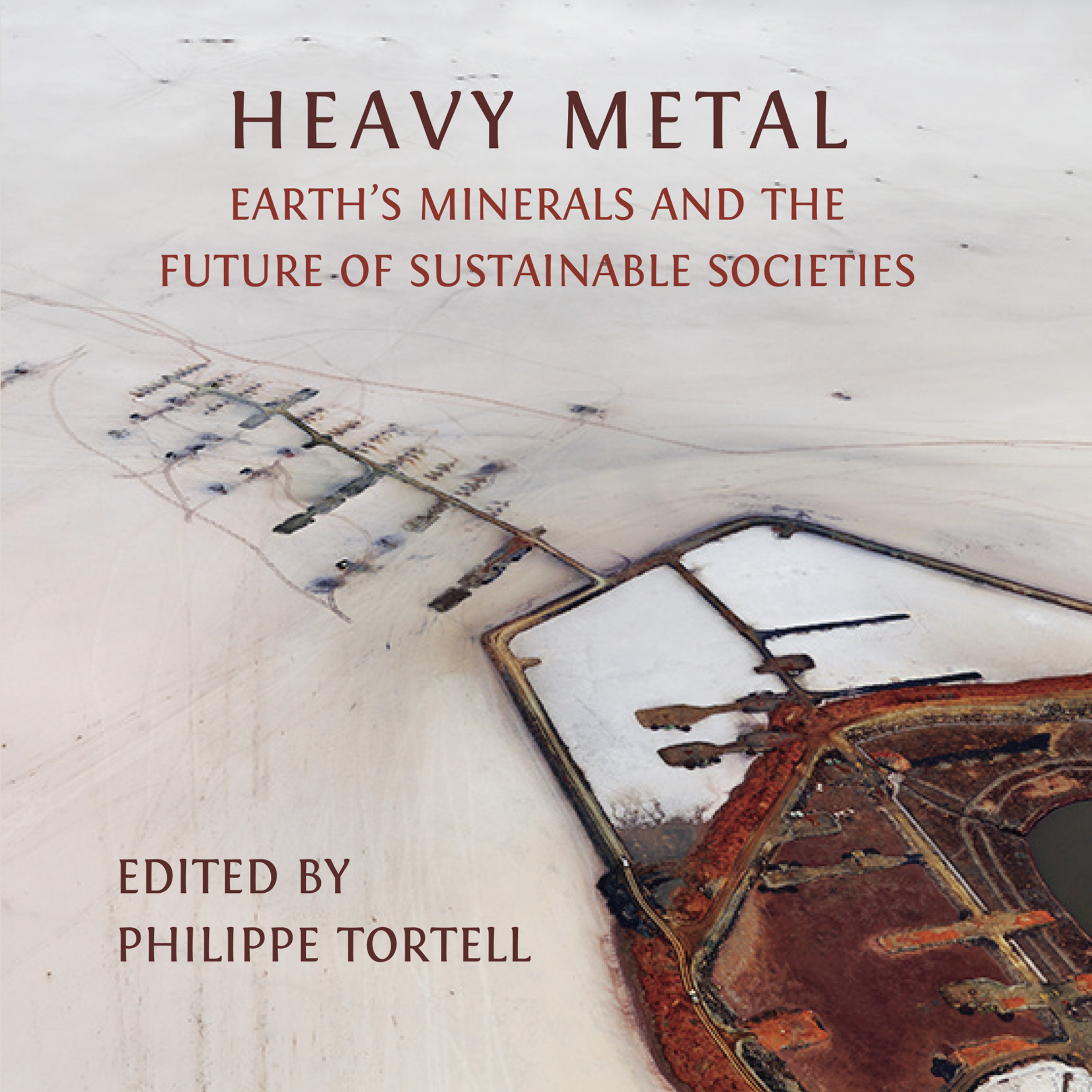

HEAVY METAL

EARTH'S MINERALS AND THE FUTURE OF SUSTAINABLE SOCIETIES

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Lithium

Lee A. Groat

Lithium (from the Ancient Greek *lithos* or 'stone') is the third element on the periodic table. It contains just three protons, three electrons and four neutrons, and was one of the first elements (along with hydrogen and helium) created when the universe formed almost fourteen billion years ago in the Big Bang. The element, abbreviated chemically as Li, was discovered in 1817 by the Swedish chemist Johan August Arfwedson, and its basic chemical properties are now well known. Pure metallic lithium is silvery-white and soft enough to be cut with a knife. It is the least dense of all metals and can float on water. Like all so-called alkali metals, including sodium and potassium, lithium is highly reactive and flammable and must be stored under an inert atmosphere without oxygen or with a hydrocarbon coating, such as petroleum jelly. Over the past two centuries since its discovery, lithium has found its way into a wide range of applications, from metal alloys used in airplanes, trains and bicycles, to ceramics, lubricants and fuel for nuclear weapons. It has also been used in some medical applications, most notably in the treatment of bipolar disorder. Despite its widespread use, most people rarely think about lithium, and just a few years ago, few, if any, would have suggested that it might hold the key to the future energy transition.

