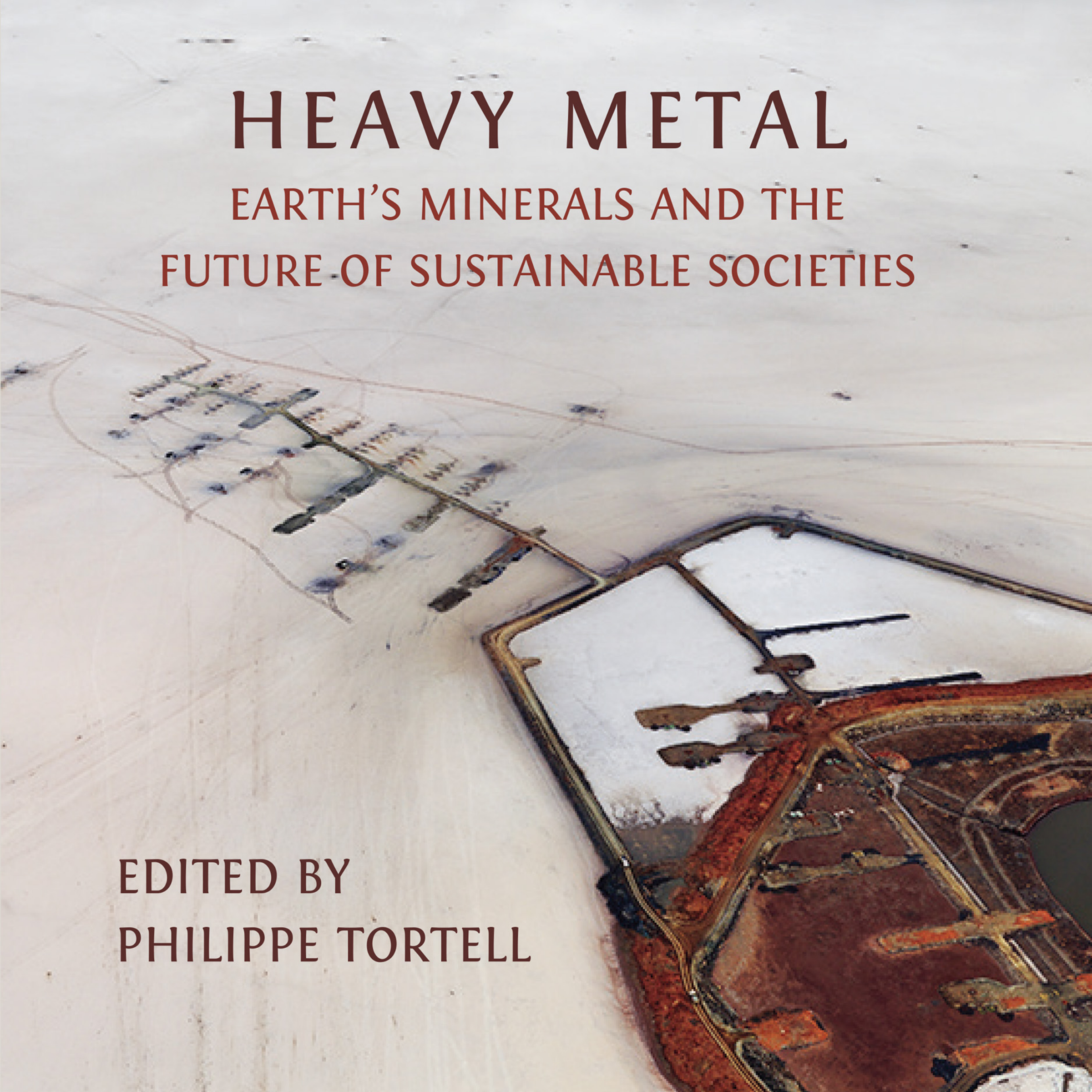
HEAVY METAL

EARTH'S MINERALS AND THE FUTURE OF SUSTAINABLE SOCIETIES



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Digital material and resources associated with this volume are available at https://doi.org/10.11647/OBP.0373#resources