The importance of lithium for renewable energy and electric transportation dates to the early 1990s, when Sony commercialized re-chargeable lithium-ion batteries.

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Back then, about 10,000 metric tons of lithium were mined annually around the world. With the widespread adoption of mobile electronic devices over the subsequent quarter century, lithium production increased about ten-fold, reaching slightly more than 100,000 metric tons by 2021. Much of this increase has occurred in recent years; over the past decade alone, lithium production has nearly quadrupled, and in just one year, between 2021 and 2022, production jumped by 30%.[1] This sharp rise in lithium production has been triggered by the rapid expansion of rechargeable lithium batteries used for electric vehicles (about ten kilograms of lithium per vehicle), portable electronic devices and grid storage applications.[2] As expected, surging demand is driving significant price increases, with a three-fold jump in lithium price just between 2021 to 2022. The situation is expected to get significantly worse, as the International Energy Agency predicts a large (forty-fold) increase in global lithium demand by 2040.[3] Today, lithium is now considered as one of the 'critical minerals' essential for the transition to renewable energy and green technologies. With our growing reliance on this metal, important questions are now being raised about how and from where we can supply enough lithium to meet society's future needs.

Compared to many other metals, lithium is not particularly scarce. It is the twenty-fifth most abundant element in Earth's crust, with about one hundred million metric tons present at concentrations ranging from twenty to seventy milligrams (mg) per kilogram (kg) of rock. There are additional large sources of lithium in the oceans, with seawater concentrations ranging from about 0.14–0.25 mg per kg, and up to 7 mg per kg near hydrothermal vents. Yet, despite the high abundance of lithium, its extraction into useful forms is surprisingly challenging. The metal does not occur freely in nature (as is the case for some forms of mined copper, gold and other elements), but rather exists trapped in various hard rock minerals, or as salts in underground brines.

Lithium-containing minerals are rich in silicate, and have names like spodumene, lepidolite, amblygonite and eucryptite, which evoke a superhero fantasy world. These minerals occur in a rare type of rock called pegmatite that is derived from cooling molten lava often associated with granite. When waters separate from the cooling magma in the late stages of crystallization, various elements are enriched in the liquid phase, including lithium, niobium, tantalum, tin, cesium and rare-earth elements (REEs). These mineral-rich fluids are incorporated into pegmatite crystals, which have been called 'scientific wonders',[4] due to their enormous grain-sizes. In extreme cases, such as the pegmatites found in the Black Hills of South Dakota, individual crystals can reach more than ten meters in length, forming at a rate of up to one to ten meters per day[5]—stunningly fast relative to most geological processes. These enormous crystals are not only a rich source of critical minerals, but also of quartz, feldspars and micas for industrial uses, as well as many of the world's finest gem and mineral specimens, including varieties of beryl, topaz and tourmaline.

Lithium minerals are recovered from pegmatites using standard hard-rock mining techniques, similar to those used for other metals such as copper. This involves extracting an ore through drilling and blasting, followed by crushing and chemical processing to concentrate the metal into a useful form. This may sound simple, but it is challenging, particularly for lithium. From a chemical perspective, lithium minerals are very stable, so that large amounts of energy are needed to extract the metal from host minerals. Current approaches typically only recover about 60–70% of lithium from mined rocks. The main forms of lithium obtained from pegmatites are lithium oxide (Li_2O), and lithium hydroxide (LiOH). These chemical species are the ones used in batteries, and this has created continued demand for rock-based lithium sources.

Another important source of lithium comes from brine pools, where it can accumulate to high concentrations as lithium carbonate salt (Li_2CO_3). The largest accumulation of brine lithium occurs in a region known as the 'Lithium Triangle', which stretches across a large expanse of the high Atacama Desert in Chile, Bolivia and Argentina.[6] This region contains more than half of the known global reserves of lithium. It also contains unique and fragile ecosystems, including Chile's Salar de Atacama, Argentina's Salar de Arizaro and Bolivia's Salar de Uyuni, which has been designated as a UNESCO World Heritage Site.