ISBN Paperback: 978-1-78374-956-0
ISBN Hardback: 978-1-78374-958-4
ISBN Digital (PDF): 978-1-80064-977-4
ISBN Digital eBook (EPUB): 978-1-80064-390-1
ISBN HTML: 978-1-80511-043-9

DOI: 10.11647/OBP.0373

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Cover design: Jeevanjot Kaur Nagpal

Mine Waste

Roger Beckie

The Mount Polley copper and gold mine is located near the small town of Likely, in south-central British Columbia. The area is popular with outdoor enthusiasts seeking adventure in the Cariboo and Coast Mountain Ranges, and on its many lakes and rivers, including the Fraser, Chilcotin, Chilko, Quesnel, Cariboo and Horsefly. With an economy based on ranching and natural resources—forestry, logging and mining—the town is typical of many rural places in the province; at one time, the nearby Williams Lake Stampede was the second largest professional rodeo in Canada.

When the mine opened, in the mid-1990s, it brought significant employment and tax revenues to the region. At its peak, with operations spread across two large open pits and an additional underground site, the mine produced nearly forty million pounds of copper and 45,000 ounces of gold per year. But alongside these valuable minerals, the mine produced something much more problematic—enormous quantities of mine waste. The wastes, containing more than four hundred metric tons of arsenic and nearly two hundred metric tons of lead, were stored in large tailings ponds adjacent to the mine, overlooking Likely at one end of Quesnel Lake, the third deepest lake in North America, and a major source of drinking water for the region.

Early in the morning of 4 August 2014, an earth dam at the perimeter of the mine's tailings storage facility slumped about five meters. The dam was soon completely

 https://doi.org/10.11647/OBP.0373.27

breached, and over the next few days, eight billion liters of tailings and seventeen billion liters of contaminated water flowed into Hazeltine Creek, Quesnel Lake, Polley Lake and the Cariboo River. The spill carried trees, mud and other debris downstream, increasing water levels in Polley Lake by about 1.5 meters, and impacting fish spawning habitat and drinking water. A local state of emergency was declared, water restrictions were put in place, and the Chinook salmon fishery was closed. Local residents, including several Indigenous groups, staged demonstrations and mounted blockades, while local business owners launched legal challenges against the mine's operator, Imperial Metals. In the end, the company was not subjected to any significant fines or legal penalties, but three engineers who worked on the tailings facility were found guilty of professional negligence, and fined a combined total of 200,000 dollars; their employers paid Imperial Metals a reported 108 million dollars in compensation for the disaster.

Not long after the Mount Polley disaster, two other mine tailings failures occurred in Brazil, with even more catastrophic results. In November 2015, a tailings release at the Samarco Mine killed nineteen people, and about three years later, in January 2019, 270 people lost their lives during flooding from the tailings pond breach at the Córrego do Feijão Mine. Both Brazilian mines had been developed in the mid-1970s, with a cheap, but potentially risky, dam construction method that has now been banned in many countries. Mount Polley, on the other hand, was significantly newer, and the failure of its tailings dam, one of the largest mining disasters in Canadian history, raised many questions about how such an event could happen in British Columbia, at a relatively new mine, with a dam designed and monitored by some of the best geotechnical engineers. The answer to these questions would profoundly change the way that mine wastes are managed around the world.

The problem of mine waste is not a new one. More than five thousand years ago, the Phoenicians first mined copper, gold and silver in what is now the Huelva province of southern Spain. By the time the Romans came to rule that territory in the second century AD, waters of the Odiel and Tinto Rivers were already contaminated by mine waste drainage. The famous red color of the Rio Tinto (Tinto means red in

Spanish) comes from the high concentrations of iron oxides (rust) and other heavy metals released with the acidic drainage from mine waste. Although the problem of mine waste is not new, its scale has grown steadily over the past century as the footprint of mining operations around the world has expanded.

Mount Polley, Samarco, Córrego do Feijão and Rio Tinto illustrate two principal hazards posed by mine waste. Tailings dam failures cause the most dramatic impact, resulting in immediate and intense damage in response to a catastrophic loss of physical containment, as in the cases of Mount Polley, Samarco and Córrego do Feijão. But longer-term impacts are also significant, resulting from a relatively slow, but steady, drainage of contaminated water from mine waste, as in the case of Rio Tinto. One effect is dramatic and graphic, the other slow and gradual, both are damaging.

At the most basic level, mine wastes are the materials left over after the mineral or metal of economic value has been extracted from host rocks, brines or other geological repositories. These wastes generally fall into three broad categories. More often than not, mineral containing rocks ('ores') are buried underground, covered by an 'overburden' of non-ore containing rock. This overlying waste rock is typically blasted in the ground, excavated, then hauled and placed into large piles. Below the overburden, within the ore body itself, minerals of interest are closely associated with unwanted rocks and minerals, the 'gangue' from which they must be separated using various chemical or physical processing methods. What is left behind after this processing are the tailings, which accumulate on-site and must be managed over the long-term.

Depending on the particular mineral deposit, different methods are used to process ores from gangue. Typically, the ore is processed on-site to purify target minerals into a more concentrated form prior to shipment to refineries. It is usually blasted in the ground, hauled to a crusher, then milled to a uniform particle size. This milling is the most energy-consuming process at a hard-rock mine, and the operators must balance higher energy costs of a finer grind, against the benefit of enhanced recovery of target minerals, as smaller particles have a relatively higher surface area to react with processing chemicals. Most commonly, the ore is ground to relatively uniform sand or silt size, with particles of about 0.01 to 2 millimeters. In heap-leach operations, the ground ore is piled up on impermeable pads and irrigated with a solution that chemically extracts the target resource from the solid phase. A cyanide solution is often used for gold, and sulfuric acid for copper; both these chemicals can pose significant risks to groundwater.

Another approach to separating metals from gangue is based on floatation with air bubbles. In this method, which is extensively used to process gold, copper and zinc, the ground ore is mixed with an oily chemical solution that alters mineral surface chemistry. Air is pumped from the bottom of the tank to form bubbles that selectively attach to the target minerals. The bubbles and attached minerals float to the surface to form a froth that looks like a muddy bubble bath. The froth is skimmed off from the top, while the residual gangue minerals, the tailings, sink to the bottom as suspension of solids. This leftover material is then pumped out of the floatation tank for further processing or disposal.

Many of the current methods used to extract and process metals, and the associated problems of waste management, have a relatively long history. The use of cyanide to process gold dates back to the late nineteenth century, while floatation tanks have been used to process zinc and copper since the early 1900s. (In a historical twist of fate, the inventor of the floatation method, Daniel C. Jackling, built a sprawling house in Palo Alto which Apple founder, Steve Jobs, bought in 1983.) Although the basic technology has not changed much, the quantity of rock being processed has increased massively. Before the advent of steam power in the eighteenth century, mines were relatively small. A typical medieval copper mine would excavate a few tons of rock per day from which tens of kilograms of copper could be extracted. The ratio of the total rock excavated to the mass of metal recovered is called the rock-to-metal ratio. In medieval copper mines, the ratio was about fifty, meaning that for every fifty kilograms of rock excavated, forty-nine kilograms were waste. By comparison, contemporary mines accessing lower-grade deposits have higher rock-to-metal ratios, and thus generate proportionally more waste for each unit of metal produced. In 2018, the average rock-to-metal ratio was about nine for iron, five hundred for copper, one thousand six hundred for lithium and three million for gold. To put these numbers into context, the copper contained in a single electric vehicle (EV) produces about thirty metric tons of rock waste, while the gold in a single wedding ring produces about fifteen metric tons of waste.

Worldwide in 2016, approximately ninety-eight billion US dollars of copper, some twenty million metric tons, was recovered from almost fifteen billion metric tons of excavated rock. It's hard to understand that scale. The hulking Caterpillar 797 haul truck, one of the largest in the industry, can carry 350 metric tons per load, about the volume of a thirty-person classroom. Hauling all the rock excavated for copper mining in 2016 would require fifty-seven million Caterpillar 797 loads, approximately one load every second, around the clock, every day of the year; all mining together would require about eight loads per second. At that rate, a typical professional football stadium could be filled to the top in twenty-five minutes. The quantity of tailings generated from all mining since the eighteenth century is enough to cover the state of Connecticut ten meters deep; waste rock would cover the state of New York, an area about ten times larger than Connecticut, to the same depth. These rather staggering numbers highlight a fundamental aspect of mining; in the end, it is primarily a waste management business.