Relative to rock-based sources of lithium, extraction of the element from brines is relatively simple; the brines are exposed to the hot desert sun, and the concentration of salts increases as water evaporates. During this process, various salts crystallize at different times as the solution becomes more concentrated. Lithium is among the first elements to precipitate, along with manganese, potassium and others. These salts are filtered out of the ponds, and the residual liquid pumped into a new evaporation pond, repeating the process until the brine attains a lithium content of about 6%, after twelve to eighteen months.[7] Lithium carbonate is then extracted from the concentrated brine, with a typical recovery rate of about 50% or higher. Proponents of this approach point out that the process is largely based on renewable energy (sunshine), and is much more energy efficient than rock-based lithium mining, which requires significant energy for drilling, blasting and crushing. On the other hand, the extraction of lithium from brines is extremely water intensive; an estimated 1.9 million liters of water are used to produce each metric ton of lithium,[8] and all this water is lost to evaporation.[9] The high dependence on water is particularly problematic in the desert regions where these operations take place. The Atacama Desert is the driest place on Earth; it receives about one millimeter of precipitation each year, and some areas have not seen any rain in several centuries.

As global demand for lithium soars, countries and corporations around the world are scrambling to identify reliable sources of this element. In addition to South America's Lithium Triangle, other countries with notable lithium resources include the United States (~12%), Australia (~8%) and China (~7%).[10] At present, lithium production remains highly concentrated in a few locations. In 2022, approximately 98% of the global lithium supply came from just fifteen sites; six mines in Australia (~47%), two brine operations in Chile (~30%), three mineral and two brine operations in China (~15%), and two brine operations in Argentina (4.8%).[11] The world's largest lithium mine, Greenbushes in Western Australia, produced 22,000 metric tons of lithium in 2021, representing more than 20% of global production that year.[12]

Seeking to decrease their dependence on foreign sources of lithium, nations have sought to discover and exploit their own lithium. In 2022, mineral-based lithium sources were in various stages of development or exploration in Australia, Austria, Brazil, Canada, China, the Democratic Republic of Congo, the Czech Republic, Ethiopia, Finland, Germany, Ghana, Kazakhstan, Mali, Namibia, Nigeria, Peru, Portugal, Russia, Serbia, Spain, Thailand, the US and Zimbabwe. In 2022, brine-based lithium sources were in various stages of development or exploration in Argentina, Bolivia, Chile, China and the US.[13] Other sources of lithium are also being explored. These include the leachates of geothermal wells, where the lithium can be separated by simple filtration, and lithium-containing clays, which are in various stages of development or exploration in Mexico and the US.[14] In addition, electrical methods have been proposed to extract lithium compounds from seawater.[15] Between all these sources, it is likely that the world will be able to meet its future demands for lithium, provided that new sources can be brought into production quickly. This contrasts sharply with the situation for copper, where a clear supply gap is expected to develop over the next two decades.[16]

Even if there is enough lithium to supply the world's demands, the uneven distribution of current resources sets up potential for geopolitical rivalry. Competition for battery production capacity is emerging as a key element in the race to dominate global electrical vehicle production. China, in particular, has made significant investments to position itself as a leader in this race.[17] At present, Chinese companies dominate global lithium refining, even though China has only 7% of world lithium resources.[18] To secure additional primary resources, Chinese companies have been investing in lithium mines throughout the developing world, spending about 4.5 billion dollars acquiring stakes in twenty lithium mines, mostly in Latin America and Africa.[19] Chinese-controlled mines are projected to account for 32% of global lithium supply by 2025, up from 24% in 2022.[20] In response to China's growing dominance of the global lithium market, Western nations have put limits on Chinese ownership of their own lithium mines, favoring domestic control instead.

Other political factors are beginning to significantly influence lithium production. In the South American Lithium Triangle, production has suffered at the hands of governments seeking greater control. In Bolivia, for example, lithium mining was nationalized in 2008, when the government created a state-owned lithium company, which spent nearly a billion dollars building a factory and other infrastructure. Nearly a decade after the factory opened in 2013, production remains virtually non-existent. In 2021, the state-owned mine produced 540 metric tons of lithium carbonate, representing less than two days of production from a typical mine in Chile.[21] Quite remarkably, the Bolivian electrical vehicle (EV) start-up firm, Quantum, imports lithium from China for its batteries.[22] In Chile, tight regulatory control over lithium resources has prevented foreign companies from investing in the industry, resulting in loss of market share to Australia and neighboring Argentina. By 2027, Chile's share of the global supply is expected to fall to about 15%, down from about 30% in 2022.[23] The situation was exacerbated in April 2023, when Chilean President Gabriel Boric announced plans to create a state-owned company to develop the country's lithium resources, leading to lower share prices for some of the world's biggest lithium mining companies. This proposal still needs to be approved by Chile's Congress.[24] Relative to Bolivia and Chile, lithium production in Argentina appears to be on a significant upward trajectory, with increased private investment, and plans develop up to nineteen lithium mines, with anticipated annual production of 230,000 metric tons by 2031.[25]