One of the main problems with mine wastes results from the presence of residual metals in tailings, which interact with water and air, and can be released into the environment with potentially harmful effects. Many of the common mineral deposits, such as copper and gold ores, contain sulfide minerals that are chemically stable underground when oxygen concentrations are low. But when rocks are brought to the surface, fragmented and crushed into fine particles, sulfide minerals become far more exposed to atmospheric oxygen than they were in the ground. In the presence of oxygen and water, the sulfide minerals will oxidize, producing significant amounts of heat and sulfuric acid, while also releasing dissolved metals into solution, including iron, copper, zinc, arsenic, molybdenum, selenium and antimony. The acid may be neutralized by limestone and other alkaline rocks contained naturally in the mine waste, but when the waste's neutralizing capacity is exhausted or unavailable, the water draining through the waste can become highly acidic. An enduring legacy of many abandoned mines is poor quality drainage, which can persist for centuries or, like the Odiel and Rio Tinto Rivers, millennia. These long-term effects must be managed by controlling both the physical containment of the waste, and the drainage of water through it.

Go to any operating open-pit mine and you will see large piles of waste rock. These piles can be stable over the long-term if they are placed on firm ground and properly sloped to match the geotechnical properties of the rock. In steep mountainous terrain, haul trucks tip their loads over the mountainside, shaking the ground as the largest boulders violently crash down slopes that can be several hundred meters high. In flat terrain, the waste rock piles are built progressively in layers a few meters thick. In contrast to rock waste piles, the slurry of solid tailings particles and water from the concentrator plant flows like a fluid and must be contained. These slurries are usually pumped into large, purpose-built tailings storage facilities. At some mines, tailings can be contained in a natural depression, but often, like at Mount Polley, large containment embankments or tailings dams are also required. The Mount Polley tailings storage facility covered an area of about five hundred football fields. A low-permeability liner at the bottom is sometimes needed to protect underlying groundwater. Water covers most of the tailings in the storage facility, except near the embankments and dams, where beaches are intentionally formed to reduce water content and enhance the stability of the tailings.

Water plays a critical, though double-edged, role in tailings management. On the one hand, water greatly inhibits the supply of oxygen to the tailings (oxygen has a relatively low solubility in water), limiting the extent of sulfide-mineral oxidation and acid drainage. On the other hand, the presence of water reduces the strength of tailings. When initially discharged from the concentrator plant, tailings flow like a fluid. With time, they consolidate and gain strength, but can remain liquefiable for years to decades. Tailings can liquefy in response to a physical disturbance, such as a dam breach, losing strength and flowing like a slurry.

In the aftermath of the Mount Polley disaster, an investigation found that the embankment failure resulted from an undetected natural weak layer located ten meters below the ground surface. The investigations also uncovered many other physical, operational and organizational factors that contributed to the failure. This investigation, and the more recent Brazilian tailings disasters, have prompted changes in the mining industry that will significantly affect the way that wastes are managed. The 2019 Feijão disaster in Brazil motivated a major international review of tailings management, led by the Church of England Pensions Board and the Swedish Council on Ethics, alongside one hundred other investors with over twenty trillion dollars under management in mining-related equities. The group convened an independent expert panel that built upon the Mount Polley findings and published the Global Industry Standard on Tailings Management (GISTM) in 2020.[1] The GISTM aims to guide the construction and operation of tailings storage facilities that are safe from catastrophic failure and non-polluting in perpetuity. The effects of this report on industry practice are hard to overstate. Operations that do not follow or move towards GISTM are viewed by investors as risky, and subject to significantly increased capital and insurance costs. The International Council on Mining and Metals, an association of the world's largest mining companies, has committed to full conformance to the GISTM by August 2025. This group represents about one third of active tailings facilities worldwide.

A main recommendation of the GISTM is the development of management structures and information flows to ensure that roles and responsibilities for tailings management are understood and documented. For example, the GISTM requires that an Accountable Executive be designated for each facility, with a direct reporting obligation to the Chief Executive Officer. Another role, the Responsible Tailings Facility Engineer, reports to the tailings facility operator and the Accountable Executive. An Independent Technical Review Board reports to the Accountable Executive and provides independent assessment of the facility's design, construction, management and closure plans. Although the GISTM provides specific goals and performance standards to ensure safe tailings management, it gives operators room to innovate based on evolving technology and economic considerations. Some have criticized this approach, arguing that it may delay immediate action in anticipation of discounted future (though poorly quantified) savings. Critics also argue that the approach fails to consider external and whole-life costs, including those related to mine closure and reclamation. Despite these criticisms, improvements in mine-waste management processes, technologies and outcomes seem inevitable. And the GISTM demonstrates, at least at face value, a commitment from the industry and shareholders to standards protecting the public and environment. There is also growing public awareness that higher prices are needed to fully account for pollution costs, as demonstrated by increasing (though certainly not unanimous) acceptance of carbon taxes in various countries around the world.

Innovation is essential, but it will be incremental. Feedback cycles are long, and years or decades may pass before the performance of new approaches can be fully assessed. Modeling and computer simulations can help support decisions and design, but the complexity of the underlying processes and the challenge of characterizing natural materials and future climate introduces significant uncertainty. The problems are complex, and best tackled by multidisciplinary teams that understand geology, ecology, geochemistry, microbiology, hydrology, geomechanics, climate science, law, management, governance and economics.

In recent years, many innovations have focused on the recovery of water from tailings prior to disposal. Conventional slurry tailings are about 35% solids by mass, while thickened tailings are closer to 55% solids, 'paste' tailings about 75% solids, and filtered tailings contain more than 80% solids. A higher content of solids results in greater strength and reduces overall water use, which is particularly valuable in dry climates. Slurry and thickened tailings can be pumped with simple technology, but paste tailings require more expensive pumps, and filtered tailings must be conveyed like a solid, significantly increasing costs. On the other hand, filtered tailings can be placed in stable, self-supporting dry stacks, reducing the costs of containment structures like dams or embankments. While conventional slurry tailings still dominate, more operations are moving to thickened tailings. For now, the economic case for paste and filtered tailings is not yet strong enough for widespread adoption, particularly for large mines.

As with tailings, a number of approaches are also being developed to manage waste rock. A simple approach is to segregate and specifically treat waste rock that has the potential to produce poor-quality drainage. More benign waste rock can be re-purposed for the construction of haul roads or tailings dams. In addition, waste rock can sometimes be co-located with tailings to improve waste stability. Whereas waste rock is strong and self-supporting, tailings are fine and inhibit airflow, and these different characteristics are useful when combined. Fine-grained tailings can fill in the void air spaces in waste rock piles, giving the combined mass greater stability, while also limiting the replenishment of oxygen. Current efforts are focused on developing methods to mix tailings and waste rock to achieve optimal performance. Another common reclamation approach for both tailings and waste rock is to cover the waste, with the goal of minimizing water and airflow, and limiting oxygen supply. Proper cover design requires a good understanding of local climate and ecology as the sites revegetate over the long term. The use of water to cover waste can be very effective in reducing or eliminating oxidation, but only where there is no risk of loss of containment, drought or dispersal into food webs. As new approaches are tried, and lessons learned, it seems inevitable that significant progress will be made in the effective management of mine waste. The question is whether this progress will be fast enough.

Much has changed over the ten years since the Mount Polley tailings failure. A new global standard of tailings management has been established, and the risk of liquefaction and sudden catastrophic damage has become better understood, reduced and, in some cases, eliminated. Many promising technologies are now emerging, but these are not yet cost effective and will likely take significant time for widespread adoption. Continued innovations are needed to drive down costs, but society will also likely have to accept increased prices associated with greater environmental protection. In the long term, mine waste management will have to be a temporary problem—a bridge to a circular economy based on the reuse and recycling of metals.[2] In the meantime, the Mount Polley Mine has now resumed operations, with about another ten years of productive life left.

Endnotes

1 Global Tailings Review, *Global Industry Standard on Tailings Management* (2020), https://globaltailingsreview.org/wp-content/uploads/2020/08/global-industry-standard_EN.pdf

2 See also ‘A New Life for Old metals’ by Maria Holuszko in this volume.