The expansion of global lithium production may ultimately be limited more by environmental and social factors than by our ability to locate and access this metal. When present in high environmental concentrations, lithium can pose significant risks to both humans and wildlife. This element can be readily taken up across cell membranes, interfering with the biological functions of other ions, such as sodium and magnesium.[26] Breathing low concentrations of lithium dust or lithium compounds can irritate the nose and throat, while higher exposure can lead to the accumulation of fluid in the lungs. Potential environmental impacts of mineral lithium mining include habitat degradation, water pollution and the adverse effects of mining wastes from the chemicals needed to extract the lithium from rocks.[27] Though some have argued that extracting lithium from brines is more environmentally friendly due to its reliance on renewable energy, this neglects the significant impacts on water use in arid regions. In Chile's Salar de Atacama, for example, mining activities consume 64% of the region's water, negatively affecting local farmers who grow quinoa and herd llamas.[28] There are also significant concerns about the potential leakage of toxic chemicals from the evaporation ponds into the water supply. These chemicals include the waste products that are filtered out from brine concentrates, which may contain large amounts of magnesium, alkaline calcium hydroxide and hydrochloric acid.

In the face of such environmental impacts, there has been growing resistance to lithium mining in many countries. In May 2016, hundreds of protesters threw dead fish into the streets of Tagong, in southwestern China. They were protesting a chemical leak from the Ganzizhou Rongda Lithium Mine, the third in seven years, which killed masses of fish in the Liqi River.[29] In Chile, local communities have clashed with mining companies over enormous piles of discarded salts, and canals filled with contaminated water.[30] In 2022, when the Chilean government awarded a lithium mining contract to Chinese EV giant BYD Company, local Indigenous communities demanded that the contract be canceled over concern about impacts on local water supplies. The Chilean Supreme Court sided with the protestors, canceling the contract on the basis that the government had failed to adequately consult Indigenous communities.[31] Increasingly, the need to achieve free, prior and informed consent (FPIC), as stipulated under the United Nations Declaration on the Rights of Indigenous People (UNDRIP), is being held up as a standard for lithium mining operations. In 2021, Indigenous protestors occupied a proposed lithium clay mining site at Thacker Pass, Nevada, arguing that they had not been adequately consulted in the face of significant impacts on their cultural, social and religious practices. In 2023, the US District Court in Nevada ruled that the mine could go forward, a decision that was subsequently upheld by the US Court of Appeals.[32] It remains to be seen if other lithium projects will be blocked by the courts.

Looking to the future, we will need to reduce our dependence on primary lithium extraction to support the transition to renewable energy and electric vehicles. Significant efforts are being put towards developing new battery technologies that use alternatives to lithium, including sodium and magnesium, which can be extracted in great quantities from seawater. Sodium-ion batteries, in particular, have been the focus of much research over the past few years. These batteries have the added advantage of not requiring other rare elements, such as cobalt and nickel, and also being less flammable. But the larger size of the sodium ions reduces the energy density of these batteries relative to lithium-based versions, so it is unlikely that we will move entirely away from lithium batteries any time soon.

In the meantime, new recycling technologies will be needed to reduce our dependence on primary lithium extraction.[33] Past recycling efforts have been inefficient and rather haphazard, but significant progress is now being made. Construction of lithium battery recycling plants is increasing rapidly; as of 2022, over one hundred companies in North America and Europe were either recycling lithium batteries or planning to do so soon. But even with significantly increased recycling capacity, we will still see an increase in new lithium-containing consumer products. The first all-electric car with lithium-ion batteries, the Tesla Roadster, was only introduced in 2008. Many of these vehicles have not yet reached their end of life, and the number of new electric vehicles is expected to grow significantly over the coming decades.[34] As countries around the world race to transform their energy and transportation systems to mitigate the worst possible effects of climate change, it is almost certain that lithium will continue to be critically important. With adequate attention to legitimate social and environmental concerns around lithium supply, we should be able to responsibly meet the world's future needs for this element.

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